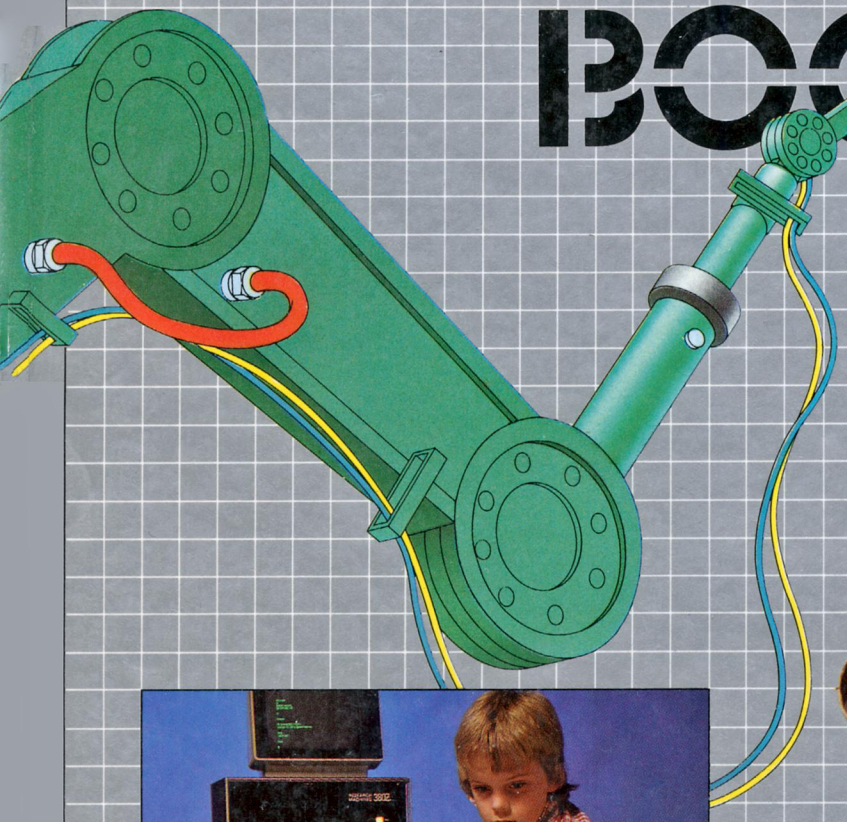
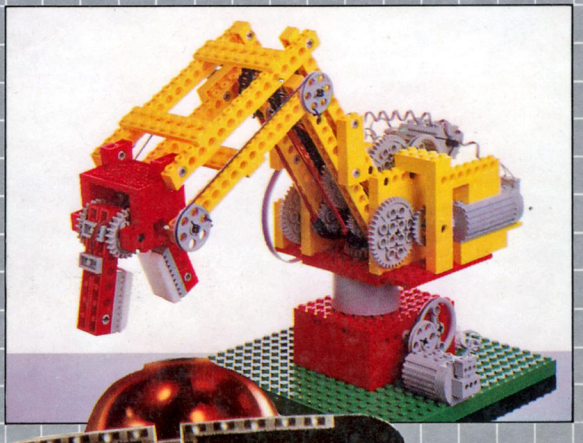
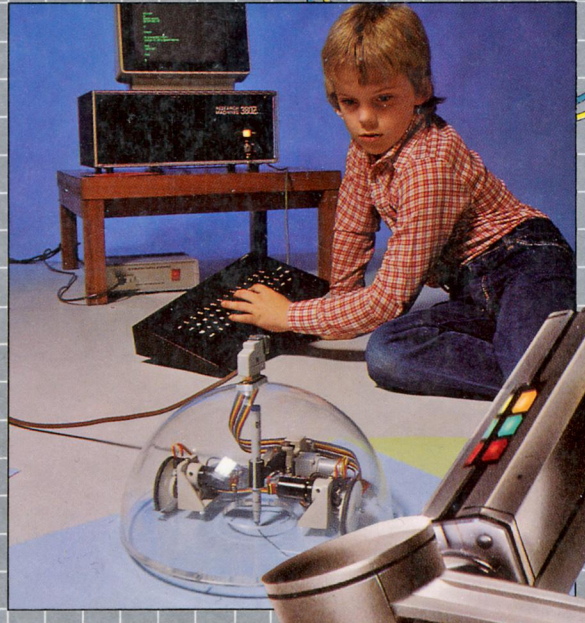
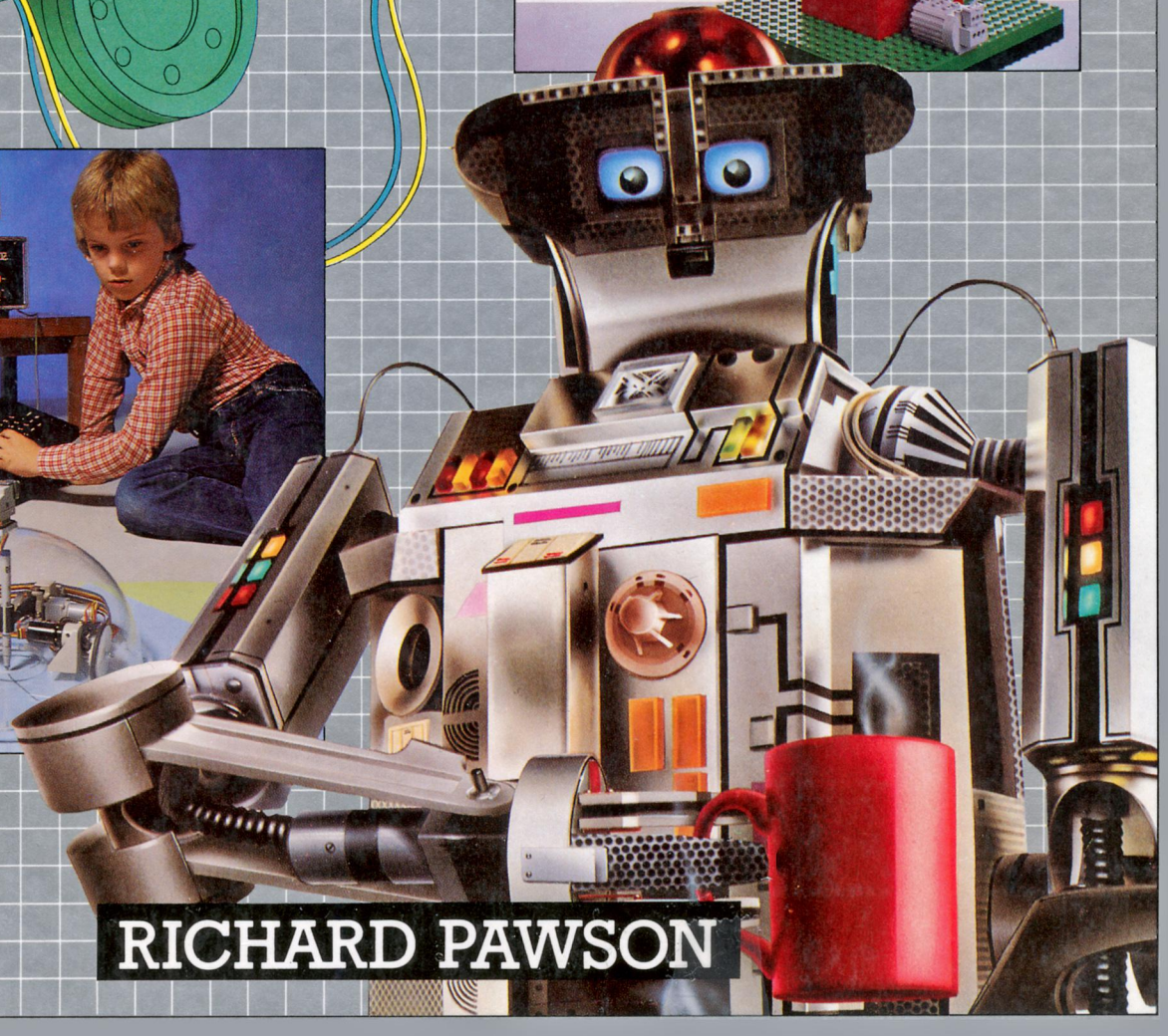
THE ROBOT BOOK









RICHARD PAWSON

THE ROBOT BOOK

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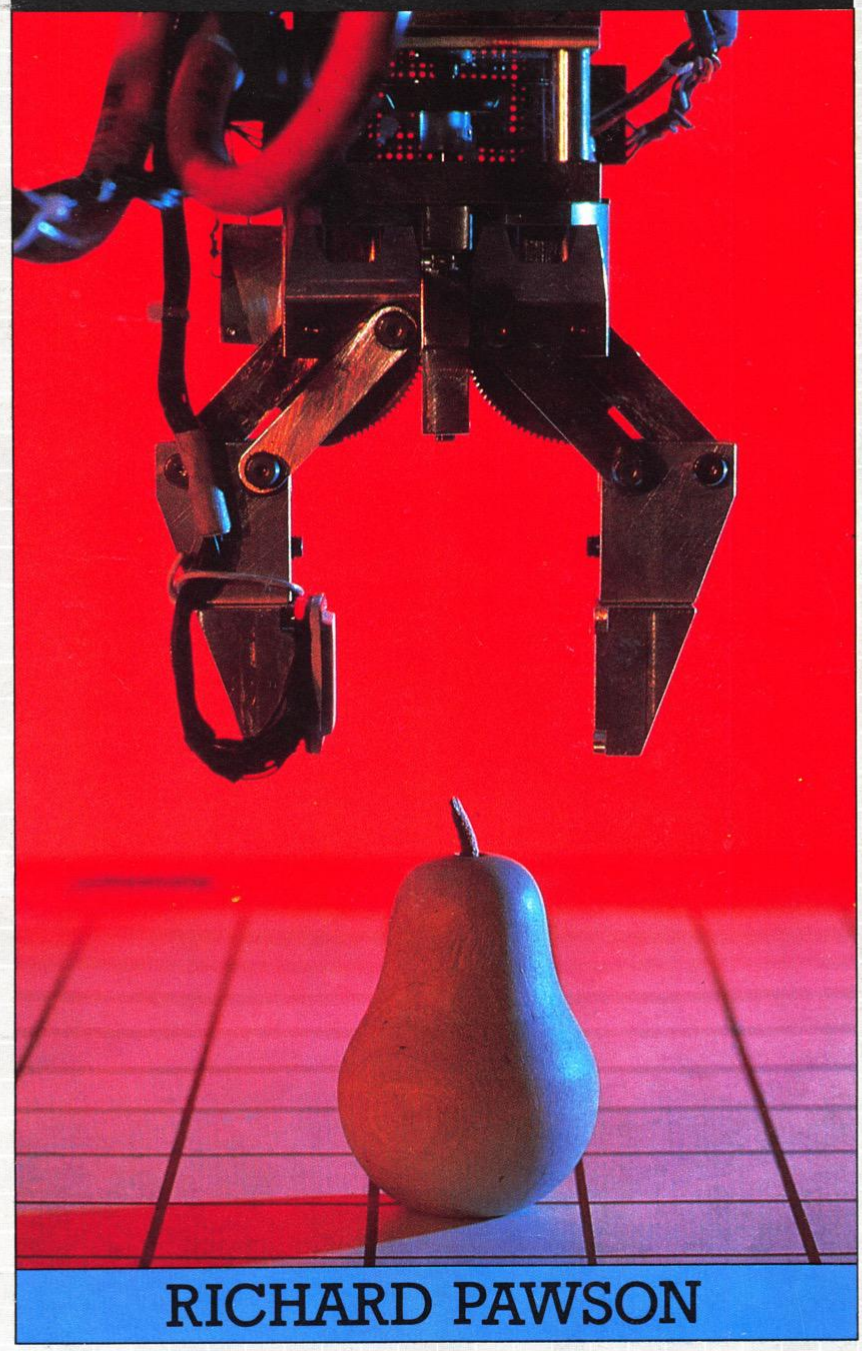

RICHARD PAWSON

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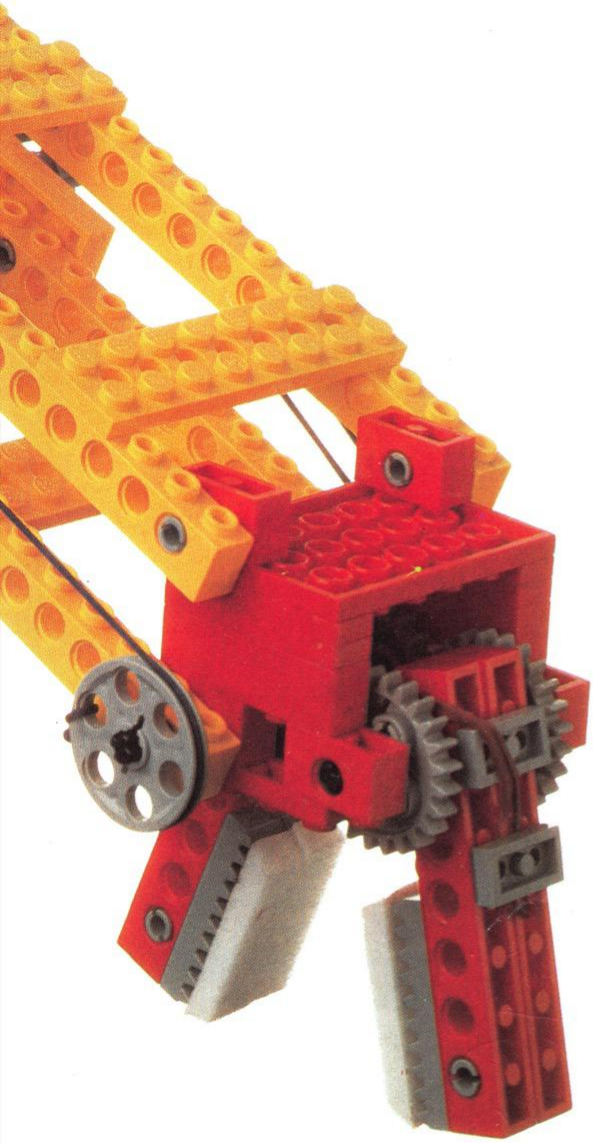
CONTENTS



INTRODUCTION 6

PART 1 HISTORY OF ROBOTS 8
The origins and development of robots in fact and fiction

PART 2 ROBOTS IN ACTION 28
The types and applications of robots in use today

PART 3 HOW ROBOTS WORK 58
Robot theory and technology for the home robot user or experimenter

PART 4 PRACTICAL PROJECTS 100
Robot devices to build and to control with a home computer

COMPONENTS CHECKLIST FOR PROJECTS 182

GLOSSARY 183

USEFUL ADDRESSES 186

FURTHER READING 187

INDEX 188

ACKNOWLEDGEMENTS 191

INTRODUCTION

All through history, human beings have sought means of amplifying their own effectiveness. The lever, the wheel, the bow and arrow, explosives, the steam engine – each invention increased humanity's ability to influence the environment. Then came the computer and, with it, the possibility of enhancing the scope of the brain, not merely the muscles.

The problem with amplifiers, as any hi-fi enthusiast knows, is that they amplify whatever is fed into them, not distinguishing desirable from undesirable signals. Amplifying people's muscles and mind has the secondary effect of amplifying their underlying nature. In short, such devices increase their power for doing good and for doing evil. Today, we face the prospect of the most comprehensive amplifier ever built – the robot. A robot is a machine made in the image of a human being and, while it may lack the versatility of the original model, in some respects it will improve on the specification.

There is an uneasy feeling in most of us that a machine made in our image would reflect our vices rather than our virtues, and this has been a recurrent theme in science fiction. It need not be the case, however, and certainly for the moment, beneficial applications for robots far outnumber sinister ones.

The greater the number of people who understand robots, the greater the chance we have of maintaining that balance, for the most dangerous science is the science constrained to the domain of experts. Fortunately, robotics is a science that can readily be understood by anyone prepared to try, and it is a science in which anyone can participate. The kitchen table is a perfect substitute for the laboratory workbench – something that distinguishes robotics markedly from biotechnology, particle physics and microelectronics.

Moreover, robotics is an embryonic science, and for the next couple of years at least, anyone prepared to experiment with building their own robots, at home or in school, stands a good chance of contributing to the state of the art.

Real robots (as distinct from the fictional variety) have been around since the 1950s, yet it has taken until the mid-1980s for there to be a real explosion in their application. One of the main triggers for this has been the birth of the personal robot market.

To many people, the term 'personal robot' is a contradiction in terms, and very few have identified the real significance of the idea. It is best understood by comparison with the dawn of the personal (micro) computer. Prior to the micro, computers were large and expensive items. They could only be installed in air-conditioned computer rooms, had to be managed by trained data processing staff (who saw themselves as the high priests of computation), and their huge cost made them usable only to very large-scale applications, such as stock control and accounts.

The personal computer represented a revolution not only in price (reducing the entry-level by a factor of twenty or more) but also in availability. It required no more installation than a mains plug, and it was available for use as soon as it was switched on. However, because the first microcomputers were all bought by home enthusiasts, large computer manufacturers dismissed them as toys. Effectively, the microcomputer put computing power into the hands of people whose imagination wasn't constrained by formal training in computers and, therefore, by preconceived ideas of what is and what isn't possible. People started to apply computers to much smaller, but still highly productive, tasks.

Currently, the applications for large robots are very limited – paint spraying, stacking pallets and so forth. Large robot manufacturers may well dismiss the new generation of personal robots costing from £30 to £3000 as mere toys, but the fact is that personal robot owners will do more to widen the scope of robotics than the manufacturers ever will. The availability of a robot camera for home computers costing around £100, for example, will probably achieve more for robot vision than twenty years' research in academic institutions.

The main problem facing the personal robot is that, thanks largely to *Star Wars* and its like, it is a technology that, unlike any other in history, comes complete with a mass of preconceptions that it cannot live up to. *Newsweek* magazine summed it all up: 'Now one can actually go out and buy something that looks like R2D2. But this R2D2 won't help rescue Princess Leia. In fact, it won't even take out the trash.'

Really, this is the fault of the manufacturers, who have attempted to sell the personal robot in terms of usefulness and cost-effectiveness. The fact is that applications such as vacuuming the floor, patrolling for burglars and 'fetching a beer from the fridge' are not only impracticable using today's technology – they aren't even particularly desirable.

But seen as an educational tool, the robot in the home becomes a viable concept. For robotics encompasses the whole subject of computing (computer scientists will doubtless take issue with that statement; nobody likes their field to be labelled as a mere subset of another) and the greater part of engineering, too. The microcomputer has done a lot for education in the home. Learning to program is useful even if you never use a computer again, since it instils a logical approach to solving problems. One way to view personal (or micro) robots is simply as microcomputers that can interact directly with the real, physical world. Another way is to see that home robotics offers all the educational value of traditional hobbies like scale-model making, with the added dimension of computer control.

This book attempts to present the whole field of robots and robotics to the lay person. If it provides some readers with a more encouraging vision of the future, if it so outrages others that they take an informed stance against certain kinds of research or if it simply introduces a fascinating and highly educational hobby to people who thought they had stopped learning, then it will have achieved the objective.

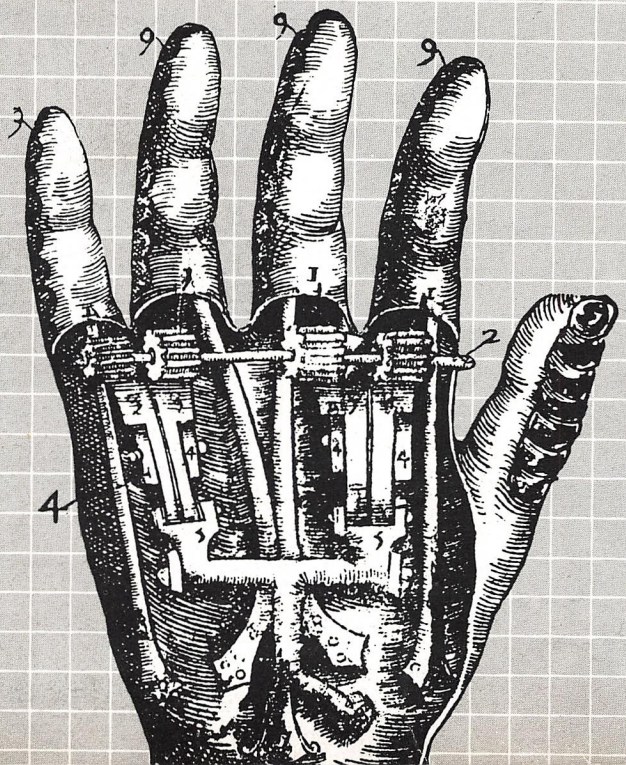
No book is entirely the work of one author alone, and I am indebted to a number of people for ideas and assistance. In the course of my research, many individuals in the robot industry and in universities gave freely of their time, and I regret that I cannot acknowledge them all personally.

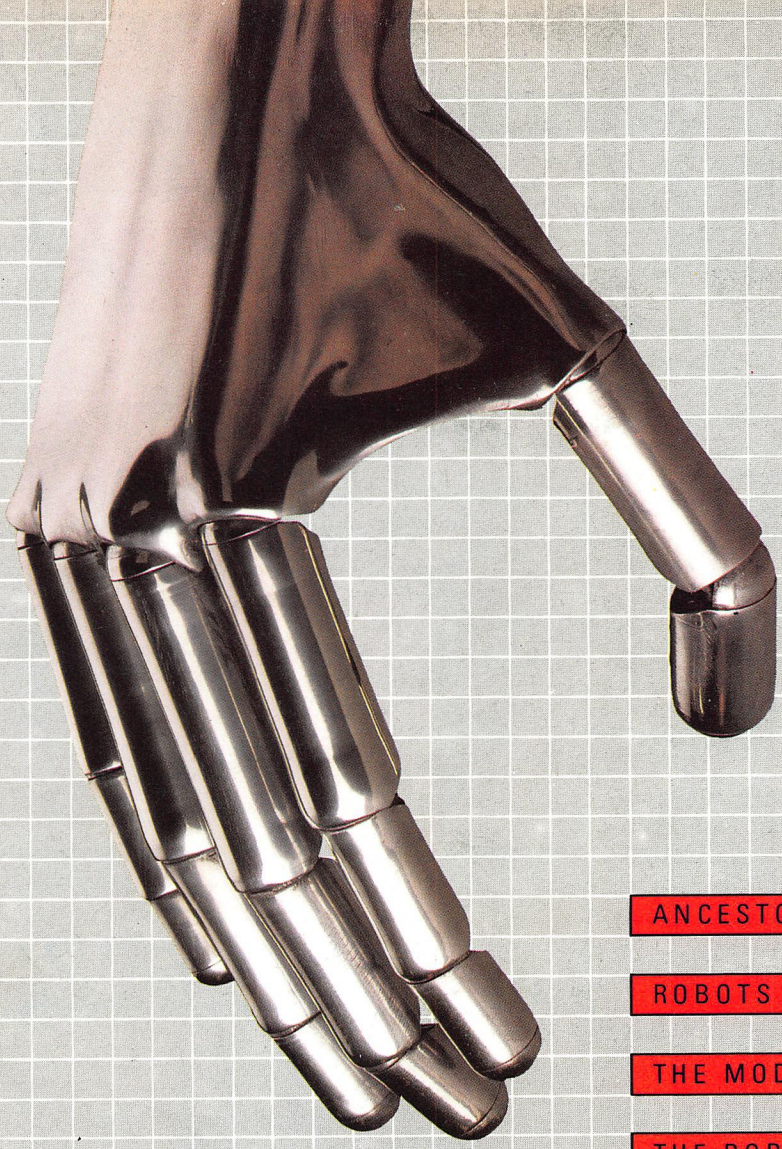
I wish to thank the whole editorial and design team involved with the production of the book, particularly for their patience in dealing with a headstrong author! Several people provided help on the Practical Projects section, in particular Martin and Nick at Fischertechnik UK and Paul Roberts whose encouragement assisted me through the doldrums that form a large part of any endeavour. I owe a great debt to my assistant, William Clark, without whose considerable inventiveness and engineering skill most of the projects would never have left my drawing board. But most of all I should like to thank my father, who taught me from an early age to inquire into how things work, and to whom I should like to dedicate this book.

Richard Pawson Henley-on-Thames, 1985

PART 1

HISTORY OF ROBOTS





ANCESTORS OF THE ROBOT 10

ROBOTS AND CONTROL 12

THE MODERN ROBOT 14

THE ROBOT IMAGE 16

THE IMPACT OF ROBOTS 24

THE FUTURE FOR ROBOTS 26

ANCESTORS OF THE ROBOT

The last quarter of a century has seen more technological innovations than in the rest of history combined. Yet among them, the robot is unique. First, because it existed as a concept for centuries before it became a reality and, second, because of the diversity of concepts, devices and technologies that contributed to its invention.

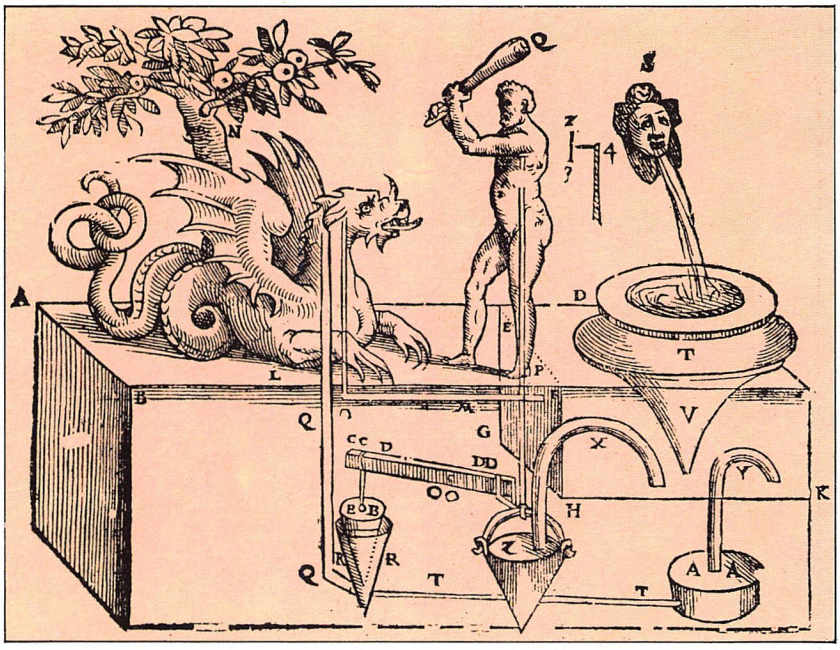
The development of the robot cannot therefore be charted in the same fashion as the motor car, the aeroplane or even the computer. Part of the difficulty lies in outlining the nature and scope of the robot – a problem tackled in the *Robots in Action* section of this book. For the moment we shall have to work with this fairly loose definition: that a robot is a machine made in the image of a human being.

On this page some of the distant ancestors of the robot are shown. Most of them are really automata (defined by one dictionary as 'mechanical devices operating under their own hidden power') rather than robots in the modern sense. Powered by clockwork or, in some cases, water pressure, the precision engineering in these devices has yet to be bettered.

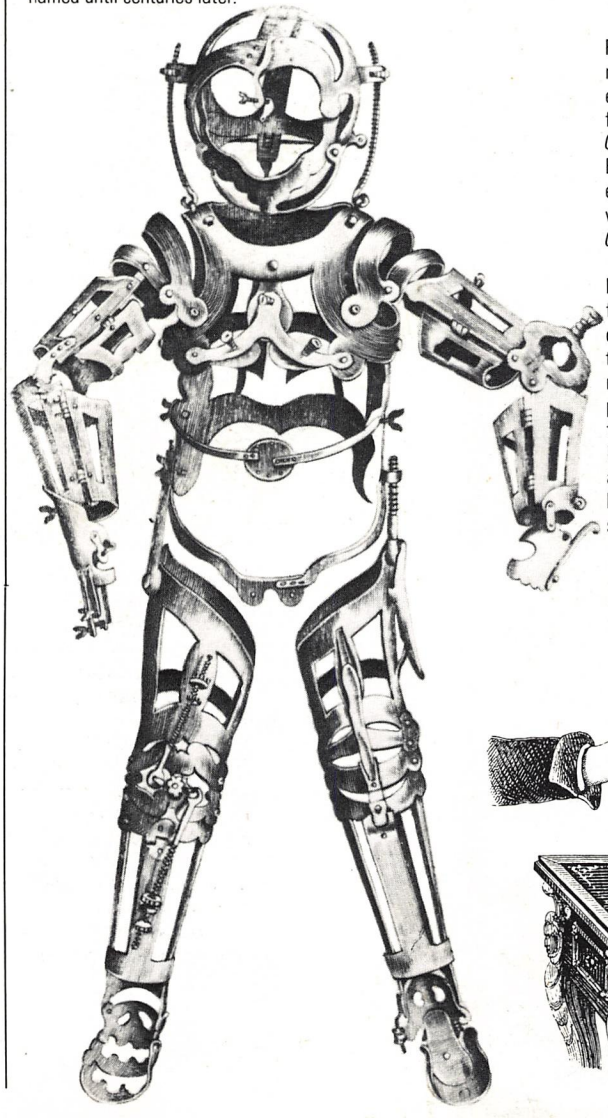
Some were designed as toys or exhibition showpieces, others as political or philosophical statements – the most famous being Pierre Jaquet-Droz's figure that could write *Cogito Ergo Sum* (I think, therefore I exist) – René Descartes' proof of existence. Few of these automata still survive, which makes it difficult to separate the genuine items from the myths. Descartes himself, for instance, is mythically supposed to have created a mechanical woman, called Francine. Apart from carrying his baggage, her purpose was to demonstrate the order and rationality of the universe, her own existence being abruptly halted by a sea captain who feared the influence of black magic.

The proliferation of automata coincided with the emergence of a philosophy holding that man himself was a sophisticated machine. Eventually, as knowledge of biology increased, the technique of explaining the body's operation as a series of intricate mechanisms gradually died away – although the concept was to be revived in the 1940s by Norbert Wiener (see page 14). However, while mechanistic views held sway the publication of *L'Homme Machine* (Man as a Machine) by Julien La Mettrie in 1748 was an influential development. His argument was that man could be explained entirely by comparison with clockwork mechanisms.

These ideas were gradually to be absorbed into popular culture, giving rise to the robots of legend, literature and film (see page 18 onwards). The birth of the real robot, however, had to wait upon more scientific developments.

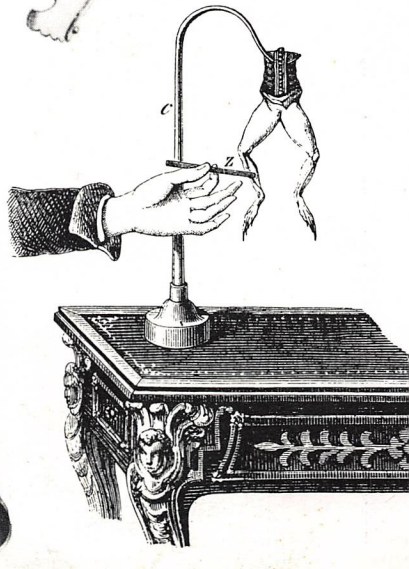


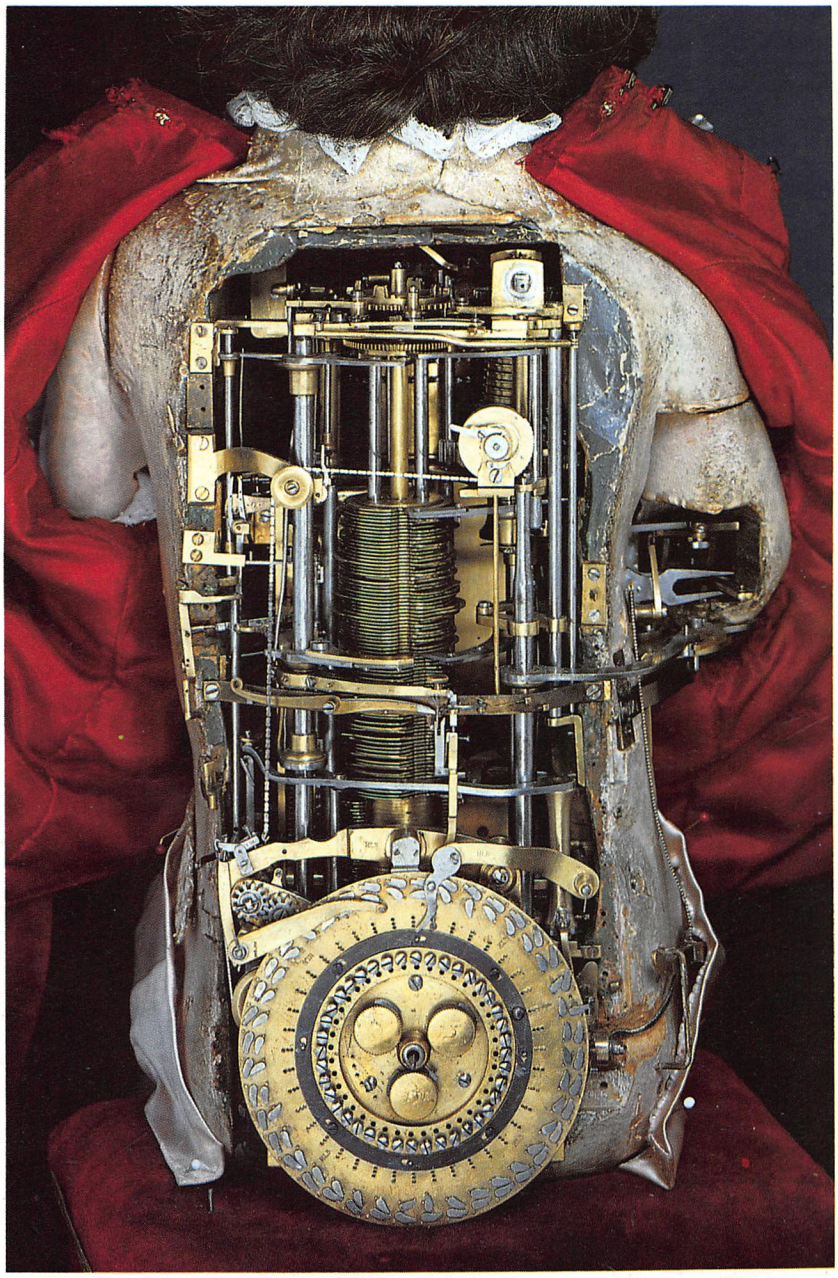
Ingenious air- and water-driven machines, this one showing Hercules slaying the dragon, were constructed by Hero of Alexandria in the first century AD. Hero used mechanisms such as cranks and cams that weren't named until centuries later.



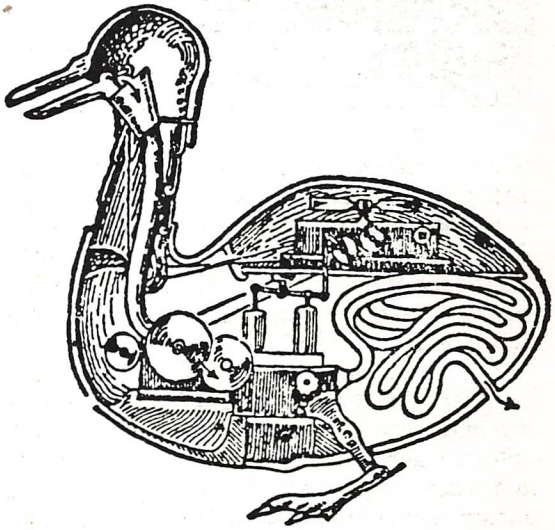
Pioneers of surgery used robot-like constructions to explain human anatomy. The figure on the left is taken from *Opera Chirurgica,* published in Bologna in 1678. The idea was effectively revived in the 1940s with the publication of *Cybernetics* (see overleaf).

Luigi Galvani's experiment with frogs' legs (below), first conducted in 1791, demonstrated the link between electricity and muscular operation – which probably provided the inspiration for Mary Shelley's *Frankenstein*. In his subsequent paper, Galvani advanced the first theory of the human electrical feedback system.

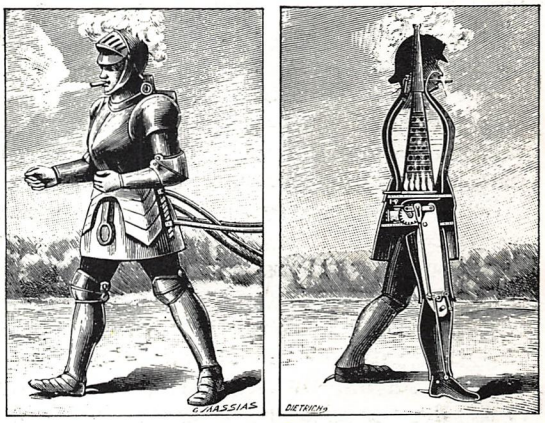




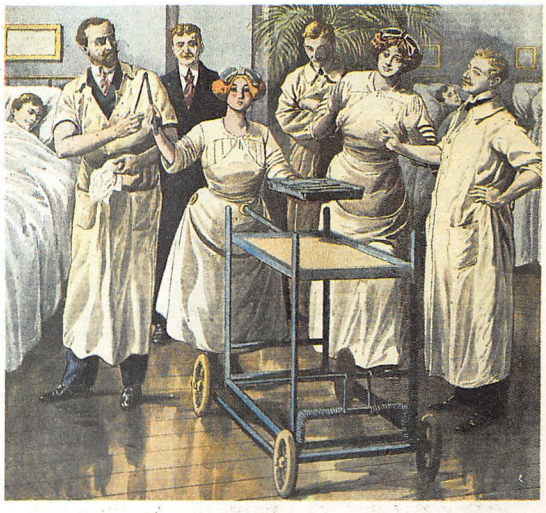
Although the automata (sophisticated clockwork novelties) of the eighteenth century contributed little to the current science of robotics, they did much to advance the concept of the mechanical man. The Writer (above and left), made by Pierre Jaquet-Droz, is one of the finest remaining examples. He dips his pen in the inkwell, shakes off the excess, and proceeds to write *Cogito ergo sum* in beautiful copperplate handwriting. The two driving drums can be thought of as an early example of programming.



Jacques Vaucanson was a contemporary of Jaquet-Droz, and something of an engineering genius. His mechanical duck (above) could take in grain, digest and then excrete it. Vaucanson is referred to by both Voltaire and Julien La Mettrie, as well as by Karl Marx in *Das Capital*.



These engravings, from *The Picture Magazine* in 1893, show a steam-driven man, invented by George Moore, claimed to be capable of about 13km/h (8mph). Exhaust from the gas-fired boiler is expelled through the helmet; the cigar was a steam outlet. The machine was described as 'a walking locomotive'.



At the turn of the century 'Mademoiselle Claire', an automaton designed by Robert Hardner, was to be found in l'Hôpital Bretonneau, handing out surgical instruments from a trolley pushed in front of her. This is perhaps a rather idealized image.

ROBOTS AND CONTROL

Building a robot, whether a walking machine resembling a human being or a faceless manipulator for a production line, is fundamentally a problem in control. There are two main aspects: maintaining precise movement under varying conditions, and enabling the machine to execute a sequence of previously determined operations. Advancement in these two fields – the former essentially a mathematical problem, the latter one of technology – provide the greatest contribution to the development of the modern robot.

One of the earliest forms of automatic control was the flyball governor, incorporated by James Watt into his steam engines from 1788. The governor worked on the principle of feedback: measuring the output of the system (in this case the speed) and feeding that information back to the input controller (the throttle).

The formal study of feedback and control systems is called cybernetics; it dates back to a book of the same name, by Norbert Wiener. He argued that the study of control and the communication of information in humans would help us build better machines and that, conversely, machines could give us insight by analogy into man's functioning – proving the point by successfully analyzing the human nervous disease ataxia. Wiener did not claim that men fundamentally were machines, but that is how the public took it, and this gave rise to fictional creations called Cybernauts or Cybermen: half men, half machines.

The other aspect of control, which we now call programming, dates back to the invention of the automatic weaving loom in 1801 by Joseph Marie Jacquard. The movements of the loom were governed by a train of punched cards (he borrowed the idea from music machines), which could easily be changed to create a new pattern. In 1886, Hermann Hollerith devised the first electromechanical card punch specifically to tabulate the US census in 1890. His Tabulating Recording Company changed its name in 1924 to International Business Machines – IBM.

Jacquard's contribution to computing was to separate the hardware (the mechanics) from the software (the control program). Charles Babbage, regarded as the father of the computer, attempted to apply the same concept more generally. His colleague, Lady Lovelace, described his Analytical Engine as weaving 'algebraic patterns just as the Jacquard loom weaves flowers'.

Today's computers are largely based on a design laid down by John Von Neumann in 1947, but the principles of operation were clearly identified by Babbage. From this point, mechanical engineering and computer control were now sufficiently advanced for the real robot to be born. All that was needed was an application.

The flyball steam governor, invented in 1788 and used to regulate speed on James Watt's steam engines, was the first widespread use of feedback. Any increase in the speed of rotation of the shaft caused the two flyballs to rise up by centrifugal action. Transferred by a suitable linkage, this movement closed the throttle slightly, causing the speed to fall back to the set value.

Surprisingly, attempts to improve accuracy by increasing the sensitivity of the governor, often resulted in violent loss of control. This phenomenon was not understood for eighty years until the physicist James Clerk Maxwell conducted the first systematic study of feedback, in his analysis of Watt's governor.

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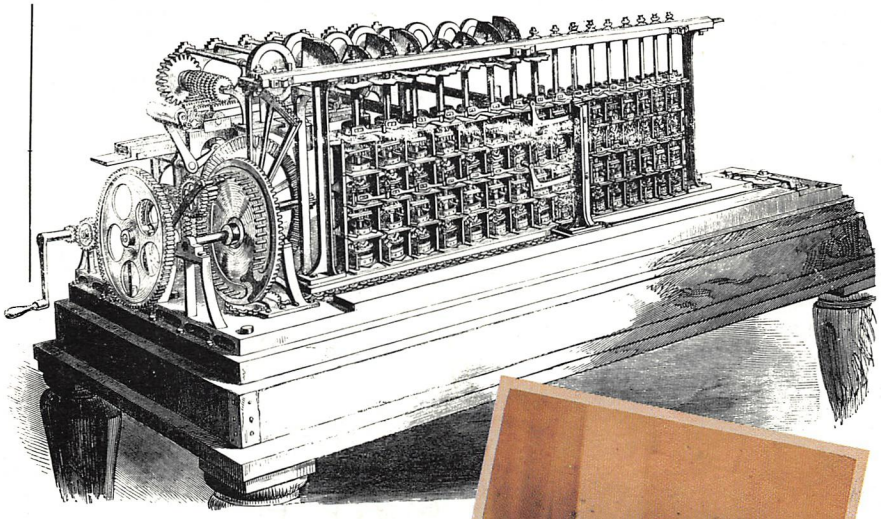
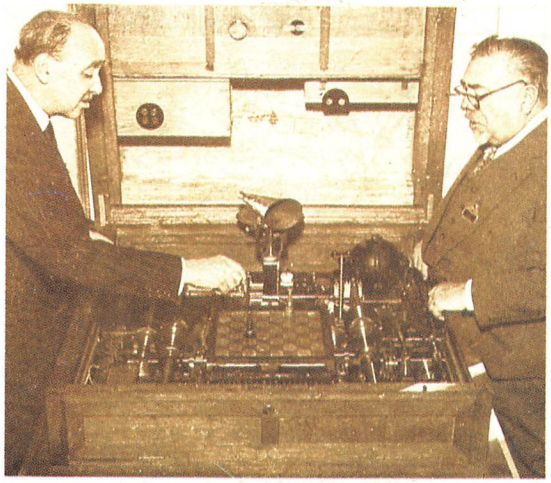


Charles Babbage (right) is regarded as the father of the modern computer. The Difference Engine (above) was conceived in 1812 in order to calculate the vast tables of the Nautical Almanac. Its development, however, was hampered by both engineering and financial constraints – the government withdrew after expenses topped £17,000.

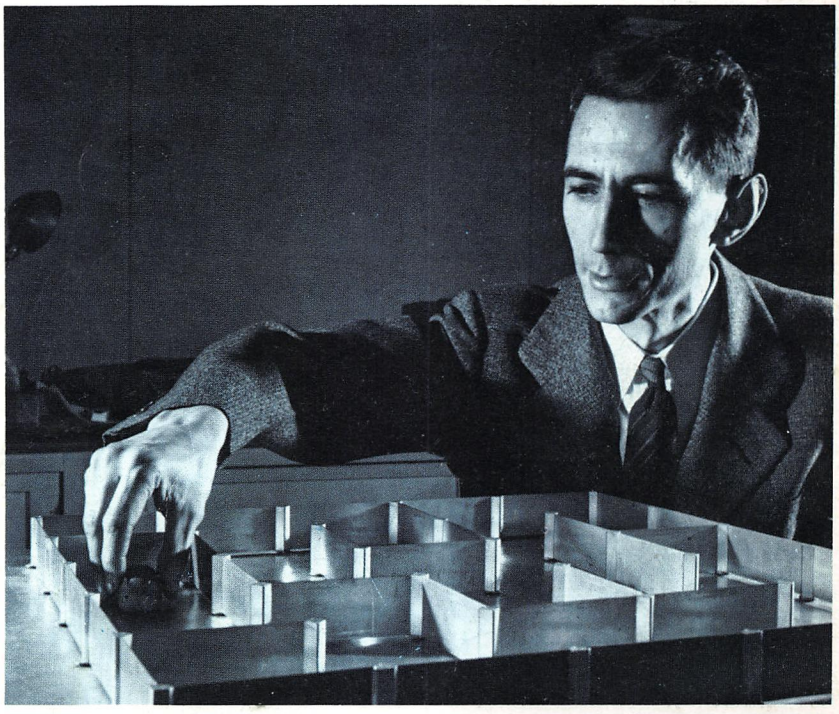
Babbage went on to devise the Analytical Engine, which, though never constructed, featured a mill (equivalent to the central processing unit on a modern computer), printed output, and could be programmed using a punched-card system borrowed from the Jacquard weaving loom.

Another important figure in the history of computing was the British mathematician Alan Turing, who devised the Turing machine – a purely theoretical machine that could decide whether a problem was computable or not – and worked on the first British computer, the Ace. He also proposed a theoretical test for machine intelligence. In this, a human examiner has to ascertain which of two test participants – a man and a machine, both hidden from him – is the machine, by asking any questions he likes and receiving answers over a teletype machine. Both test participants must try to convince the examiner, through their answers, that they are the human player. Turing proposed that if the examiner were unable to distinguish consistently the replies of the machine from those of the human, then the machine could reasonably be described as intelligent.



Norbert Wiener founded the science of cybernetics – the study of control systems in humans and machines. A child prodigy, Wiener took his first degree at age 14, and doctorate in logic at 18. During the war he worked on a gunsight that could predict the semi-random manoœuvres of aircraft. In the photograph above, Wiener is seen on the right, observing an endgame of chess played against a machine invented by Leonardo Torres Quevedo in 1912. The player was the inventor's son, and the machine won every time.

Wiener held that humans and machines were comparable at some levels, but the public interpreted his theories as indicating that man was really a machine. Despite his attempt to correct this false notion with the publication of *The Human Use of Human Beings* in 1950, cybernetics rapidly lost its initial popularity.



Claude Shannon demonstrated in 1938 that electrical relays could perform logical operations, and then devised the first general theory of information. His relay-driven mouse (above) prompted Bell Telephone Laboratories to investigate applications of computers other than for numerical calculation.

THE MODERN ROBOT

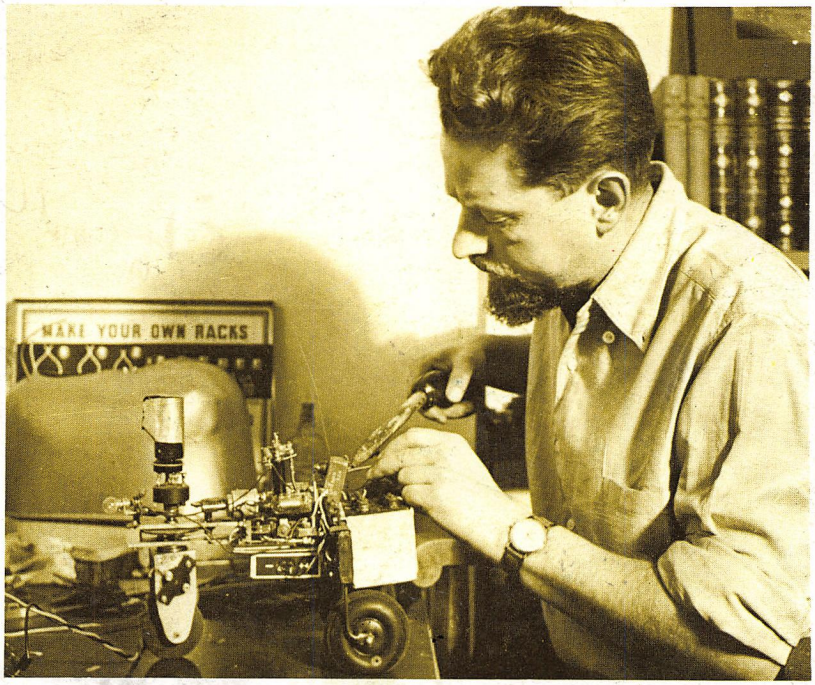
The word 'automation' came into being in the period after World War II, when large manufacturers like the Ford Motor Company started looking to improve the efficiency of mass production. Previously, the emphasis had been on mechanization – devising machines that could improve the productivity of human workers. Numerically controlled machine tools were one of the outcomes of this initiative – lathes and drilling machines programmed by punched paper tape and latterly by computer.

An American inventor, George C. Devol, recognized that this programme of automation still contained many gaps, principally in the transferring of parts from one process to another, which still had to be done by hand. Accordingly, in 1954, he filed a patent application for Programmed Article Transfer, describing what amounts to the modern industrial manipulator. This background perhaps suggests why so many industrial robots are employed in so-called pick-and-place applications, and that more imaginative uses are a very recent development.

At a cocktail party in 1956, Devol met up with Joseph Engelberger, a man whose own enthusiasm for robotics was fired up by reading the early Isaac Asimov novels. Engelberger's company, Unimation Inc., was the first to have robotics as its sole line of business, installing its first manipulator in 1961 to tend a die-casting machine. Today, Unimation remains one of the largest suppliers of industrial robots and Engelberger is one of the industry's most outspoken pundits.

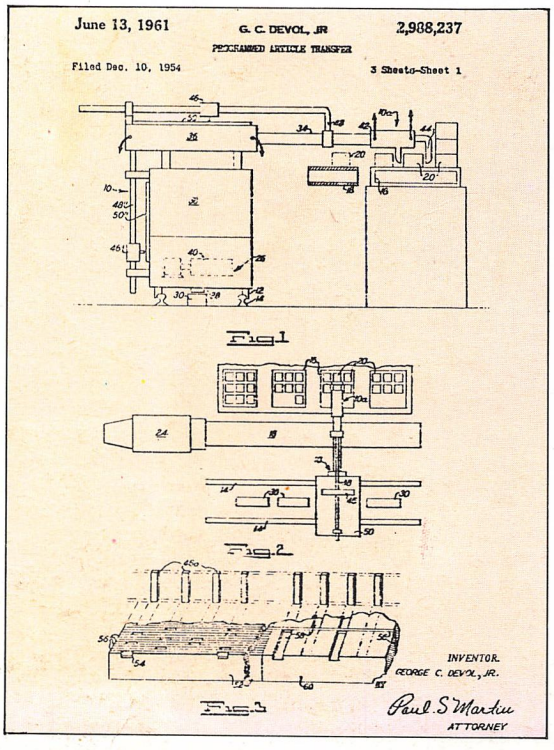
Of all the industrialized nations, the Japanese responded to the robot the most enthusiastically. Kawasaki Heavy Industries took out a licence from Unimation in 1968, and by 1971 the Japanese Industrial Robot Association (JIRA) had been formed; the Robot Institute of America followed suit four years later, and the British Robot Association in 1977. By 1983, the Japanese had installed some 16,500 industrial robots, compared with 8,000 in the USA, and 1750 for the UK.

Throughout this time, developments in non-industrial robots were confined largely to the academic community, or to ingenious novelties displayed at exhibitions in the 50s and 60s. It was not until the early 1980s, following the incredible success of the microcomputer and the accompanying fall in its price, that the idea of the personal robot came into being. 1984, coincidentally, saw the First International Personal Robotics Conference in Albuquerque, which was to become an annual event. All current prognostications suggest that the next ten years will see more innovations in the field of robotics than in its entire history up to this point.



In the late 1940s, the neurologist Dr. Grey Walter constructed a series of electronic tortoises, including Elsie (shown above), which were sensitive to light and could avoid obstacles. Elsie gave the appearance of intelligence because, when her batteries were running low, she automatically returned to her 'hutch' and plugged into the recharging socket.

Joseph Engelberger (right) founded Unimation Inc., the first company to have robotics as its sole line of business, and has remained one of the industry's most outspoken pundits. But the real father of the industrial robot is George C. Devol, who, in 1954, filed a patent application for Programmed Article Transfer. The patent (shown below right) was issued in 1961, No. 2,988,237. The illustrations may appear crude, but all the elements of contemporary industrial robots were anticipated by Devol, including program control and positional feedback (see pages 74–75). 'Unimation', a contraction of Universal Automation, was Devol's generic description for this new type of equipment.


June 13, 1961 G. C. DEVOL, JR 2,988,237

PROGRAMMED ARTICLE TRANSFER

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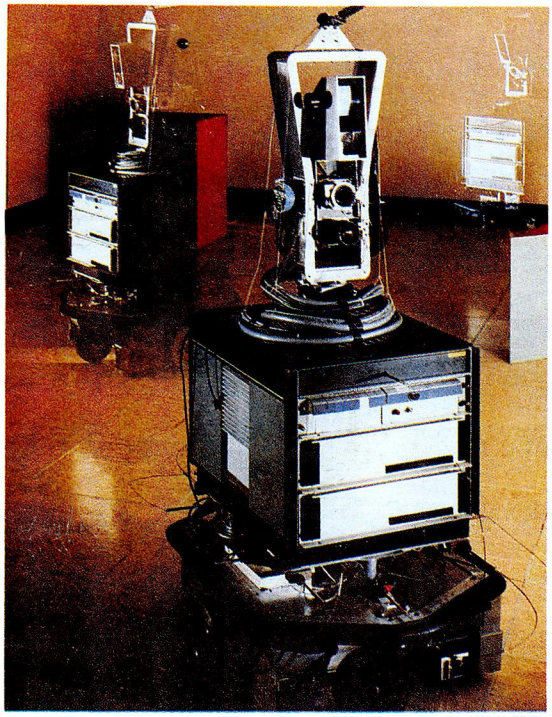
Fig. 1

Fig. 2

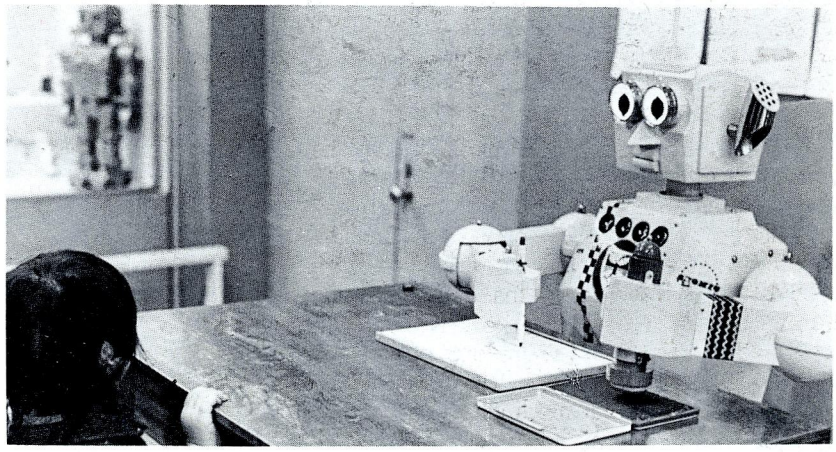
Fig. 3

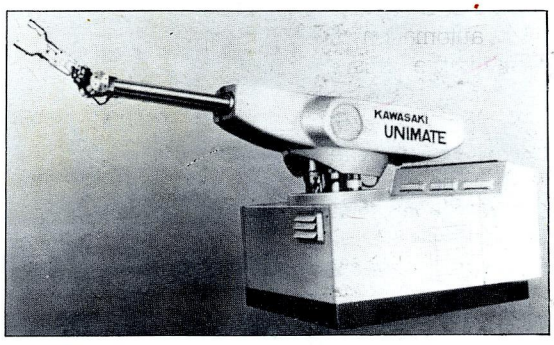
INVENTOR. GEORGE C. DEVOL, JR.

Paul S. Mardu ATTORNEY



Shakey (above), developed in 1968 at the Stanford Research Institute, was the first sophisticated mobile robot. It featured a television camera, optical rangefinder, bump detectors and radio link to a computer.





Nowhere has the robot caught the public imagination more than in Japan, where androids are a common sight at exhibitions and in department stores (above). The Japanese were also very quick to realize the potential of the industrial robot in labour-intensive manufacturing. Kawasaki Heavy Industries manufactured their first industrial robot (left) in 1968, under licence from Unimation, and Japan now has more robots than any other nation.

The personal robot came one step closer to being a reality when Nolan Bushnell (founder of the Atari computer and video games company) established Androbot. Bushnell is seen here with TOPO, a domestic robot, controlled from a personal computer by means of an infra-red link. There are now dozens of small companies pursuing the goal of a low-cost robot that can perform a useful task and advances are being made all the time.

THE ROBOT IMAGE

For centuries before it became a reality, the robot existed in the popular imagination. The word 'robot' wasn't coined until 1917, in a story called 'Opilec' by Karel Capek, followed shortly by his better-known play: *R.U.R.* (Rossum's Universal Robots). 'Robotics', too, comes from fiction rather than science – Isaac Asimov first used the word in *Runaround*, published in 1942. But the concept of the artificial man existed in legend and literature long before that.

Myth

According to Greek legend, Pygmalion carved a beautiful marble statue and promptly fell in love with it. The goddess Athena was touched at his devotion and brought the statue, Galatea, to life, whereupon they were married and lived happily ever after. Or so one supposes . . . ; in his acclaimed manual on industrial robotics, *Robots in Practice*, Joseph Engelberger opines that after the honeymoon, Pygmalion put Galatea straight to work!

Prometheus, by contrast, took matters into his own hands – stealing fire from heaven to bring alive the first man and woman, which he had made from clay. This sort of behaviour, it seems, doesn't please the gods – similar stories exist in many religions, and the perpetrator invariably receives his comeuppance.

By the nineteenth century, however, religion was starting to give way to science as a popular obsession. Luigi Galvani had already demonstrated that there was at least some connection between (animate) life and (inanimate) electricity, and the public was generally suspicious of the new breed of medical scientists who were widely believed to be grave robbers.

Monster

It was against this background that Mary Shelley published *Frankenstein* in 1818. Although it has inspired film directors for the greater part of the twentieth century, few have managed to convey the powerful ideas of the original story. The sinister Dr. Frankenstein constructs his monster from human spare parts and then brings it to life using electricity. At first the monster is quite benign; it is only when the Doctor realizes the enormity of his actions and rejects the monster that it turns against him. Although Frankenstein did not invoke any supernatural powers, the suggestion was that life was sacrosanct and to meddle with it was to court disaster.

The Luddite riots, in which textile workers smashed new weaving machines, had preceded the book by just a few years – these were the first serious opposition to technology encroaching on traditionally human domains. From that time, the robot can be seen as a metaphor for mechanization – the ultimate machine, capable of emulating every function of a person. The artificial men and women of literature, sculpture and art thus became more mechanical in appearance.

Master

The suggestion that the robot would eventually dominate the scene became more subtle. Instead of turning against their creators, the new, improved version of humanity would simply supersede the previous model. Charles Darwin's *Origin of Species*, published in 1859, suggested that man had only made it to the top of the evolutionary ladder by natural selection and that there was no fundamental reason why he shouldn't be displaced. The invention of the computer – it was only natural to call it the electronic brain – seemed to be the last nail in the coffin. The muscles of human beings had been superseded by machines many decades previously, now the intellectual uniqueness of the species was being questioned.

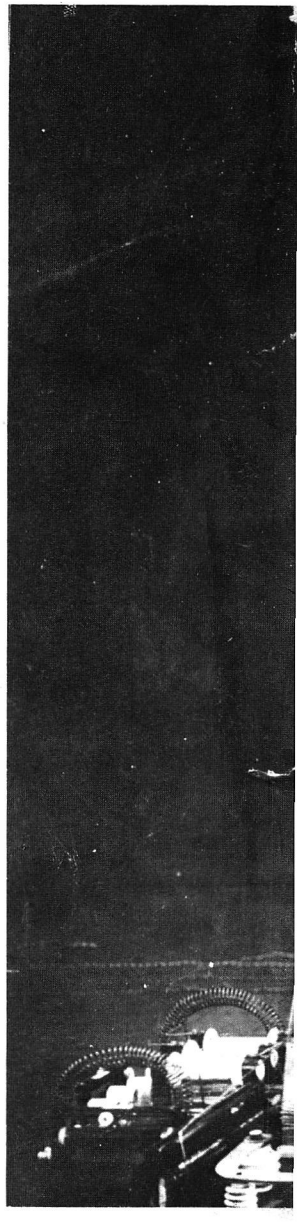
The legend of the *Doppelganger* held that a person's impending death was signalled by the appearance of his double. Such a spectacle would undoubtedly be unpleasant, but what is especially eerie is the suggestion that the person is no longer a unique identity and his end must follow shortly. Some people view the robot as a mechanical equivalent of the Doppelganger – not so much a physical threat, but a challenge to our individuality.

The fictional robot, then, is usually just a manifestation of our deep-rooted and often subconscious fears. Some science-fiction writers have suggested that robots are an altogether too dangerous quantity to coexist with man on this planet, and that their application should be restricted to the exploitation of outer space. Others have explored the consequences of such outlaws breaking loose from their colonies and returning to earth.

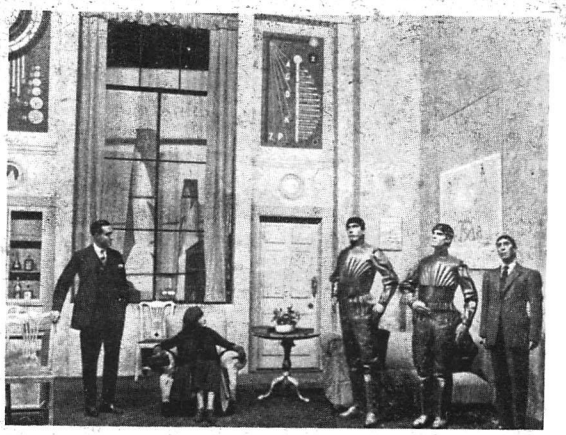
Manservant

Not all fictional robots are so sinister. Cartoonists have long seen the potential of the robot as a device for illuminating our own foibles, and many artists have used the powerful imagery of the mechanical man. Isaac Asimov was among the first science-fiction writers to pursue the idea of the robot as a figure of pathos. More recently, and particularly since *Star Wars*, film-makers have portrayed the robot as both a servant and companion to humans, rather than their enemy. What follows in the next few pages are just some examples of how the robot has been portrayed and of its place in popular culture.

Mary Shelley (above) wrote the novel *Frankenstein* (published 1818) while in Switzerland, and she is known to have seen the automata of Pierre Jaquet-Droz (see page 11). Frankenstein's monster (above right) is perhaps the best-known example of artificial man.

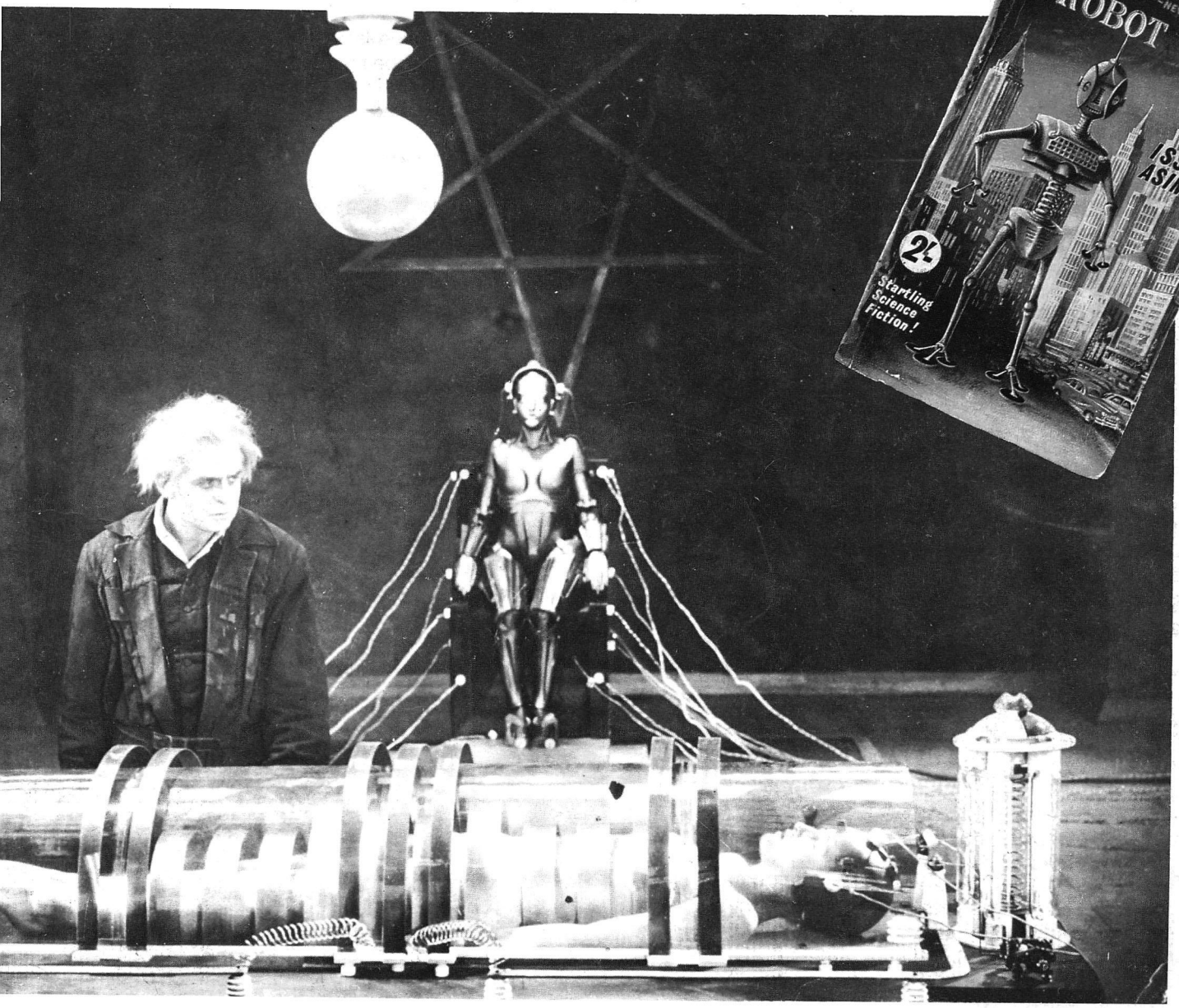


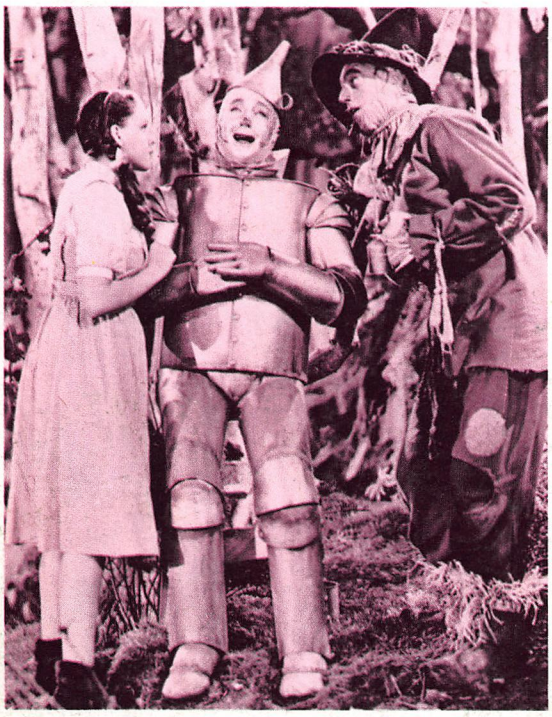
Der Golem (right) was a dramatization of the Jewish legend of golems – figures of clay brought alive to protect the community. Fritz Lang's futuristic *Metropolis* (below) suggested that human beings would eventually be made redundant by machines made in their image.



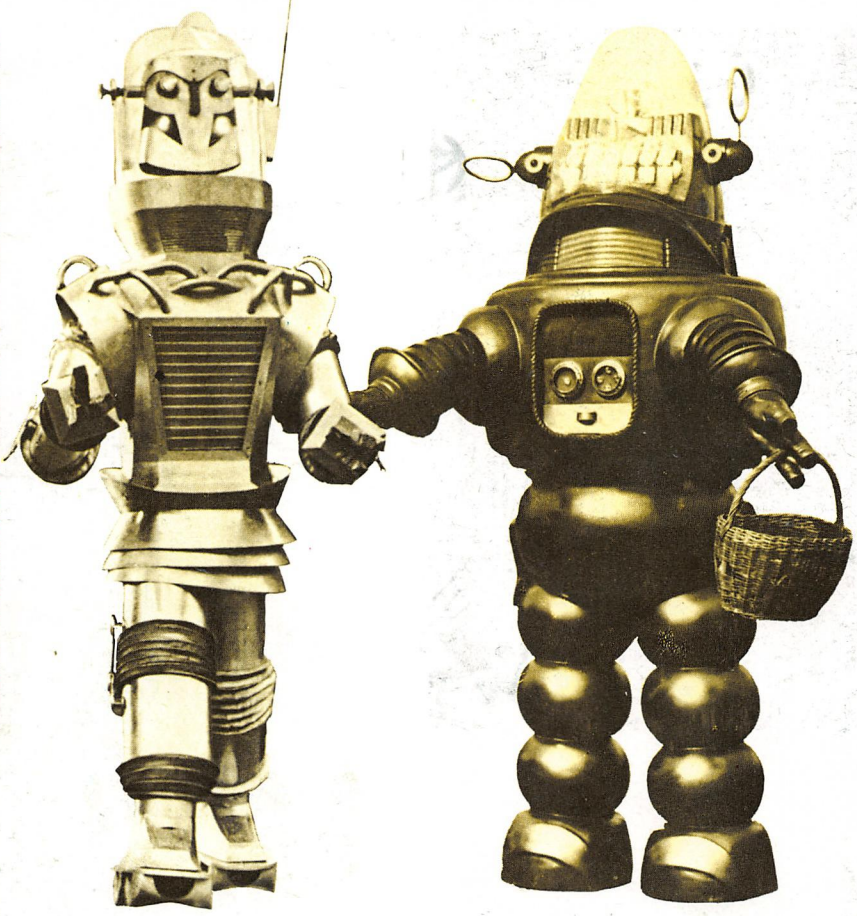
R.U.R. (Rossum's Universal Robots) (above) by Karel Capek gave us the word robot, from the Czechoslovak word for slave labour. As the robots become more and more sophisticated, they start to covet human feelings, eventually rising up and exterminating the humans.

The word robotics, meaning the science of robots, comes from fiction, too. Isaac Asimov first coined it in *Runaround*, one of several short stories published in his first robot book (below).

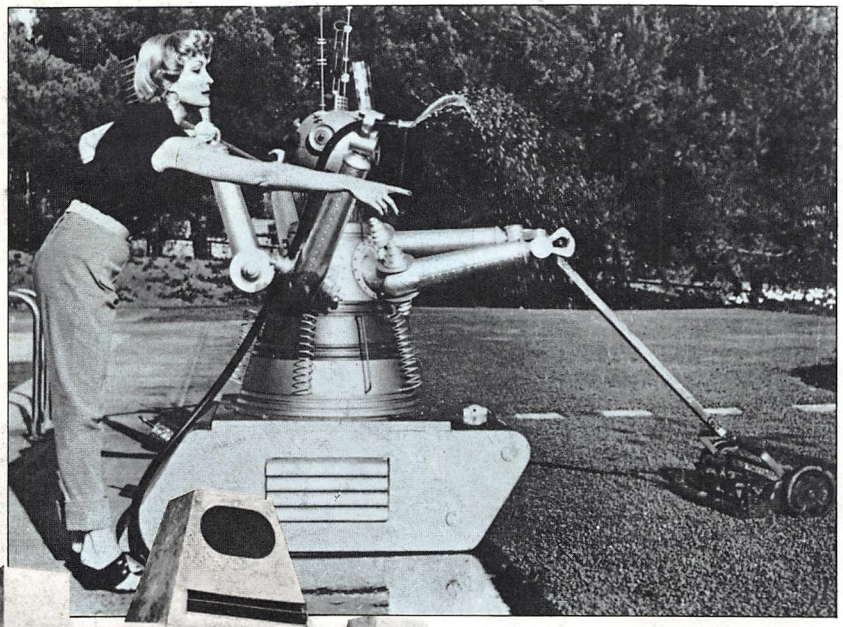




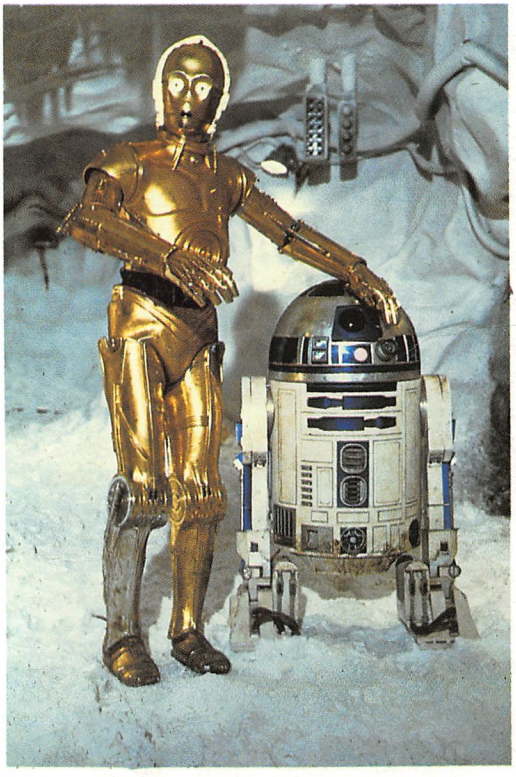
The Tin Man from *The Wizard of Oz* characterizes the image of robots for nearly half a century. The theme of a robot searching for a heart is recurrent in fiction.



The star of *Tobor the Great* (right) was constructed to assist in space missions. Robby (far right) appeared in both *Forbidden Planet* and *The Invisible Boy*.

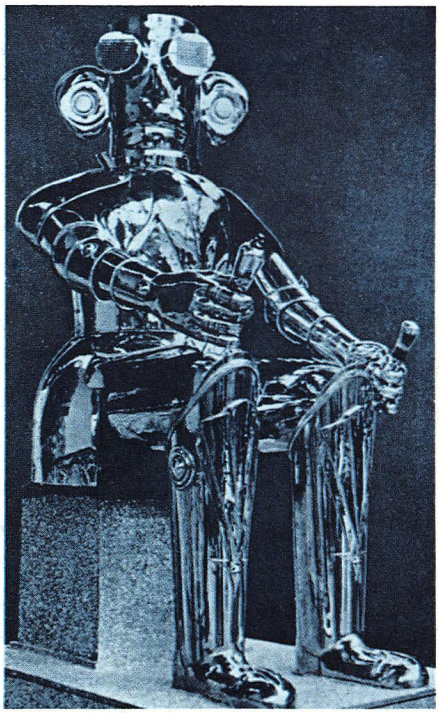


Low special-effects budgets did not seem to deter Hollywood from capitalizing on the robot. The apparently domesticated *Gog* (above) could play tennis and mow the lawn, but ran amok in an atomic laboratory. The terrifying scene on the left depicts a Venusian invasion in *Target Earth*!



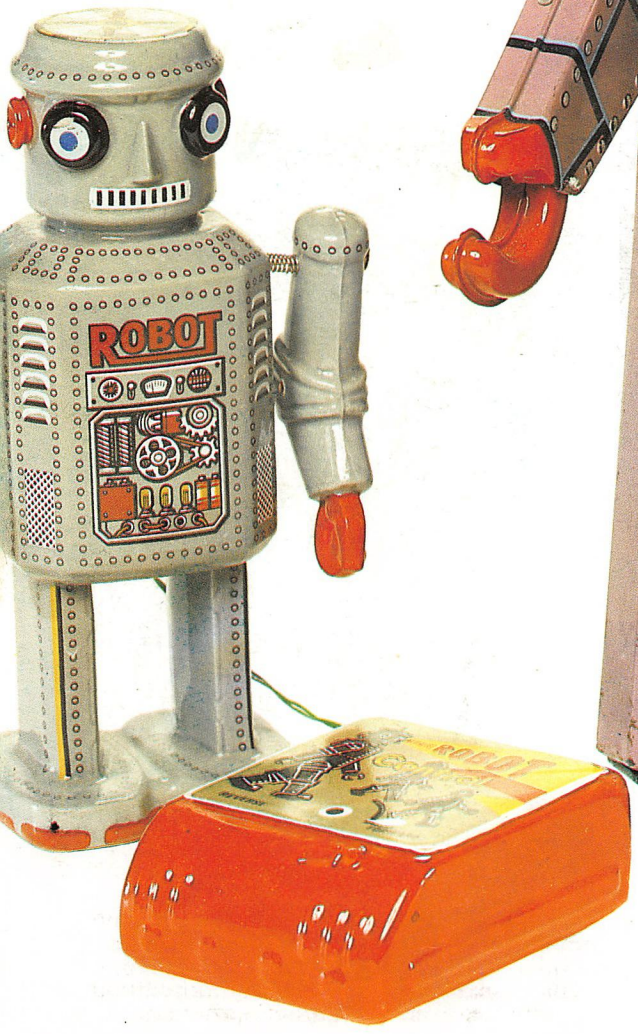
Star Wars was the first film to resolve the conflict between what we would like a robot to look like and what is more feasible, technically, by using both images. R2D2 and C3PO are now the best-known robots in the world, and their almost comic double act has earned them the label of the Laurel and Hardy of robots.

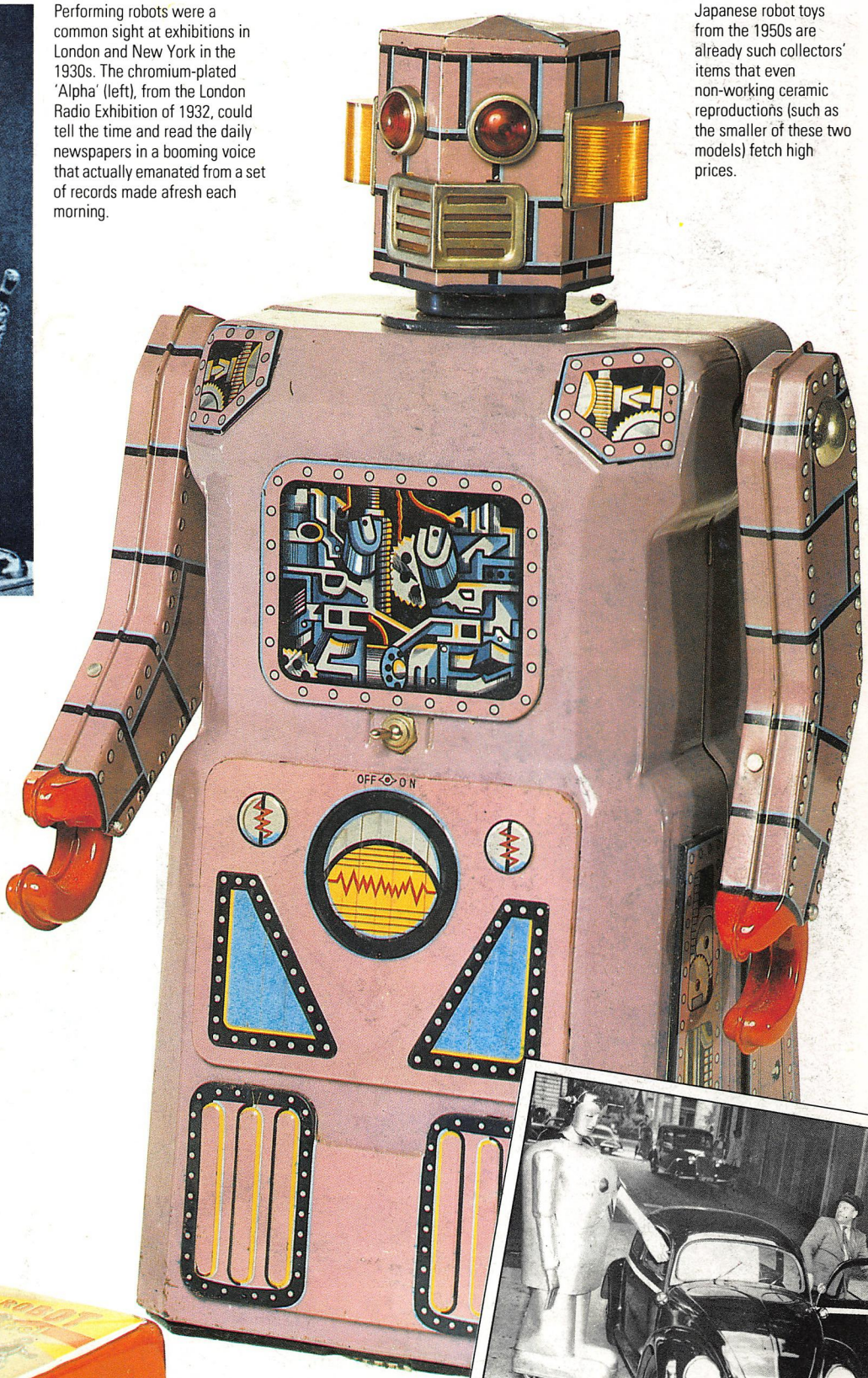
Courtesy of Lucas Films Ltd.

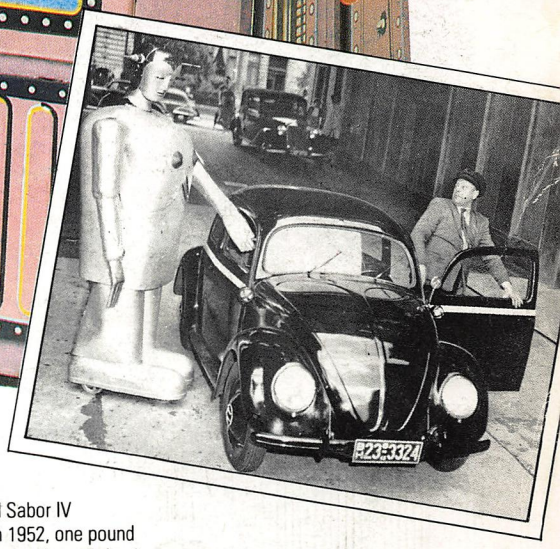


Performing robots were a common sight at exhibitions in London and New York in the 1930s. The chromium-plated 'Alpha' (left), from the London Radio Exhibition of 1932, could tell the time and read the daily newspapers in a booming voice that actually emanated from a set of records made afresh each morning.

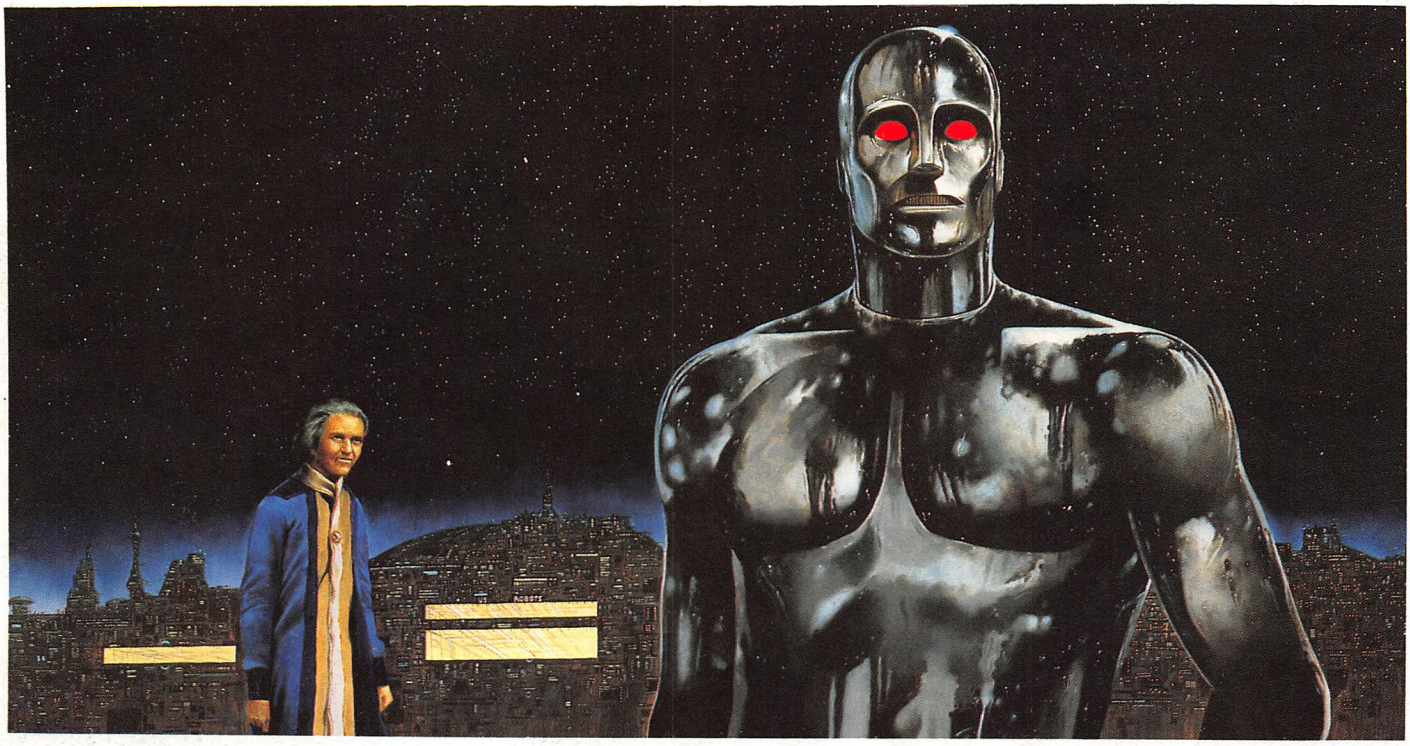
Japanese robot toys from the 1950s are already such collectors' items that even non-working ceramic reproductions (such as the smaller of these two models) fetch high prices.



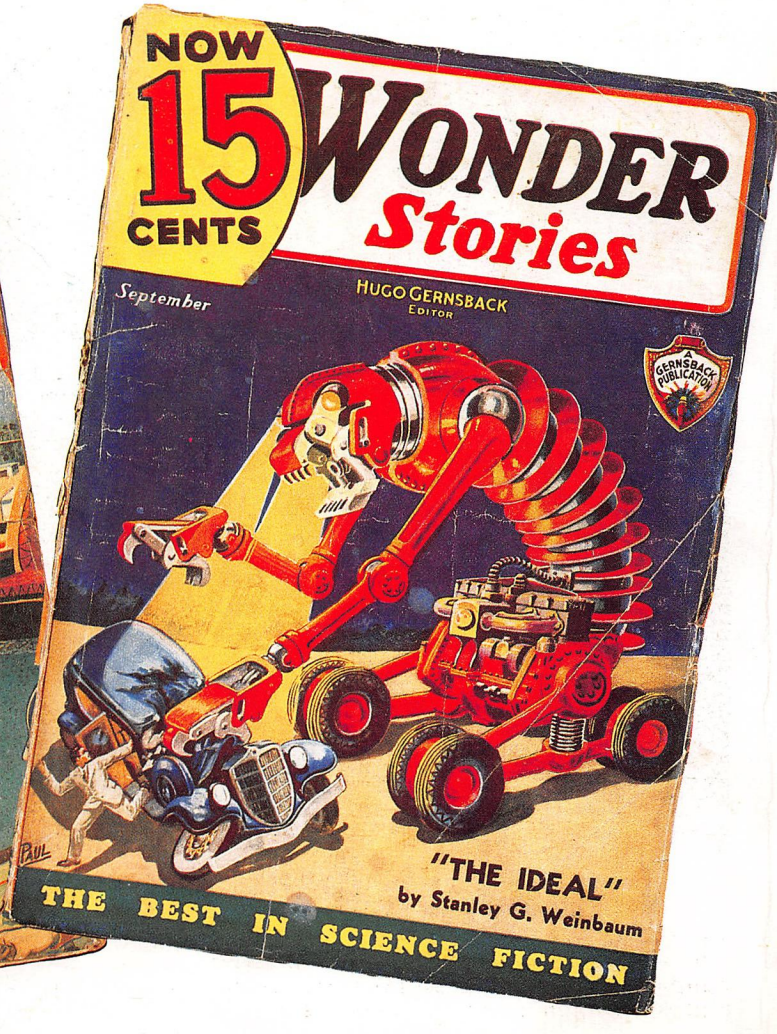


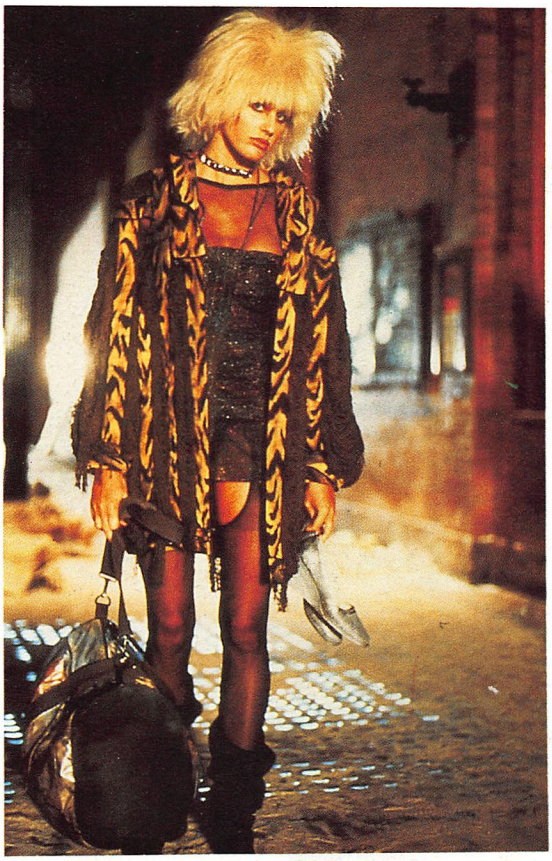


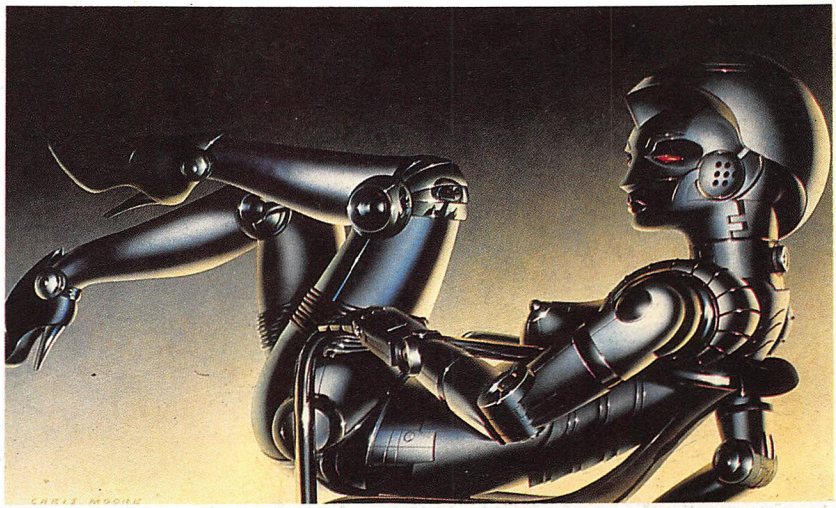
For the man who has everything . . . the radio-controlled Sabor IV would have set him back £2500 in 1952, one pound for every kilometre of wire he supposedly contained.



The book jacket above, by Les Edwards, is one of the few illustrations to depict the formidable Susan Calvin, robopsychologist from US Robot and Mechanical Men Inc., manufacturers of Isaac Asimov's fictional robots.

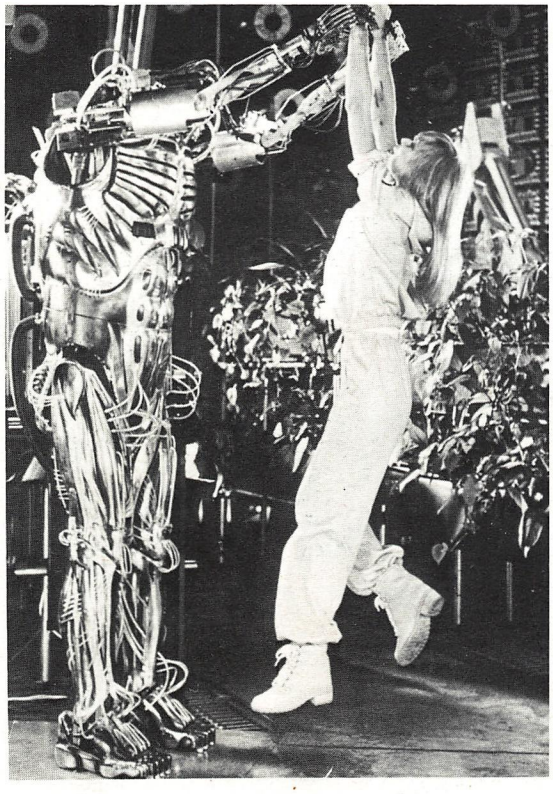




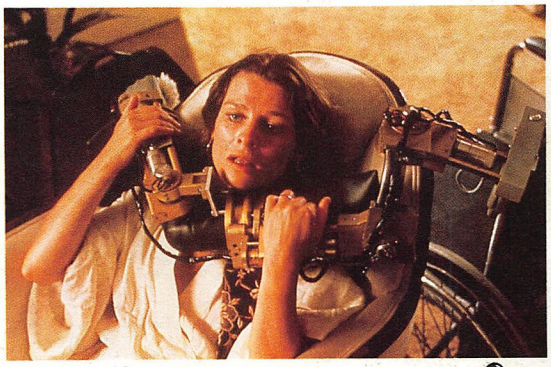


Several writers and artists have concluded that the way to make robots appealing is to add glamour. In *Blade Runner* (left) the replicants are virtually indistinguishable from humans. Chris Moore's airbrush illustration (above) is more inspired by pin-up tradition than computer technology.

Logan's Run is the story of the individual trying to escape from the system – in this case a futuristic earthbound city, run entirely by computer and patrolled by robots.

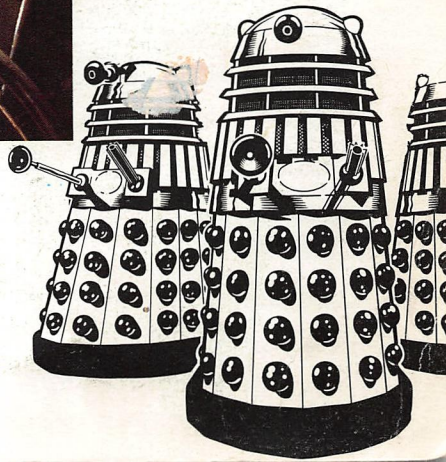


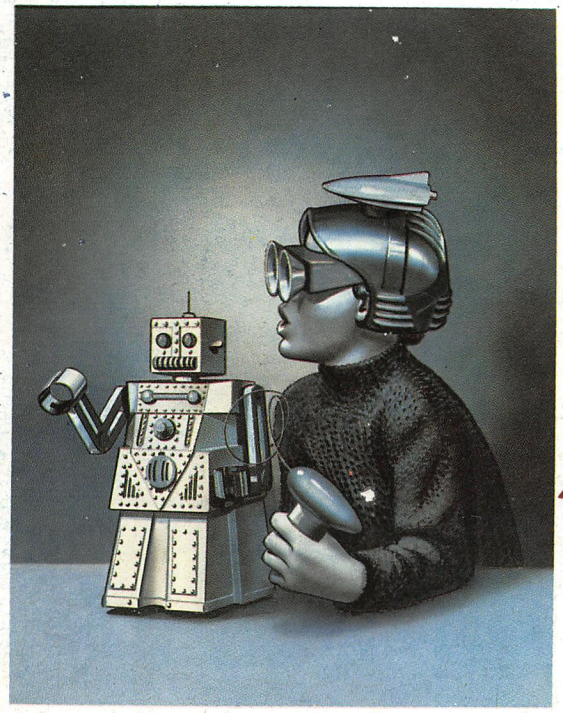
(Left) Many prominent science fiction writers published their first work in *Wonder Stories* or its successor, *Thrilling Wonder Stories*. Frank Paul illustrated all of the original covers, and his robots are some of the finest examples of the science fiction illustrations of the day.

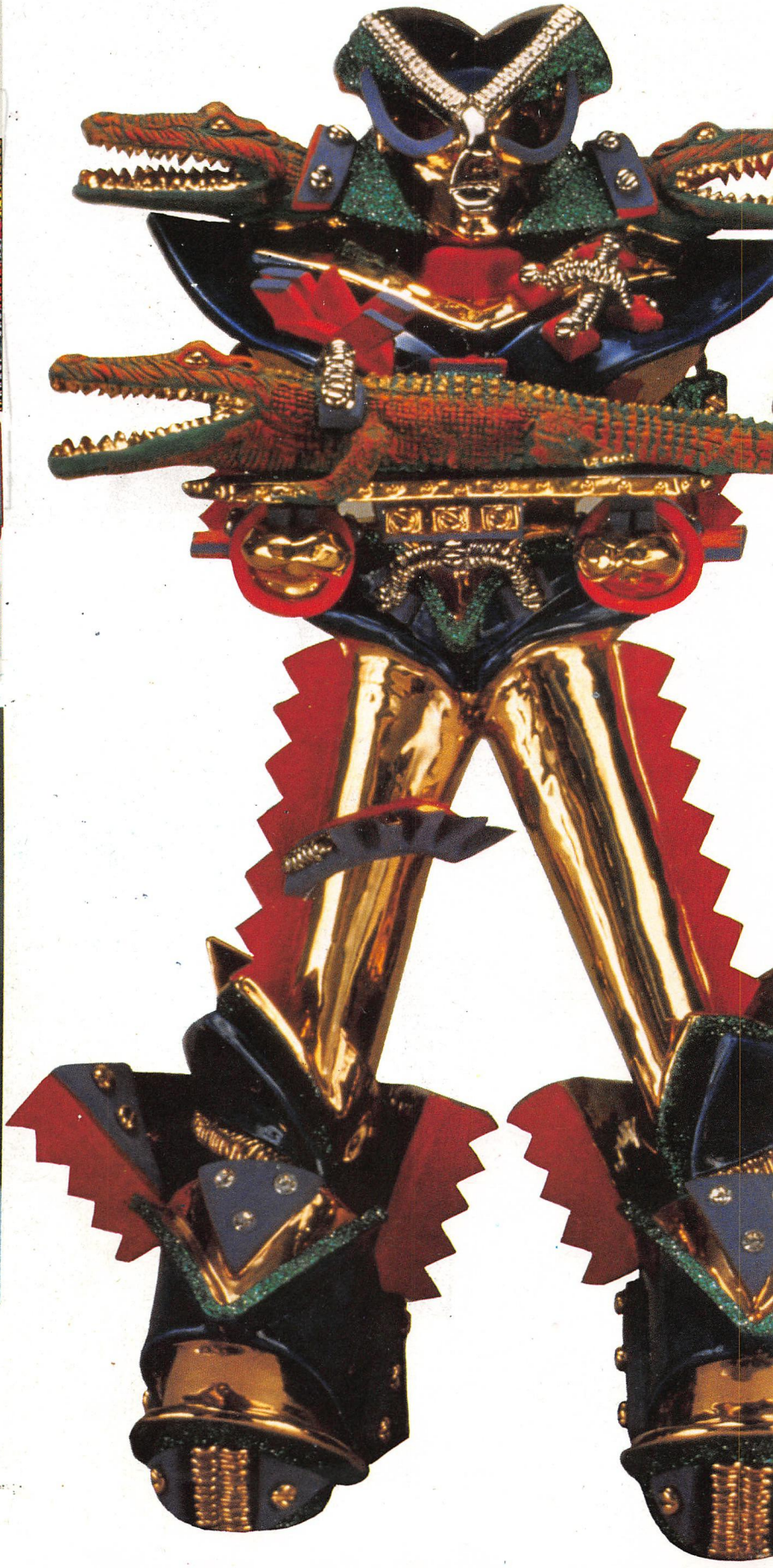


In both *Saturn 3* (left) and *Demon Seed* (above), super-intelligent robots develop a desire to procreate – an ambition that first necessitates the removal (temporary or permanent) of the chosen partner's husband. In *Demon Seed*, the robot is successful in its quest; Julie Christie gives birth to a human baby that has the mind of the robot.

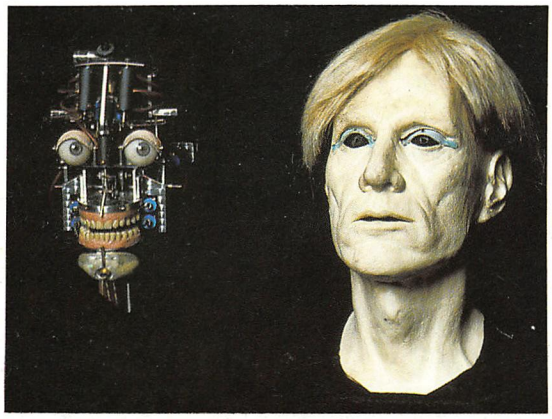
The Daleks from *Doctor Who* were really mechanical exoskeletons, housing a biological brain – the survivors of a former race. In reality, it was the motive power system that was biological; it was a man sitting inside on a tricycle.



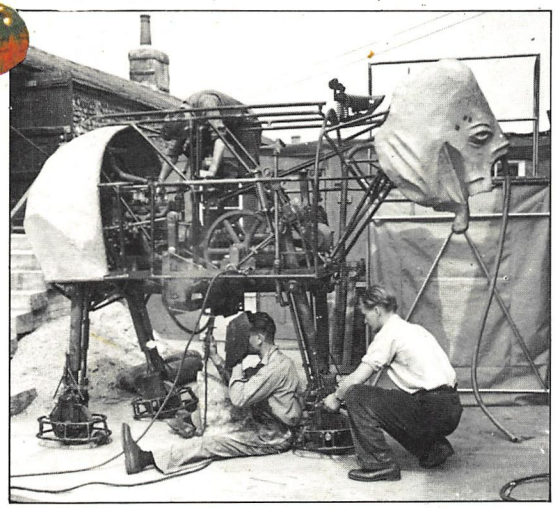




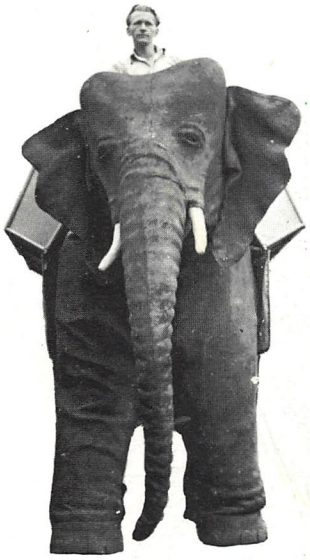
The robot has been an extremely popular and important subject to many modern artists. Perhaps one of the best-known of these is Eduardo Paolozzi, who often uses robot images in his work. He describes *Bash* (top) as 'a collection of metaphors which add up to the twentieth-century experience'. Robert the Robot (above) appears in one of a pair of images from Paolozzi's suite *Cloud Atomic Laboratory*.



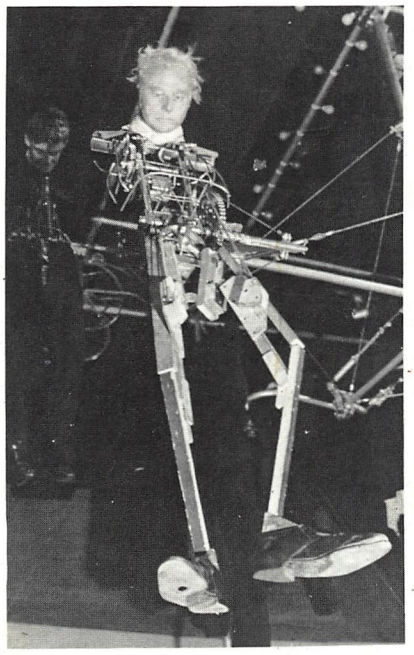
Andy Warhol is known to have said 'I've always dreamed of being a robot'. This waxen image of him (above) contained 54 moving parts, and was built at a cost of $400,000 for a television special in 1983.

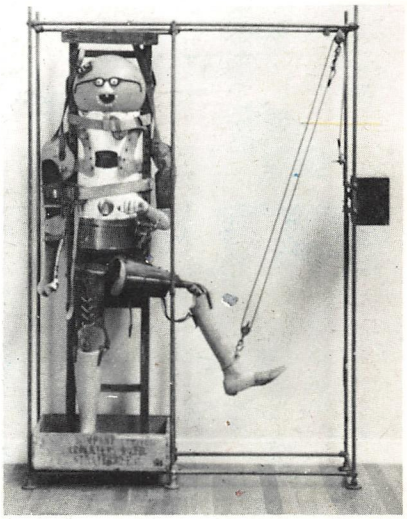


The world's first robot Elephant (above and right) was built in Essex in 1950. Driven by an eight-horsepower petrol engine, the elephant had a claimed walking speed of 45km/h (28mph), waving its trunk and flapping ears at the same time. The robot required a special licence to use public roads.



Toby Buonagurios' handbuilt painted clay sculpture – *Robot with Alligators* (left) – measures 60cm (24in) tall, and is made from clay, acrylic, glitter, lustres and flocking. It was shown in the American Craft Museum's 'The Robot Exhibit' of 1984.





Bruce Lacey's *Boy, Oh Boy, am I Living* (above) is a pessimistic comment on man's future if he keeps on replacing his functions by machines. Jim Whiting's sculptures (left) combine art with technology – most are controlled by a Sinclair Spectrum.

Wonderful things by Chris McEwan (right) portrays robots in a magical light.

THE IMPACT OF ROBOTS

'It is impossible to communicate the human voice over wires by means of electricity, and even if it were possible, it would have no practical value whatsoever.' These recorded words of a British politician, on hearing of the claimed invention of the telephone, typify a prevalent attitude towards new technology. Prime Minister Disraeli made scathing attacks on the work of Charles Babbage (see pages 14–15), intimating that the only application for his machine 'would be to calculate the enormous sums of public money squandered on its development'. Pioneers of the motor car even had to contend with 'medical' evidence that travelling at 30 miles per hour would cause brain damage!

What will the impact of robots be on our society? And, perhaps more importantly, what should our attitude be towards them? These questions are very much in vogue, and there have been some excellent books devoted solely to them. This book does not pretend to supply the answers – rather the objective is to present a sufficiently comprehensive overview of robot capabilities, current and future, for readers to form their own opinions on the issues involved.

Some people, notably those employed in the robotics business, view robots through rose-tinted spectacles, seeing only their benefits to mankind. Others take a more pessimistic viewpoint, seeing the only effect of the use of robots being mass unemployment. One dangerous stance is underestimating the scope of the robot, although predicting the future is not easy – Thomas J. Watson, a founding father of IBM, believed there to be a world market for around five computers, and a team of scientists despatched to evaluate these calculating machines concluded that Britain probably needed one!

Ironically, the body of people who have spent the most time considering the impact of robots on society are not the scientists but the science-fiction writers. There is little technological that can be written about technology that doesn't yet exist, so the action for most robot stories has centred on the social effects of the machines and their interplay with humans. Asimov's celebrated Three Laws of Robotics may well be impossible to implement or enforce, but that doesn't detract from their enormous contribution to our thinking about robots.

Robots and the workforce

In the short term, the impact of the robot will primarily be felt in industry. Robots are being applied to many traditionally unpleasant or dangerous tasks, from mining to high-pressure water cleaning, on a more or less one-for-one replacement basis. Here, the social changes are not so dramatic, and the moral questions perhaps less severe. Individual job losses, even if opposed, can be weighed against the benefits of having a robot, rather than a human, do the work.

In manufacturing, productivity is the sole motivation for installing robots, and this raises more complex issues. Installing the first few robots may entail that some jobs be redefined rather than that massive redundancies take place. Here, it is claimed, robots will take care of the more repetitive tasks, leaving humans with the more intricate and perhaps more rewarding stages. However, as their mechanical dexterity, sensing power and intelligence increases, robots will be capable of an increasing proportion of human tasks. There are already small factories run entirely by robots, with a residual workforce limited to the monitoring and maintenance of the machines. If this is to be the trend, it makes a nonsense of the claims about creating more rewarding jobs, and it raises the worrying spectre of the virtual elimination of a human workforce. However, we cannot simply put a stop to automation, since any company or country that fails to keep abreast of the new technology will simply lose its competitive edge.

The robot revolution

One school of thought suggests that, in the long term, robots will eliminate the need to work altogether – and hence that we should be concentrating more on how to enjoy our leisure time. After all, the great empires of the past were all built on slave labour, and robots provide this without the accompanying moral problems.

Will we end up in a kind of latter-day Periclean Athens, passing the time in intellectual and cultural pursuits? One pundit has suggested that if future robots are intelligent enough to perform all human tasks, they would be intelligent enough to realize that it might be more fun to play the masters! This would indeed be an ironical use of the phrase 'the robot revolution'.

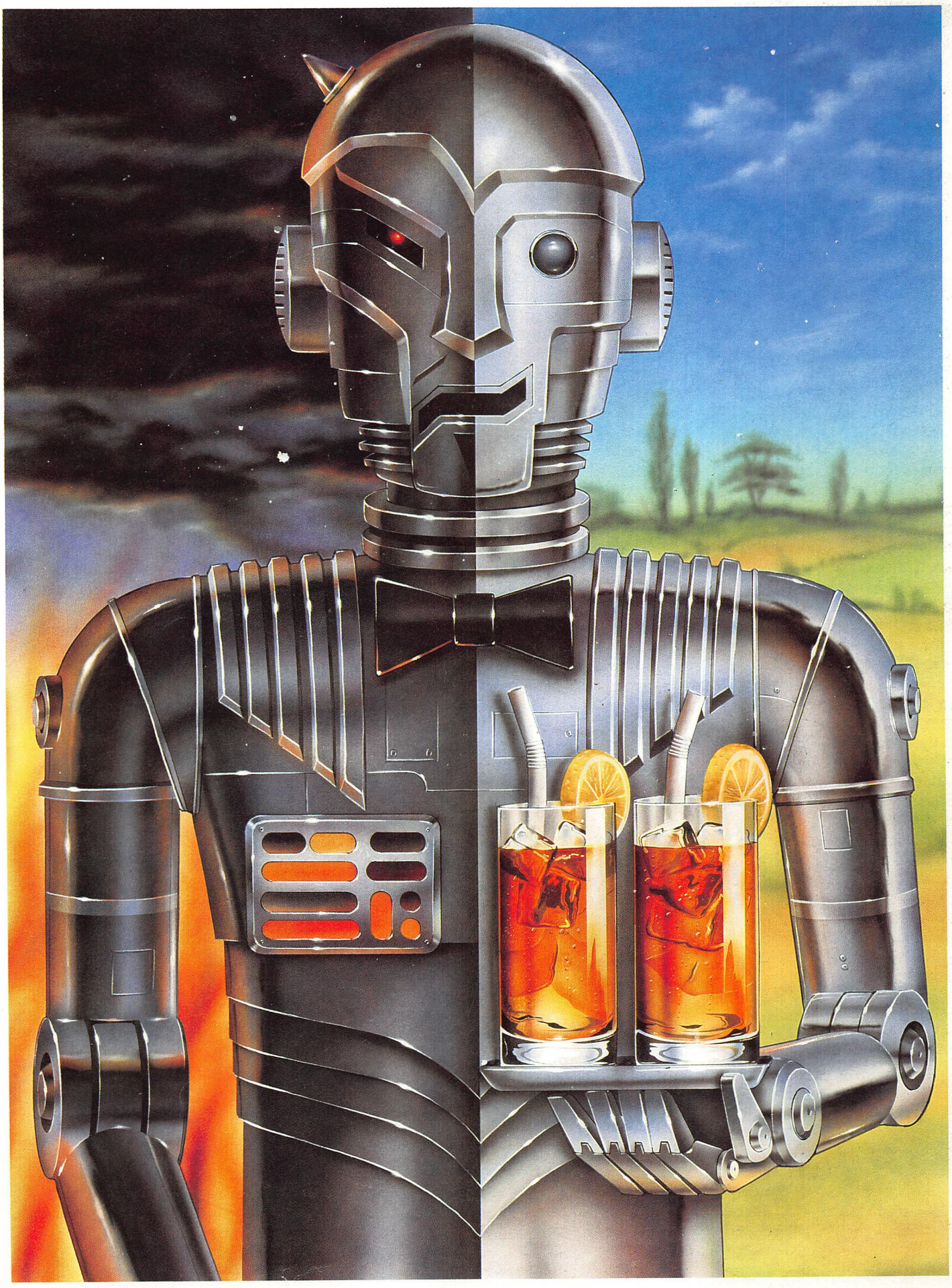
However important robots are to our industrial future, it is wrong to view them purely in terms of economics and productivity – their value may be much broader. Overleaf we look more specifically at how robots will develop in the future, and particularly in our homes, as a source of both entertainment and education.

Furthermore, building sophisticated machines may teach us much about human beings, both in physiology and psychology. Many people simply reject this facet of robotics and many do so out of fear. But the person who fears comparisons is the person who is secretly afraid to lose by comparison. Perhaps the survivors of the robot revolution will be those who have sufficient confidence in their own standing.

Thinking about the likely impact of robots on society often gives rise to feelings of unease. We should like these machines to serve humanity in a helpful way but we fear their possible capacity for harm.

In the robot stories of Isaac Asimov he envisages a future world in which there are safeguards to ensure that robots cannot be harmful to human beings. Built into the 'brain paths' of these machines is obedience to the Three Laws of Robotics:

1. A robot may not injure a human being or, through inaction, allow a human being to come to harm.
2. A robot must obey the orders given it by human beings except where such orders would conflict with the First Law.
3. A robot must protect its own existence as long as such protection does not conflict with the First or Second Law.



THE FUTURE FOR ROBOTS

What part will robots play in our future world? Prophets of doom might argue that the structure of the question is incorrect, and that 'What part will we play in the robot world of the future?' is more appropriate. The idea of a future world dominated by mechanical men, however, existed long before true robots materialized, and, in reality, such a scenario is no closer than it was thirty years ago. Attempts to predict the development of an emergent technology further than ten years ahead has little more factual value than science fiction.

Of greater relevance to the reader of this book is what the next ten years will hold for robotics, both in terms of technology and applications. 'The most distressing thing that can happen to a prophet', said Aldous Huxley, 'is to be proved wrong. The next most distressing thing is to be proved right.' We shall consequently eschew prophecy, and restrict ourselves to an overview of some of the current goals of researchers and marketeers.

Robot capabilities

To begin with, robots must become more mobile: tricycle arrangements of wheels have enough difficulty with carpets, let alone stairs, and tracked vehicles are little better. The true android (i.e. something resembling C3P0 from *Star Wars*) is not a prospect for the next ten years (if at all), but a domestic robot with legs is. A biped isn't necessarily the answer – three or four legs may entail more processing, but the control problems are considerably reduced because balance is so much easier.

Still on the mechanical side, robots can only become more nimble and agile if lightweight materials such as plastics and carbon fibre replace traditional structures of steel. Such materials give the robot design greater freedom and flexibility in terms of shape, allowing robots finally to diverge from the traditional image of the tin man in *The Wizard of Oz*.

One area where it is difficult to see any imminent change is in the actuators – the devices such as electric motors and hydraulic rams that power the moving parts of the robot. Actuators constitute a large proportion of a robot's mass, so any reduction in size and weight would widen the scope of applications considerably.

If robots are to advance then they need to be more aware of their environment. Sensors are discussed in detail here in the section *How Robots Work*, but for the next ten years, priority will be given to developing a system for robots to identify their position within a fairly limited environment (such as a house and garden) and to navigate their way around obstacles. This could be achieved with a single television camera and rangefinding equipment based on lasers, microwaves or ultrasonics.

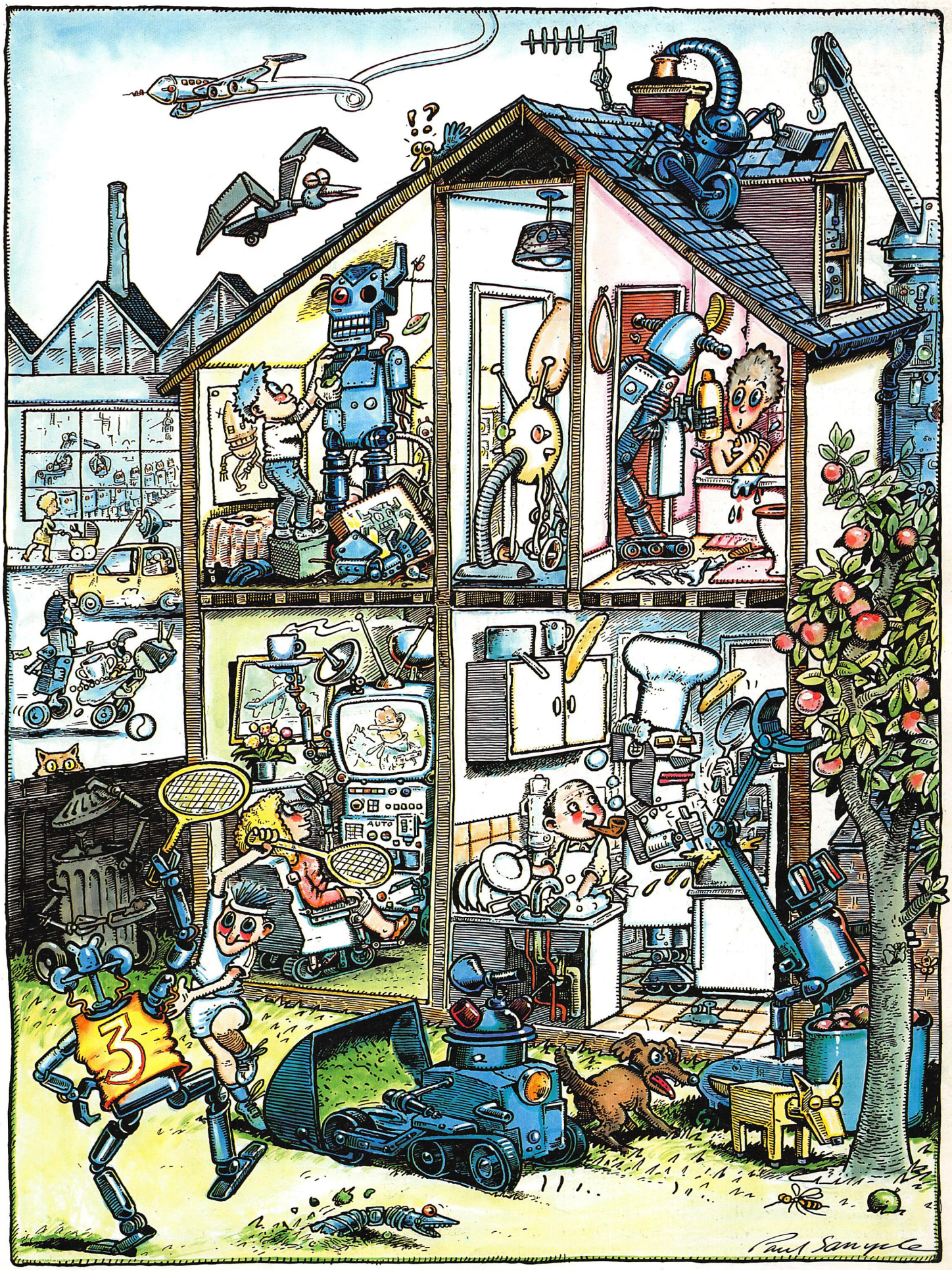
Specialization

One of the main arguments relating to robots of the future is whether they will be more general or more specialized. One view holds that industrial robots are merely a stop-gap solution on the way to purpose-designed automation equipment. The latter will run more efficiently, but it will be more costly to design and install than off-the-shelf robots. Furthermore, dedicated automation equipment cannot be re-configured to perform a different task – such as when the manufactured product changes.

The same argument applies to the domestic market. Will we end up with one general-purpose robot capable of mowing the lawn, vacuuming the carpet and making the tea, or will the next generation of lawnmowers, vacuum cleaners and kettles be robotized themselves? The former might be more appealing, but the latter is more likely – on two counts. First, because any general-purpose robot will have to use existing tools developed for human beings and will therefore have to resemble human geometry very closely – a goal that isn't currently practicable. Secondly, specialized robots are easier to develop and give opportunity for more companies to cash in on the market. The computer has already set the precedent: a modern microprocessor is fast enough to take care of all the processing in a sophisticated household. Yet the central domestic computer hasn't happened. Instead, we find one microprocessor in the television, one in the washing machine, the oven, the central heating programmer, and of course the home computer.

General-purpose robots will be available on the domestic market within a few years, but these will be for education and entertainment, rather than utility. The educational robot is really tomorrow's equivalent of the model-builder's kit, and indeed dedicated robot assembly kits are already appearing on the market. As the years pass, the components will simply become more sophisticated, and may include hands, eyes – perhaps even robot brains.

One of the greatest impacts of the robot will be on entertainment. The robot chess partner is already a reality; a robot that can take part in children's outdoor games is still too distant. In between, there are a whole host of possibilities, particularly in bringing physical form to the more popular computer games. Tomorrow's space invaders will be mechanical – and they'll probably be able to shoot back.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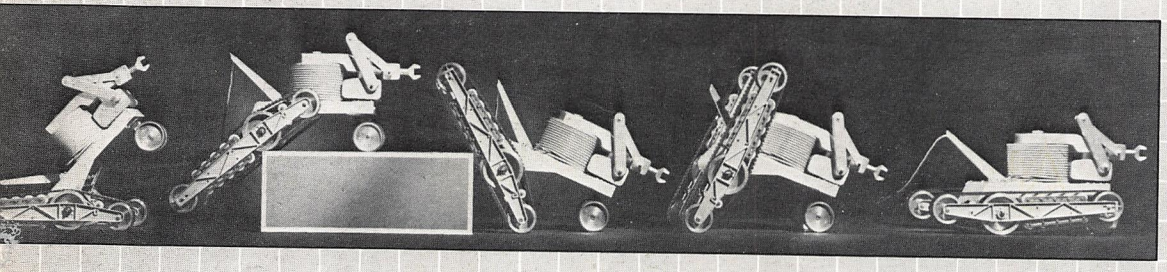
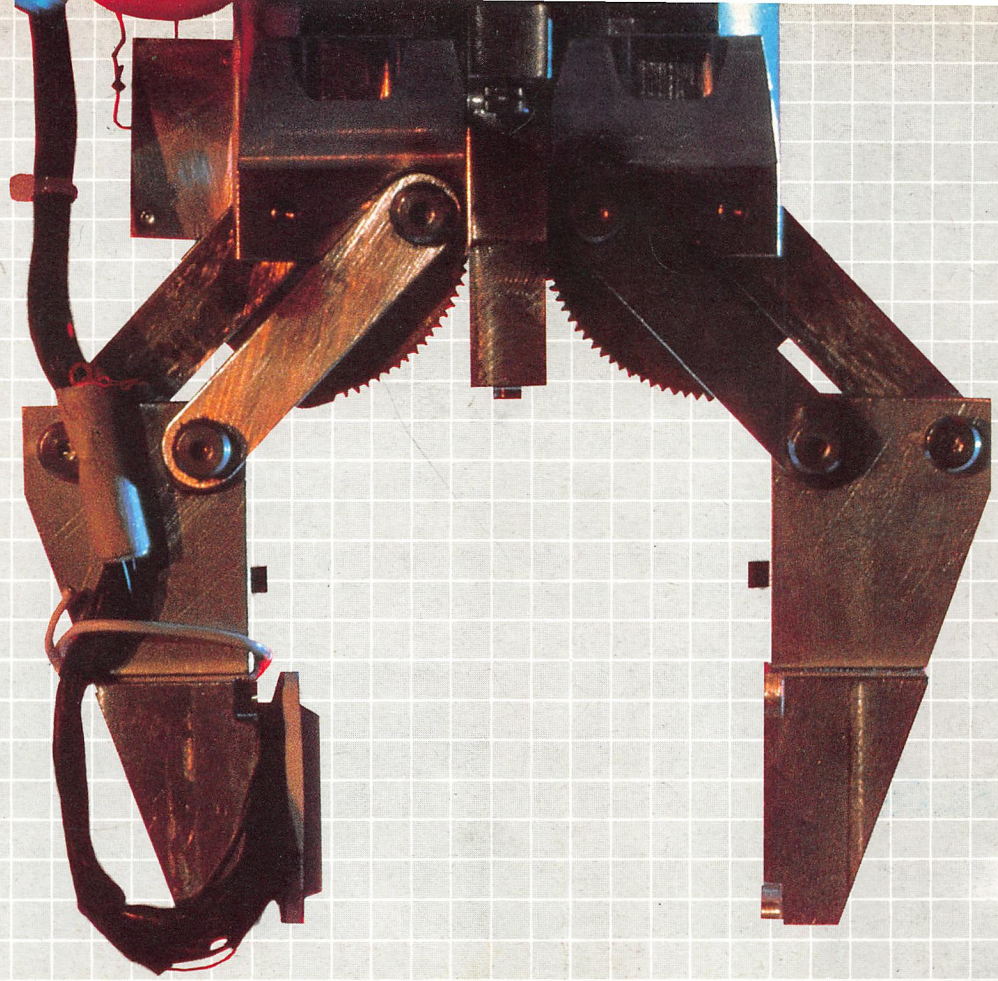
PART

2 ROBOTS IN ACTION





A HIERARCHY OF ROBOTS	30
ROBOTS IN SPACE	32
UNDERWATER AND UNDERGROUND	34
MILITARY ROBOTS	36
MOBILE ROBOTS	38
TELECHIRS	40
MECHANICAL ARMS AND LEGS	42
STATIC INDUSTRIAL MANIPULATORS	44
EDUCATIONAL ROBOT ARMS	46
EDUCATIONAL FLOOR ROBOTS	48
FREESTANDING DOMESTIC ROBOTS	50
ROBOT TOYS	52
EXPERIMENTAL ROBOTS	54
PSEUDO ROBOTS	56

A HIERARCHY OF ROBOTS

What exactly is a robot? Even if one leaves out the fictional creations of the previous chapter, a watertight definition is still difficult to produce. Any definition is bound to exclude some devices that deserve the robot label, and encompass others that don't.

At the start of this book, the robot was introduced as a machine made in the image of a human being. Some – a very few – robots are made in the visual image of a person, and some have parts that resemble human limbs. Most robots, however, are made in the functional image of a human being – they are intended to do the work that humans do and, usually, to replace people on a one-for-one basis.

One of humanity's prime assets is flexibility – in particular the speed with which new tasks can be learnt. The robot equivalent is programmability. Robots can memorize a sequence of operations and repeat it indefinitely, without error and without tiring. In that sense they surpass human capability.

What robots cannot currently emulate is human intelligence, especially the ability to cope with

Medical simulators are used to deal with emergencies such as heart attacks. The robot responds to physical stimuli as well as drugs.

Prosthetics (artificial limbs) now feature microprocessor controls similar to those found on many robots, and are coupled directly to the wearer's nervous system.

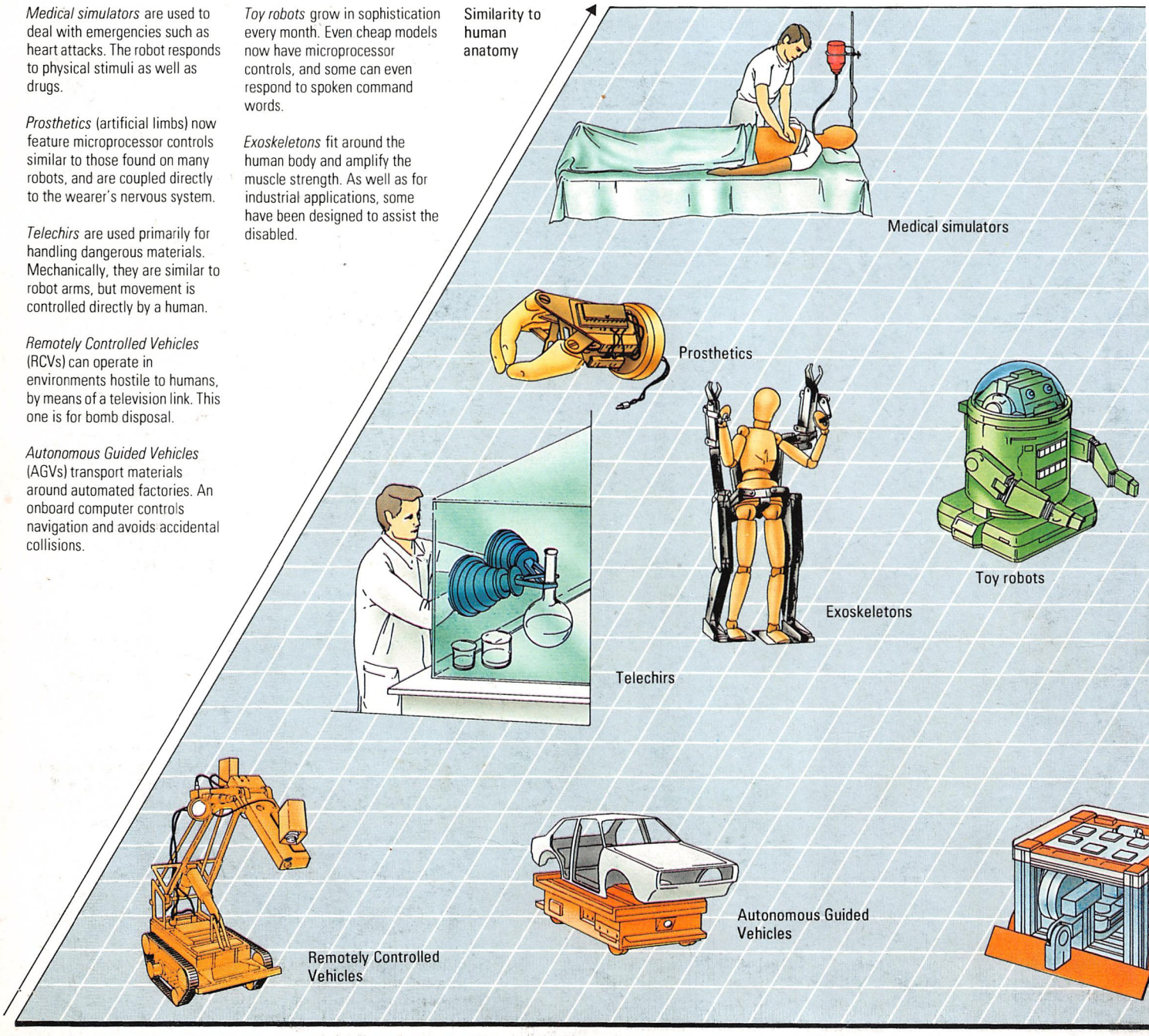
Telechirs are used primarily for handling dangerous materials. Mechanically, they are similar to robot arms, but movement is controlled directly by a human.

Remotely Controlled Vehicles (RCVs) can operate in environments hostile to humans, by means of a television link. This one is for bomb disposal.

Autonomous Guided Vehicles (AGVs) transport materials around automated factories. An onboard computer controls navigation and avoids accidental collisions.

Toy robots grow in sophistication every month. Even cheap models now have microprocessor controls, and some can even respond to spoken command words.

Exoskeletons fit around the human body and amplify the muscle strength. As well as for industrial applications, some have been designed to assist the disabled.

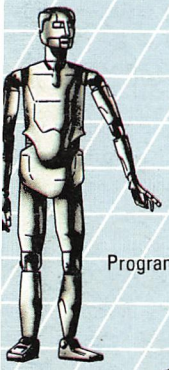


variable and even unforeseen circumstances. The first generation of robots operated solely on orders, 'unaware' of their environment or the consequences of their actions. Most robots now have sensors, of some form, which can relay information back to the controller, and can even mimic, crudely, the human senses of sight, touch, hearing and smell. However, although computers can outstrip the human mind in any form of calculation, their perceptive and reasoning abilities are still minimal – and will remain that way until research into artificial intelligence becomes more advanced and starts to pay dividends.

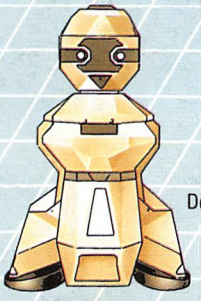
For the moment, robotics encompasses a wide variety of technologies. Some of the resulting products resemble the visual image or the mechanical geometry of human beings, others are stronger in terms of programmability and intelligence. These technologies are represented on the graph opposite. The following chapter explains the principles and the applications of each of them. Readers can decide for themselves which devices deserve to be called robots – all or none? Using the two scales of visual similarity in shape and intelligence or programmability, it is also interesting to plot the locations of other familiar devices, like programmable washing machines or jointed-arm mechanical excavators.

Future developments in robotics will extend the area of the robotics graph in both directions. Some believe that humanity corresponds to infinity in both directions and will never be equalled by the robot. Others hold that human beings lie only just off the top right-hand corner....

Displayed here is a graph showing robots and robot devices ordered into a kind of hierarchy. The nearer to the top right-hand corner a device is, the more it resembles human beings in sophistication and intelligence (measured along the horizontal axis) and in anatomy (measured along the vertical axis).

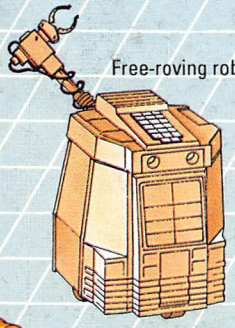


Programmable mannequins

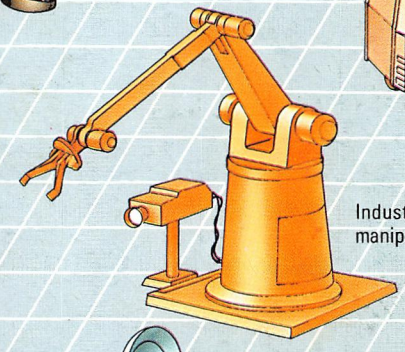


Domestic robots

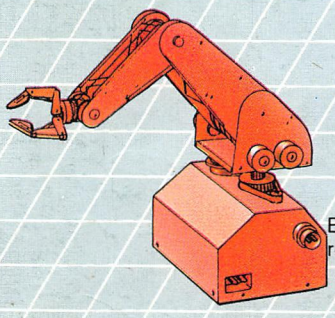
Promotional robots



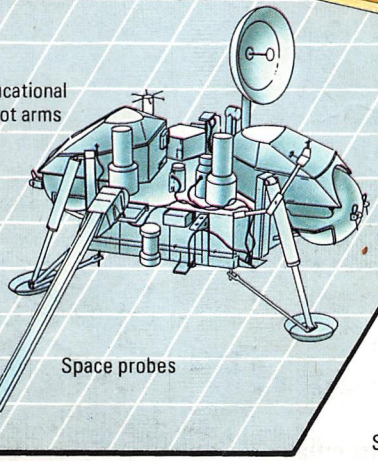
Free-roving robots



Industrial manipulators



Educational robot arms



Space probes

Educational floor robots

Sophistication and intelligence

Programmable mannequins may replace shop window dummies. They have no external sensors, but can repeat a sequence of movements,

Domestic robots are not yet capable of performing any useful household chore, but nevertheless have entertainment and educational value.

Promotional robots appear increasingly at exhibitions and in films. All movement is usually controlled by a human operator via a radio-control link.

Educational robot arms are programmed for conventional microcomputers. They are really scaled-down versions of industrial manipulators.

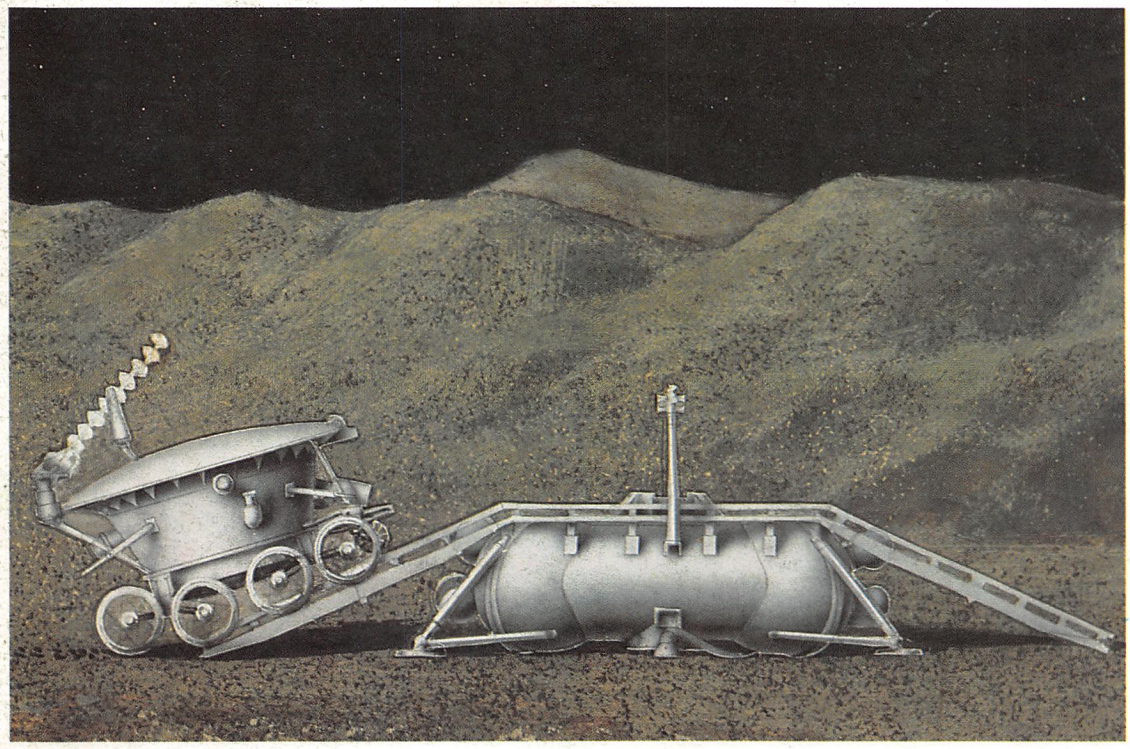
Educational floor robots have an umbilical link to a microcomputer and are equipped with a wide variety of sensors for sound, light, obstacles etc.

Free-roving robots consist of a manipulator arm on a mobile base. Designed principally for teaching robotics, they feature an onboard computer.

Industrial manipulators are ideally suited to repetitive tasks. Those equipped with vision can cope with much more variability in the items being handled.

Space probes are the most sophisticated exploratory robots. A manipulator arm feeds soil samples to a miniature analysis laboratory.

ROBOTS IN SPACE



The Lunokhod 1, which landed in the Mare Imbrium on November 10, 1970, was the first wheeled vehicle on the Moon. This artist's impression shows the Lunokhod dismounting from its base – Luna 17. Controlled by a team of four operators on Earth, the Lunokhod received its power from chemical batteries and solar cells in the opening lid. A radioactive isotope heater maintained the temperature of the craft.

During its ten-month operational life, the Lunokhod explored some 10km (6 miles) of the Moon's surface, probing it with scientific instruments and transmitting more than 20,000 pictures to Earth. The vehicle was equipped with a laser mirror, and its position was tracked by means of reflected laser beams directed to it from observatories in France and the Crimea.

Robots and outer space are two subjects with a considerable overlap – in fiction as well as in fact. Perhaps because both seemed unattainable, early science-fiction writers linked robots with the conquest of space, by humans and by alien civilizations. Even now that space travel and working robots are within our grasp, the link remains. One contemporary philosophy holds that the truly intelligent robot would constitute such a threat to mankind that it should be restricted to working on space colonies. Several stories and films have explored the consequences of such robots and 'humanoids' returning illicitly to Earth.

Back in reality, the overlap has other causes. Space is the most hostile environment we have encountered: it lacks warmth, air and gravity. Quite apart from the sheer cost of putting a human being into space and keeping that person alive, there is a very high risk factor, making it desirable to use machines in place of humans whenever possible.

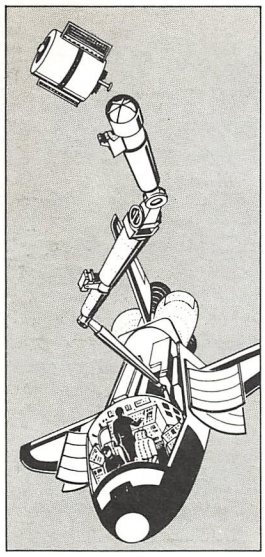
The second factor contributing to the use of robots in space has been finance. The political, military, technological and now industrial gains to be had from space exploration have secured very large research budgets from the two principal protagonists, the USA and the USSR, and now increasingly from Europe and developing countries. Much of today's household technology can be traced back to developments for the space programme and robotics is no exception.

Space probes

Even the first probes that were rocketed into the upper reaches of the atmosphere could be described as robots. They had motive power, sensors to relay information back to Earth and some measure of onboard intelligence. But it was when attention turned towards the Moon and the nearby planets that recognizable robots started to appear.

The Russian Luna and American Surveyor probes both achieved stable and successful landings on the Moon in 1966. In addition to taking thousands of photographs (partly, in the case of Surveyor, to select suitable sites for the manned Apollo landings), these probes contained a vast array of sensors for analyzing the soil and environment. One device bombarded the lunar surface with radioactive alpha particles and measured the energies released on their impact in order to analyze the soil content. Later versions of the Russian probes successfully returned soil samples to Earth.

The most robotic-looking device to reach the Moon was the Russian Lunokhod – a free-roving vehicle looking like a bathtub on eight independently driven wheels – which was not used successfully until many months after the Apollo 11 manned landing. Lunokhod was nevertheless an impressive advance in the technology of RCVs (Remotely Controlled Vehicles); its earth-bound crew of four (commander, navigator, driver and radio operator) received their feed-



The RMS (Remote Manipulator System) is the largest robot arm ever built, having a maximum reach of over 15 m (50 ft). The arm can be used for launching or retrieving satellites from its cargo hold (left), or for adjusting their attitude in orbit.

Clearly seen in the bottom right corner of the photograph is one of the television cameras that provides visual feedback to the operator in the control cabin. The end effector is quite novel too, consisting of a basket of wires that can be remotely twisted to grasp a protruding stub on the satellites.

back from stereoscopic television cameras.

It also contained a remarkable level of localized intelligence. Automatic sensors could slam on the brakes if an unseen crevasse was encountered, and the data collection systems included a device for 'thumping' the surface and measuring the reflected sound waves. During the lunar day (equivalent to fourteen of ours), the lid of the bathtub opened to reveal an array of photoelectric cells, which supplied the power. Lunokhod was intended to survive for three such periods, but in fact continued to relay data to Earth for more than ten months.

Robot arms

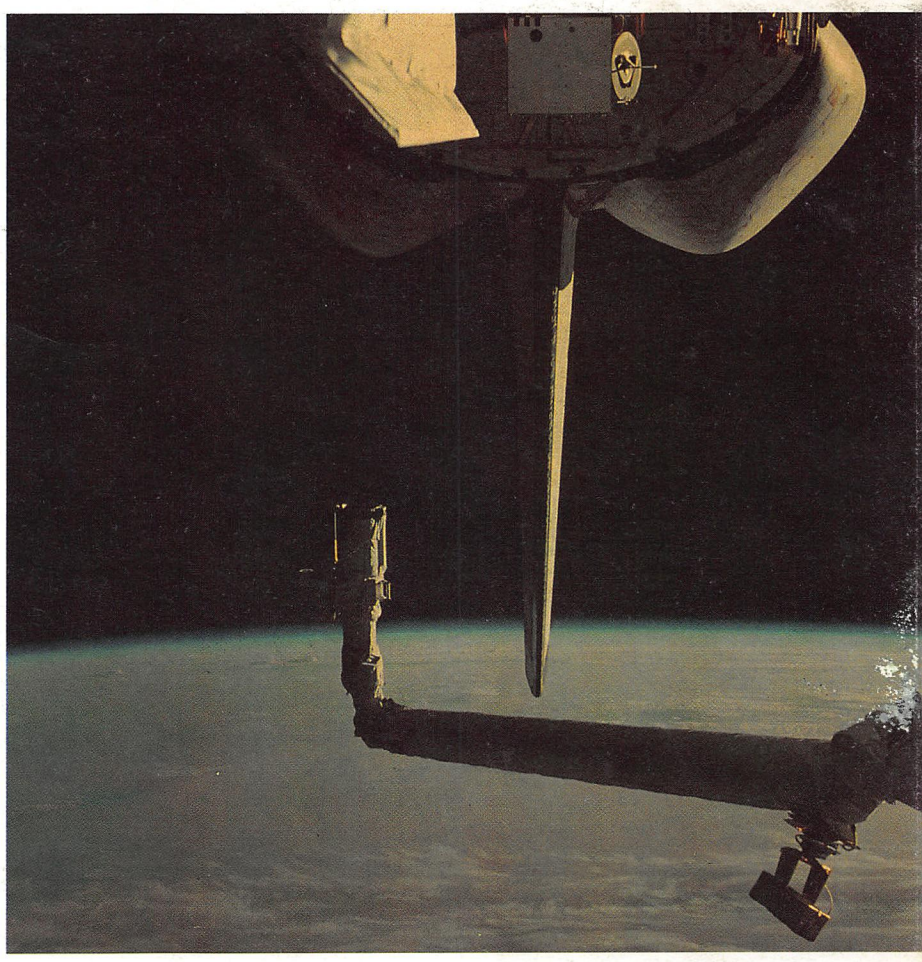
Although soil samples had been collected by lazy-tong scoops on the early Moon probes, the Viking lander on Mars in 1976 was the first to employ a recognizable robot manipulator arm. Sophistication of sensors had increased so dramatically that a complete miniature analysis laboratory had been incorporated, to be fed with samples by the arm, together with weather sensing and seismology stations. Although there were some positive results, the tests failed to prove that there was microbial life in the soil.

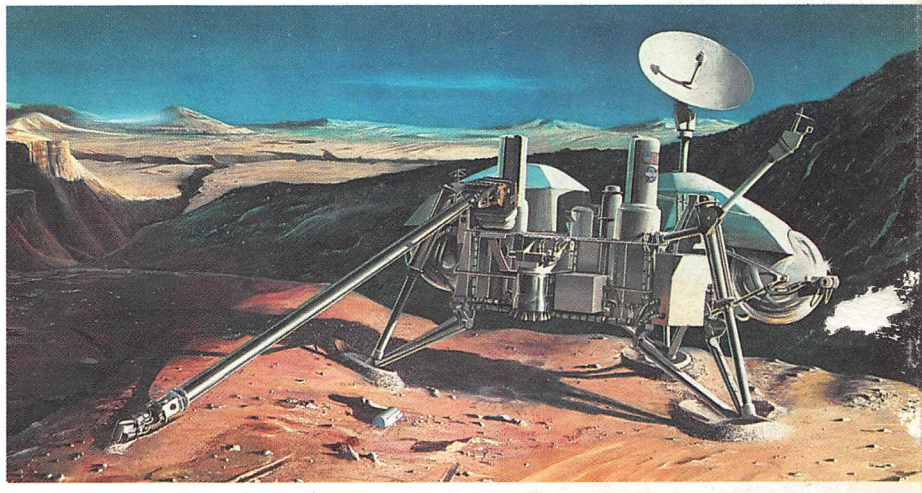
By this time, the problems of remote control had become acute. Radio signals took 38 minutes to complete the round trip between Earth and Mars and, therefore, as many functions as possible had been delegated to the two onboard computers. However, at one point in the mission the arm jammed up and was eventually freed, somewhat ironically, by jigging it backwards and forwards under remote control from Earth.

The most advanced manipulator to be used in space, or for that matter on Earth, is the RMS (Remote Manipulator System) on the Shuttle. Built at a cost of $25 million, the RMS is designed to lift satellites and other payloads in and out of the cargo bay and position them accurately in orbit. It has a maximum reach of 15.3 metres (50 feet) and, though not designed to function where gravity exists, it can shift masses of up to 15 tonnes.

Six electrical servo motors (see page 69) provide this quite incredible leverage, which is controlled by two joysticks inside the main cabin. Television cameras are mounted on the elbow and wrist, as well as inside the cargo bay, and the operator selects the images to be displayed on his two monitors.

For the next few years, emphasis is to be switched from manned exploration of the planets towards the construction of an Earth-orbit space station and the industrial exploitation of a weightless environment – using the Shuttle. Robots for the construction and for the maintenance of space hardware are now under development. So perhaps, as the writers suggested, the first fully autonomous – if not fully intelligent – robots will appear in space before they do on Earth.





The Viking 1, which landed on Mars in July 1976, represented a remarkable achievement in engineering miniaturization. Weighing only half a tonne, it nevertheless incorporated two automated chemical laboratories, a weather station, a seismology station, a photographic processing laboratory and two computers. At the end of the telescopic arm there is a backhoe for digging trenches and a scoop for collecting soil samples to be deposited in the biological and chemical processors.

UNDERWATER AND UNDERGROUND

One of the main uses for mobile robots, as distinct from static manipulators, is to give us access to environments not normally available to human beings. Such machines can best be described as exploratory robots.

If the environment is a confined space, such as the inside of a narrow pipe, then the barrier to our access is physical, and a purpose-designed robot may be the only solution. Or the environment may be hazardous – for example, where there are noxious or corrosive chemicals or dangers of fire or nuclear radiation. Here the use of a robot may not be mandatory, but it is highly desirable from a safety viewpoint.

Sometimes the motive for using an exploratory robot in place of a person is economic. This applies particularly to environments that are hostile and which would therefore demand expensive life-support systems. Outer space may be the most obvious example, but the world under the sea is equally hostile and is sometimes described as 'the final frontier', because our exploration of its depths has been so limited.

Underwater

Most underwater robots are really RCVs (Remotely Controlled Vehicles). The device is linked to an operator, usually in a support vessel on the surface, by means of an umbilical cable which carries the instruction signals, sometimes together with the power supply. Robots are either free-swimming, featuring adjustable ballast tanks and propellers like a submarine, or bottom crawling, using caterpillar tracks.

One machine that can operate in either mode is the submersible developed by British Telecom International, which is used for laying, inspecting or replacing undersea telephone cables. It is based on the chassis of a Scorpion tank, and at 7.6 metres (25 feet) long, it is larger than most robot vehicles. Unlike previous systems, Seadog actually buries the cable half a metre into the sea bed, using a powerful cutting head and suction system to dig and then fill in the trench. The whole project was conceived because so many undersea cables were being fouled by the nets of fishing trawlers, and laying them underground is the perfect solution.

Television cameras and floodlights provide direct visual feedback to the operator's sophisticated control panel, but a small computer on the vehicle itself, linked to several types of sensor, gives the unit some measure of local autonomy. A magnetic sensor protruding from the front can detect a buried cable and guide the vehicle along its path, and a small manipulator arm, together with a powerful cutter, can be used to remove damaged sections of cable.

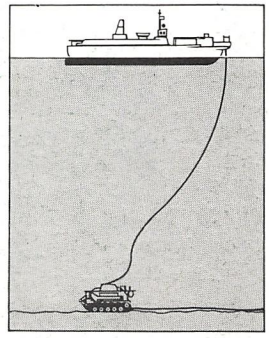
Most undersea robots are less intelligent than this submersible and have every function directly controlled by an operator. Nevertheless, they have a considerable range of applications. Robot submersibles have been used to explore the geology, flora and fauna of the deep natural trenches in the ocean floor, which are inaccessible to conventional submarines. Similar devices, fitted with sonar and other sensors, have been used by the military for detection of underwater enemy activity and for minesweeping.

Oil companies are also major users of robots, for the inspection and maintenance of oil rigs and well-heads. The costs associated with deep-sea diving are now so high (largely because of the need for very long decompression periods) that any form of automation becomes attractive.

The wide ocean, however, is not the only domain of the underwater robot. A highly manoeuvrable free-swimming device, just half a metre in length, has proved invaluable in the inspection of nuclear power station cooling systems. Indeed, a great many mobile robots have been designed for pipe inspection, from gas mains to sewers – one such device being appropriately known as the sewer rat.

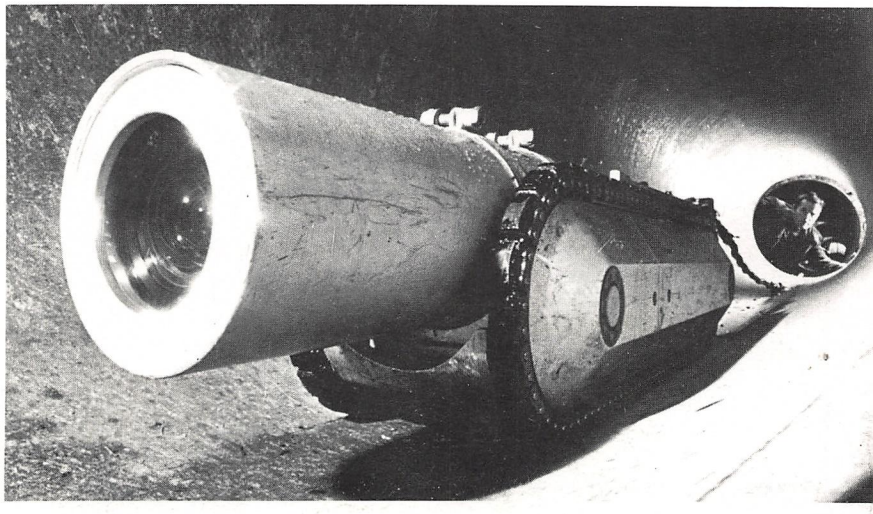
Most underwater robots are used for exploration, but British Telecom International's submersible (right) performs the useful tasks of laying and repairing underwater telephone cables. Movement is controlled from a support ship on the surface (shown below), and the vehicle also contains a sophisticated onboard computer.

The submersible can be given positive buoyancy for free-swimming, or negative buoyancy to give it a firm footing on the sea bed. It is now in constant use around the world.



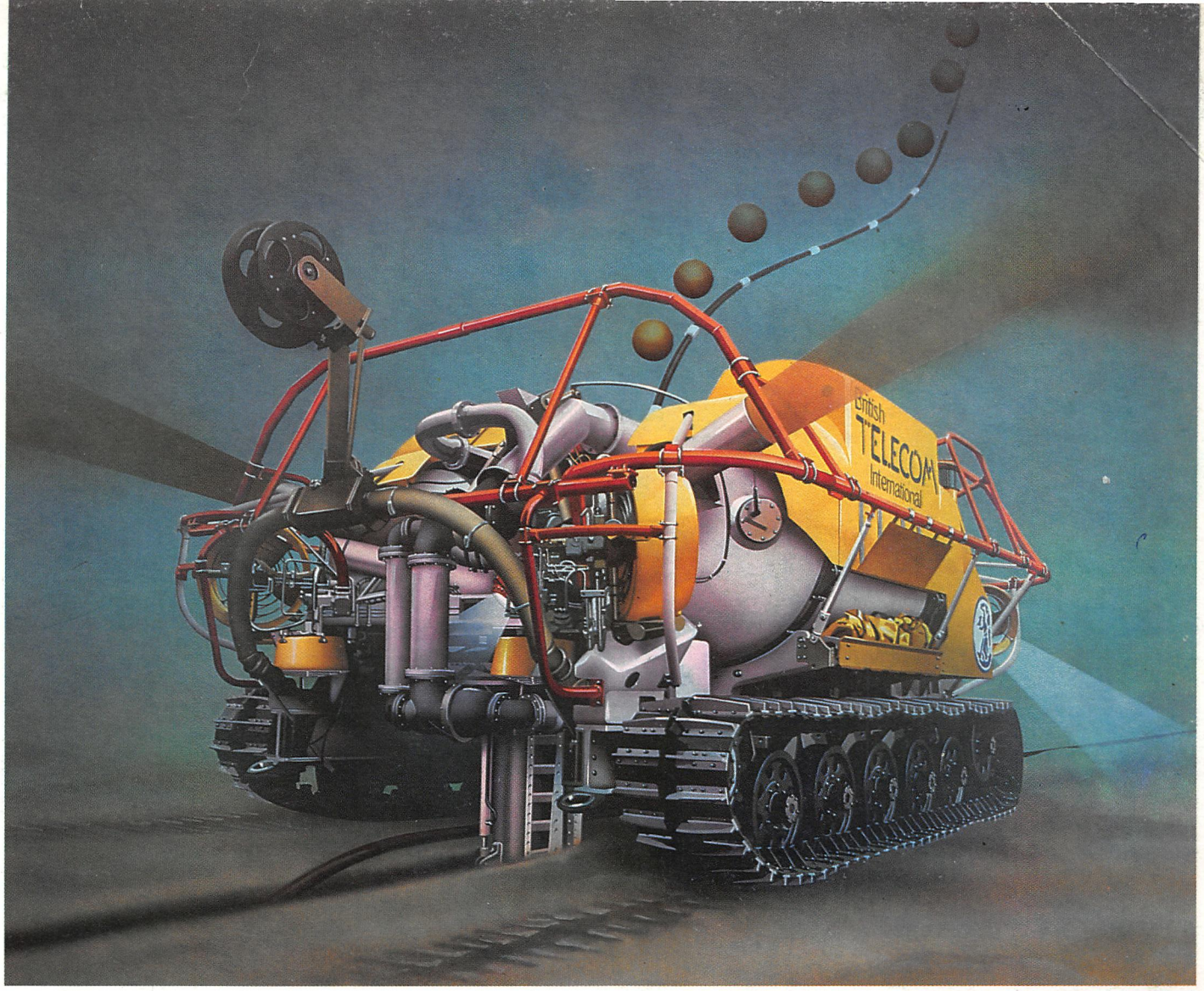
Underground

A particularly ingenious invention is a machine for laying cable television lines along the sewers directly into houses – thereby saving the need to dig up the roads. Although pulled along by wires from the surface, the miniature robot sports lights, a television camera and some sophisticated sensors for determining its exact position along the pipe. This information is used during phase two of the operation, when the device glues the cable, together with a protective sheath, to the roof of the pipe. The sheath is needed because real sewer rats are apparently rather partial to conventional PVC sheathing on electrical cables.



Miniature robots fitted with television cameras, like the one shown above, are used for cleaning and inspecting pipes and underground drains. A similar device now under development will be able to lay cable-television lines to private houses, along the sewers. The robot will be fitted with a tiny drill and a glue gun for fixing the cable in place.

If robots can operate underwater and underground, why not in mining – surely one of the most



This free-swimming robot submersible enables the cooling systems on nuclear reactors to be inspected without risk of radiation to humans. The craft is fitted with powerful lights and television cameras to send pictures to the control panel seen on the right of the picture. Buoyancy tanks control depth, and fine jets of water provide the steering. The rounded design of the casing allows it to navigate around relatively tight corners.

unpleasant jobs for humans, but one on which we are so dependent? The mining industry has invested a great deal of money into such research with fruitful results. The giant coal-face machines that break up the rock itself can now be remotely controlled and experiments have been conducted with lasers to track the cutter's position through the clouds of coal dust. Hydraulically powered roof supports can be moved automatically into position and then activated to take up the strain, and a system of conveyors and vehicles can be employed to retrieve the mined rock.

As technology improves, particularly in the areas of sensors and artificial intelligence, it is conceivable that an entire mine could be automated. The system would still rely on human management and maintenance, but very few man-hours would have to be spent below ground.

That brings us back underwater – to the prospect of mining and even harvesting the sea bed. It has been known for years that the ocean floor is rich in minerals, such as manganese nodules, and that nutritious plants could be grown for our use, too. The limiting factor has always been the hostility of the environment to a human workforce. Now it looks as if whole industries could be set up at the bottom of the sea without the need for people ever to go down there.

MILITARY ROBOTS

The Wheelbarrow is a bomb disposal robot employed by the British Army in Northern Ireland. The tracked base supports a manipulator arm and a television camera for visual feedback.

If space exploration and robots go together naturally and happily in people's minds, then warfare and robots do not. What could be less desirable than a lethally destructive piece of hardware with an electronic mind of its own? The first of Isaac Asimov's Three Laws of Robotics specifies that 'No robot may harm a human being, or through inaction allow a human to come to harm'. That these laws were laid down long before the robot became a reality is perhaps a reflection of our fears about the subject. It is a good deal easier to define such laws than it is to implement them, but the idea of deliberately contravening them is nevertheless appalling.

However, as with any advances in technology, the spread of robotics and the use of robot-like devices has occurred just as readily in military applications as elsewhere.

Harmless robots

It has to be said, however, that most robots employed by the military are remote-controlled rather than autonomous devices. As such, they do not constitute an independent threat to humans and in many cases contribute to our safety. The best example is the bomb disposal robot employed by armies, police forces and other military institutions around the world.

Bomb disposal robots are battery-powered, tracked vehicles about 1.2 metres (4 feet) long, linked by an umbilical cable to an operator up to 100 metres (330 feet) away with closed-circuit television pictures. A manipulator arm or boom, also remotely controlled, can move objects out of the way or plant a wire-linked detonation charge before withdrawing. Should the bomb explode unexpectedly, the boom is designed to sheer off at its base, thereby causing as little damage as possible to the vehicle base. A large range of additional gadgets can be fitted, including a shotgun for taking out car windows at a distance and a limited-range X-ray scanner for inspecting suspect packages without contact.

Another example of military remote-control vehicles are drones – radio-controlled pilotless aircraft used for missile target practice. Most of these are designed to break up on physical impact and the parts parachute to the ground for re-use. Though some are full-size mock-ups, the military are not averse to using refined model aircraft, both for target practice and for reconnaissance. Conventional cameras have been successfully fitted to radio-controlled model helicopters and used for aerial observation – so far in pursuit of largely peaceful goals.

Destructive robots

It is when devices are fitted with weapons *and* a measure of local autonomy that they start to pose a threat. Strangely enough, most people are unaware of just how robot-like is one of the most publicized developments in military technology – the cruise missile. Leaving aside the warhead (which may be nuclear or conventional explosive) for a moment, a cruise missile is essentially a cross between a rocket and a pilotless plane, but equipped with the most advanced position-sensing and navigation systems of any mobile robot.

Having penetrated enemy airspace, the missile drops to an altitude of just 15 metres (50 feet), using a radar, rather than conventional air-pressure, altimeter. The navigation system, known as TERCOM (TERrain COntour Matching), constantly compares readings of the ground height with a contour map stored in electronic memory. Furthermore, it can switch, at random, between the twenty-five approach routes programmed into its system. Unlike other missile guidance systems, which rely on inertial navigation, or satellite tracking, it is virtually impossible to predict the trajectory of a cruise missile and, therefore, to intercept it.

Although the USA is naturally concerned that this technology should not reach their opponents, there is nevertheless a strong possibility that the research will result in some beneficial spin-offs. The navigation procedures, on a smaller scale, would be equally applicable to a robot planetary explorer or even a robot lawnmower.

Until recently, the idea of a robot tank, which could identify and eliminate opponents without human intervention, was entirely fictional; now it is fact. The Prowler (Programmable Robot Observer With Logical Enemy Response) is every bit as sinister as its name suggests. The six-wheeled base, similar to an armoured car, supports a distinctly animate-looking turret with two M60 machine guns or other armaments.

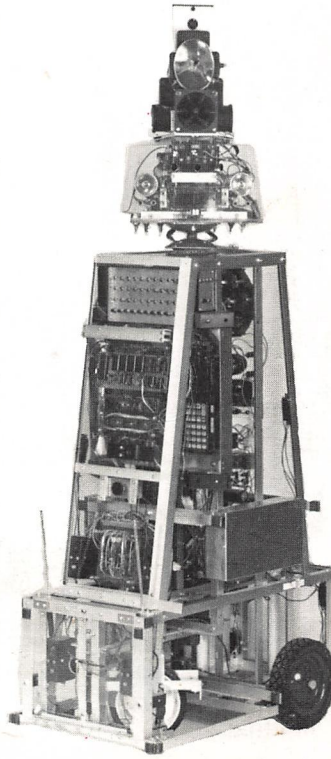
The Prowler was developed as a sentry, rather than for true military engagements. Its onboard range-finding sensors are designed for tracking a fixed and identifiable object such as an above-

The Prowler (right) is the first robot deliberately designed to break Asimov's Three Laws of Robotics – see page 24. It is a six-wheeled sentry robot intended for the patrolling of sensitive areas such as oil pipelines or military bases, and its name stands for Programmable Robot Observer With Logical Enemy Response. The Logical Enemy Response in this case is two M60 machine guns, although other armaments are available.

The Prowler is intended as an RCV (remotely controlled vehicle), with one security guard operating several vehicles. However, there are plans to increase the vehicle's autonomy, giving it the ability to identify intruders and give verbal warnings automatically.

The cruise missile (below right) is really a sophisticated robot. A contour map of the target district is stored in its electronic memory, and by means of a radar altimeter the missile can pick its own route to the destination, flying just above ground level.

ROBART-1 (below) is one of several examples of experimental robot sentries developed by the US Army, but never put into production.

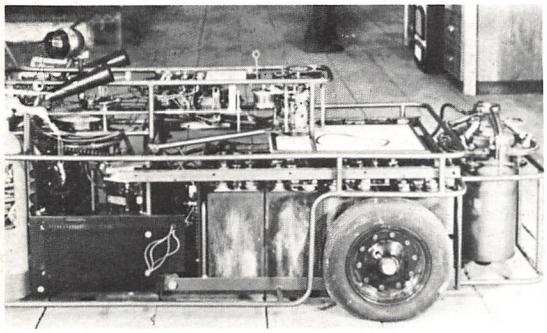


ground oil pipeline or a perimeter tence. As the ability to identify intruders is based on crude evidence such as movement or body heat, most of these devices are linked to a central human controller and have a television camera on top of the turret that can elevate telescopically some 5 metres (16 feet).

The techniques of pattern recognition, originally developed for industrial robot applications, are being pursued by a number of military bodies. In World War II, submarine captains identified ships silhouetted against the horizon using a simple book of outlines and a few rules relating to numbers of masts, funnels and superstructures. Such identification is well within the capability of the 'expert system' programs that run on today's microcomputers. Identifying enemy tanks and personnel in a battlefield is more complex, but robot vision systems are very adept at isolating objects from their surroundings and eliminating extraneous data and noise.

Fiction has already pursued the idea of wars fought out entirely by robots, with the people acting merely as observers. Like so many things, there are very real arguments both in favour and against the use of robots on the battlefield. We are certainly now at the point where their use depends upon political policies rather than technological constraints.

MOBILE ROBOTS



Fitting a robot arm onto a mobile base unit vastly increases the area that it can access – in technical terms the 'working envelope'. Most robots depicted in science fiction have been mobile – and to some extent we associate the idea of autonomy or intelligence with the ability to move around of our own accord.

Very few truly mobile robots have yet been built. There are a number of free-roving educational robots on the market (see page 48), but these are still limited in what they can perform. Then there are the remote-controlled vehicles used in exploration – underground, underwater and in outer space. Some telechirs used for handling dangerous materials are mounted on mobile bases, too. But the reason why the mobile industrial robot has yet to become a reality is largely historical.

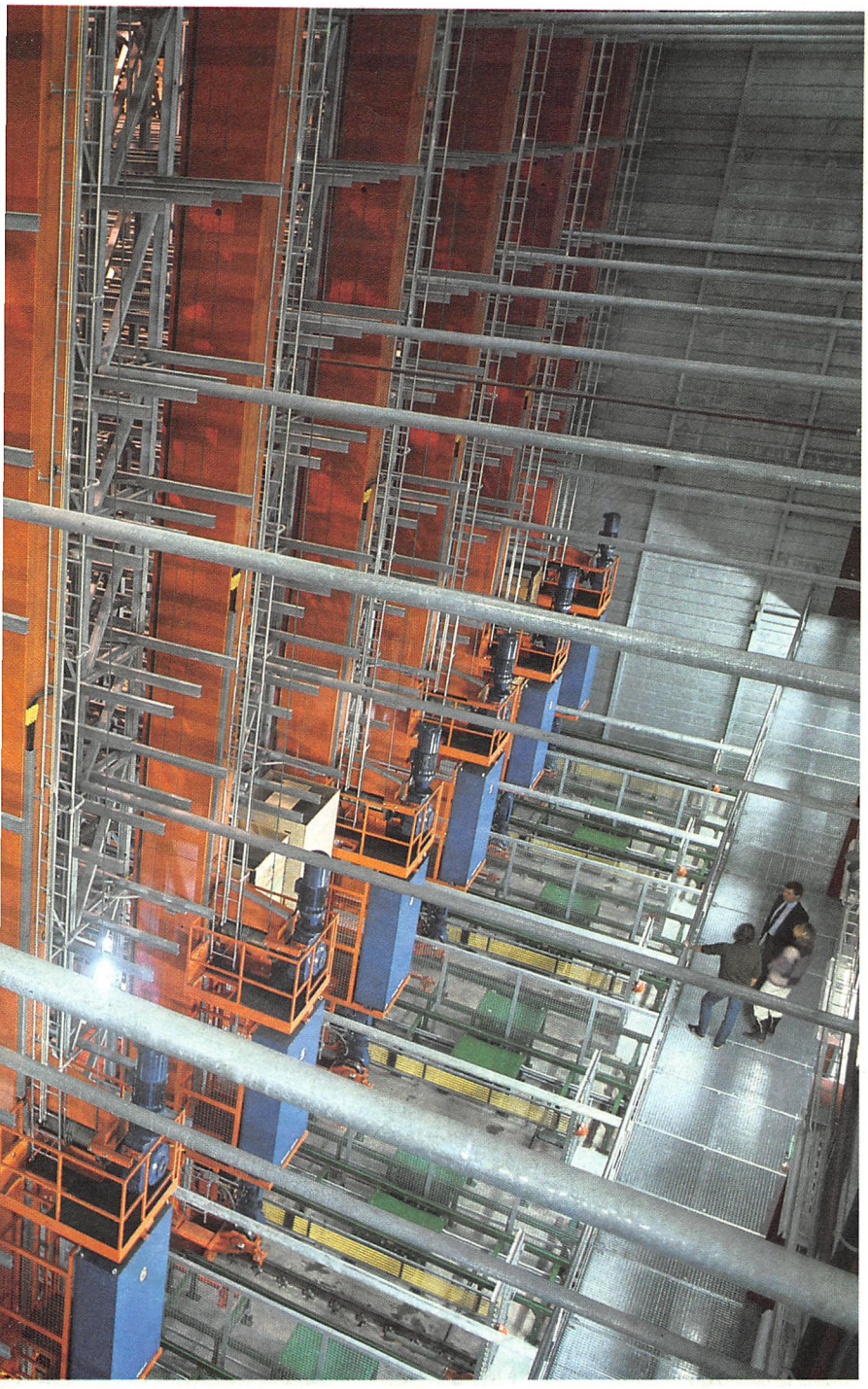
The assembly line has formed the basis of mass production since its inception. Shifting materials and components around – particularly heavy or bulky items – is a costly and time-consuming business. It therefore made sense to keep the material moving in a straight line and fit the workforce around it. Viewed as a one-for-one replacement for a person on a production line, there was little need for robot arms to be mobile. Furthermore, robot arms are considerably heavier than humans, and many can only deliver a useful force if they are bolted to the floor.

There are some exceptions. A tracking robot is essentially a manipulator arm mounted on a set of rails typically 5 metres (17 feet) in length. This gives it the facility either to service several machines or work stations or to grasp objects from a continuously moving conveyor.

The same concept has been extended into two

Robot firefighters (top left) could patrol factories, using infra-red sensors to detect heat. After phoning for help, they could proceed to apply an extinguisher.

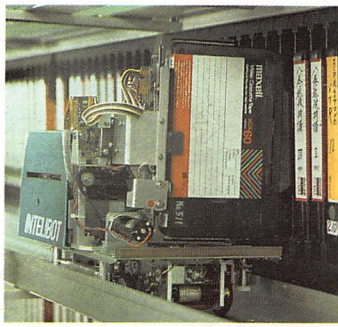
AGVs or Autonomous Guided Vehicles (left centre) follow printed tracks on the floor of a manufacturing plant. They are equipped with collision detectors for safety.



Fully automated warehouses like the one shown above can retrieve any pallet of goods from among thousands without human intervention. The control computer calculates the location of the item from its product code, and converts this into co-ordinates that the robot can follow.

and even three dimensions, to provide the robot warehouse. Items are stacked onto conventional industrial pallets (the kind used by fork-lift trucks) and these are stored on giant racks. Upon instruction from a computer terminal, the robot will traverse to the required horizontal and vertical position and retrieve the pallet. Because the computer can monitor the location of all goods, it is possible to have a complete order assembled at the despatch point directly from the invoice. Visitors to these automated warehouses find them rather eerie, not just because there are no humans at work, but because the operations are often performed in total darkness.

Similar arrangements exist on a smaller scale, too. At the Kanazawa Industrial University library, in Japan, mobile robots the size of biscuit tins retrieve video tapes from the archives and transport them to individual viewing booths. The video library functions like an oversized juke box, but the thirty-four Intellibots doing the transporting are real robots, featuring tiny manipulator arms.



The Intellibots are miniature robot librarians, employed for locating videotapes and transporting them to viewing booths. When not in use, they return to a parking bay to recharge their batteries. Thirty-four of the robots are controlled by one computer, which calculates the optimum path for each robot and averts potential collisions.

Autonomous Guided Vehicles

Large mobile bases, used solely for moving goods around a factory, have existed for some time in industry. Their sophistication and autonomous control justifies the label of robot, but they lack any form of manipulator arm. They are more commonly called AGVs (Autonomous Guided Vehicles), a description which correctly indicates that while they have onboard intelligence in the form of a microcomputer, they rely on some external form of guidance, such as tracks or rails.

The guiding rails provide information rather than physical force, however. Sometimes a line painted on the floor is sufficient. In this case the AGV features several light-sensitive cells at the front, from which the onboard computer can detect the position and direction of the line. In dirtier environments, an electrical cable is buried several centimetres under the floor and the AGV detects the electromagnetic radiation induced by high-frequency signals in the cable.

Additional marks and signals can be painted by the side of the track line, to be picked up by other sensors on the vehicle. Branches, loops and sidings can all be incorporated in the layout. The movement of the AGV can then be controlled by a central scheduling computer or by giving each vehicle the ability to choose its own course according to instructions typed in at the start of the journey.

For safety, all mobile bases are equipped with sensors to detect unexpected obstacles – including other bases or people – in the pathway ahead. As a final precaution, collision detectors looking like front and rear bumpers will stop the unit dead if physical contact is made.

With robots doing the donkey-work, materials handling ceases to be the dominant problem in manufacturing, and the work stations (themselves operated by robot arms) that, for example, make up the body shop can be arranged to suit other factors. The futuristic model of a production line manned entirely by robots may well be a false picture, since the nature of the mobile robot may make the identifiable production line redundant.

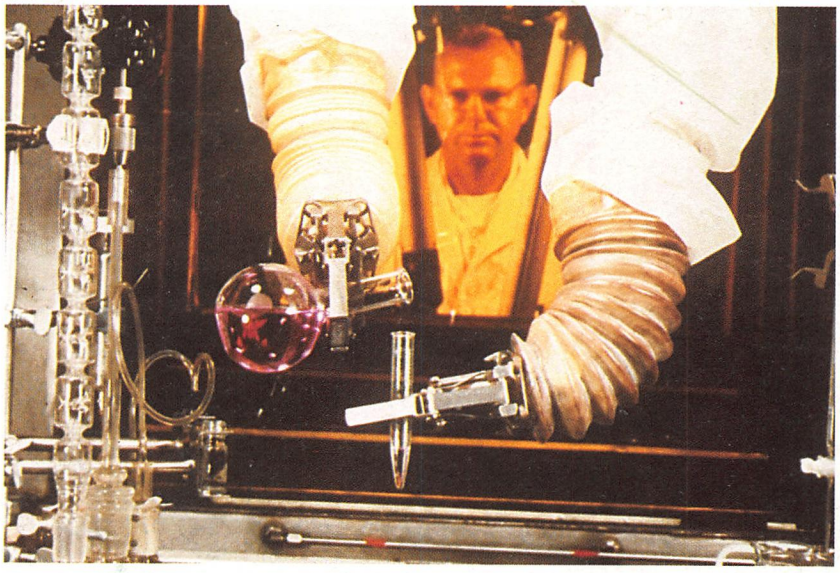
TELECHIRS

The word telechir comes directly from the Greek and it means literally 'hands at a distance'. Telechirs are not true robots, because their actions have to be controlled directly by a human – each movement of the operator is mimicked by the telechir. They can't learn a sequence of movements and then repeat it in the way that a robot can. In that sense, the telechir is to the industrial robot arm what a remote-controlled vehicle is to a true mobile robot.

The similarity in construction and specifications between telechirs and robot arms, however, means that much of the technology is common. The telechir was devised before the robot arm partly because programmed control was very difficult before the advent of the digital computer.

The first telechirs, then, merely reproduced the movements of hand or arm at a distance, either to extend a person's reach, or to protect him from a dangerous environment. Some were fine examples of precision mechanical engineering A typical device used in, say, the production of nuclear fuel rods, actually consists of two identical arms, linked by jointed rods or cables. The operator holds the end of the exterior arm, and all the movements are translated by the connecting rods to the arm inside the work cell. More complex configurations have also been tested, including one in which the operator wears a kind of mechanical sleeve that measures the position of each joint from shoulder to wrist.

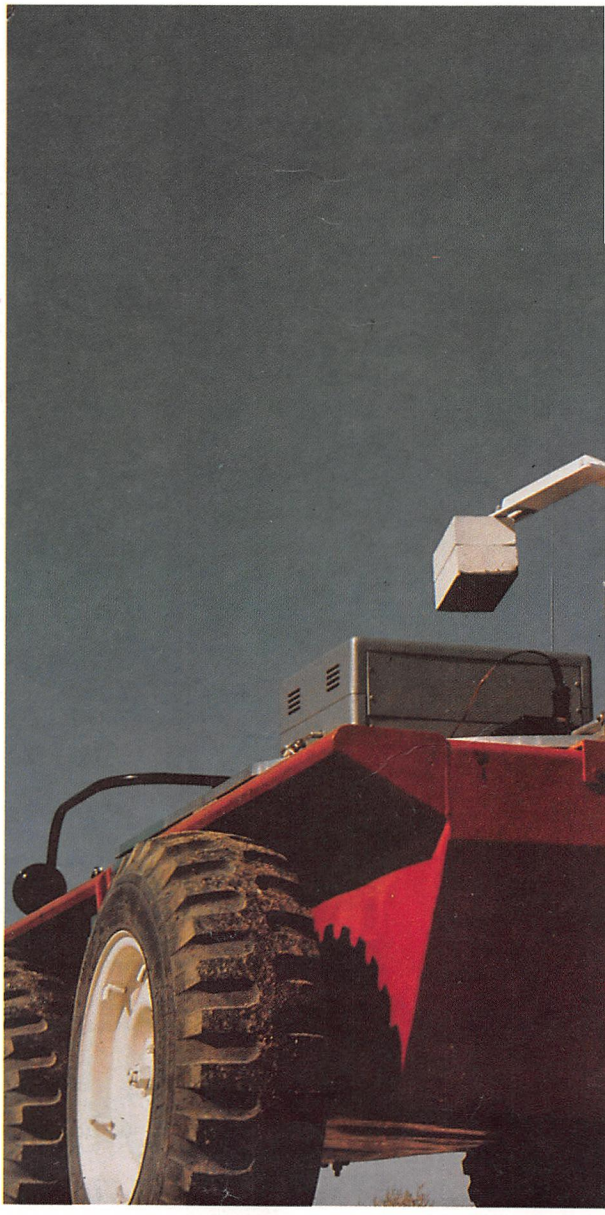
Using a simple lever arrangement, the movements of the operator can be geared down – either to increase the force applied to the workpiece or the precision and stability. In microsurgery, for example, even the steadiest



However, it was also a case of necessity being the mother of invention. The need for 'hands at a distance' arose long before industry even started to think about automation.

Simple telechirs had existed since Victorian times, if you count devices such as lazy tongs, and tools for picking apples off trees. But it was during World War II, with the handling of radioactive materials, that the need became acute. In some cases it was simply enough to maintain an airtight seal between experiment and experimenter, by means of thick rubber gloves which formed part of the casing. Other situations demanded that the operator be kept more than a metre from the workpiece and have several centimetres of lead-shielded glass for protection. As the experiments required as much manual dexterity as that needed when performing any conventional practical chemistry, the handling device needed to be quite as manoeuvrable and dexterous as the human arm itself.

The most common use for telechirs (above) is in handling dangerous materials. The operator sits in complete safety, and the mechanical arms mimic his every movement. Other forms of telechir magnify or reduce the operator's movements, or they may amplify the force available. In the latter case it is essential to have some form of force feedback, to prevent the operator from causing accidental damage.



SAM (right) – the name stands for Self-propelled Anthropomorphic Manipulator – is a mobile telechir developed by NASA for inspection and maintenance in hazardous environments. The increasing possibility is that SAM could be used in the event of a nuclear accident.

surgeon's hands could not achieve the minute movements entailed. A scaled-down telechir, however, can reduce ordinary hand movements to fractions of a millimetre and these movements can then be observed by the surgeon through a microscope.

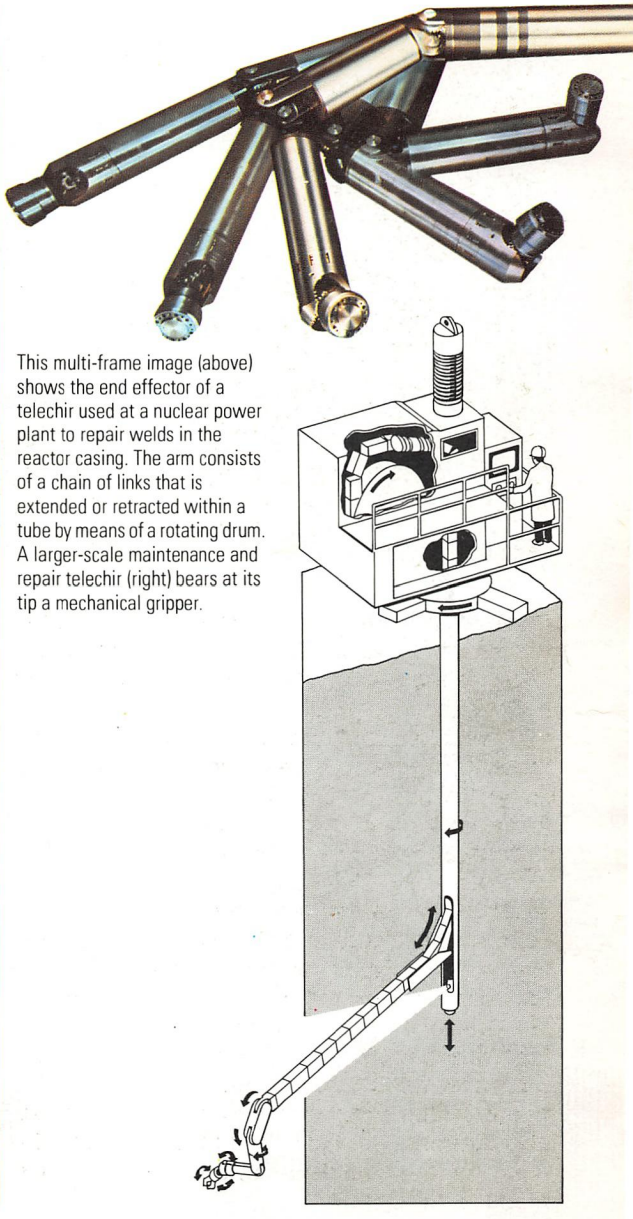
Feedback

Visual feedback is vital to all applications of telechirs – whether direct, or through shielded glass or, where the workpiece is inaccessible (such as inside a nuclear reactor), by means of a closed-circuit television link.

If the application demands considerably greater forces than the human arm can deliver, then a servo-mechanism is employed. A servo-mechanism draws on an external power supply to magnify the force and/or movement between its input and output. Most cars now have servo-assisted brakes, where the power source is the vacuum in the inlet manifold, and some have hydraulic power-assisted steering. Servo telechirs are generally electrically operated. Electrical sensors pick up the movements from the joints in the operator's control column and send instructions to electric motors at the other end.

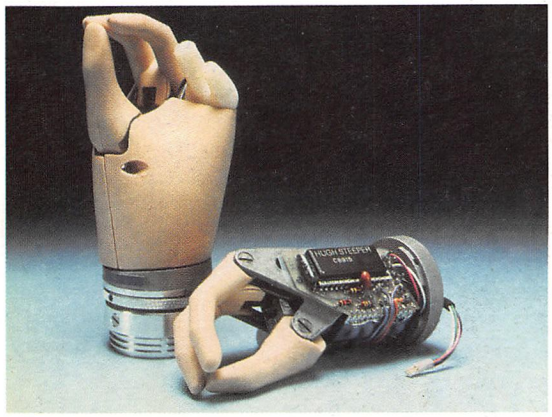
Here, feedback becomes even more important. On a purely mechanical telechir, the operator can feel both the pressure with which the object is gripped and its weight. With a servo-assisted arm, this won't be the case unless force feedback has been designed in. In cars, feedback has been designed into the more expensive models of power steering, in which the wheel becomes more difficult to turn as you corner faster. Such feedback is essential to the telechir operator either when handling very delicate objects or very heavy ones – in the latter type of case, in order that the object can be set down without dropping it or forcing it through the floor!

Telechirs can be fitted with other sensors, too, particularly for noise or heat. Just as a high-performance car must let the driver feel the road, so a telechir, whether for microsurgery or dangerous materials handling, must feel to the operator like an extension of his or her own arm.



This multi-frame image (above) shows the end effector of a telechir used at a nuclear power plant to repair welds in the reactor casing. The arm consists of a chain of links that is extended or retracted within a tube by means of a rotating drum. A larger-scale maintenance and repair telechir (right) bears at its tip a mechanical gripper.

MECHANICAL ARMS AND LEGS



The Steeper Myoelectric hand (far left) is designed for children aged 6 to 10. Electrical sensors fitted to the upper arm pick up the tiny voltages associated with muscular activity. Amplified by the control chip shown in the exposed hand, these signals can directly drive the electric motors that close the fingers.

The operator of the JPL/Ames manipulator (left) wears a mechanical sleeve containing electrical sensors in every joint. The signals from the sensors are interpreted by a computer, which in turn drives the servo motors in the joints of the manipulator itself – which could be in another room. Later versions of the arm, developed by NASA for space exploration, included a mechanical copy of the human hand.

A telechir system comprises two mechanical arms linked together, one to detect the movements of the operator and another to reproduce these movements, either in another location or amplified in strength. Integrate these two functions into one device, a kind of mechanically powered sleeve fitted around a human arm, and you have what is known as an exoskeleton.

We are used to the idea of putting on additional skins to extend the range of environments we can explore – diving suits, space suits, armour, even the humble raincoat. An exoskeleton is like putting on an external set of muscles and bone to extend strength. As the operator moves his arm, he will apply pressure to the frame. This pressure is detected by sensors in the frame, and used to control the powered actuators. Several experimental exoskeletons have been developed, and although none has gone into commercial production, they have provided invaluable insight into many facets of robotics.

For with exoskeletons, the problems of control become acute. A person strapped into a harness capable of lifting three-quarters of a tonne, has the capability for inflicting considerable damage, not only on the environment (like the proverbial bull in the china shop), but also on himself. The first need is therefore to provide force feedback, so that the operator can feel the weight of any object or the force he is applying to it. An exoskeleton should, in effect, feel just like a person's own arm. The second need is for the control system to distinguish between planned and involuntary movements. Otherwise if the operator should subconsciously reach up and scratch his ear, the consequences could be disastrous!

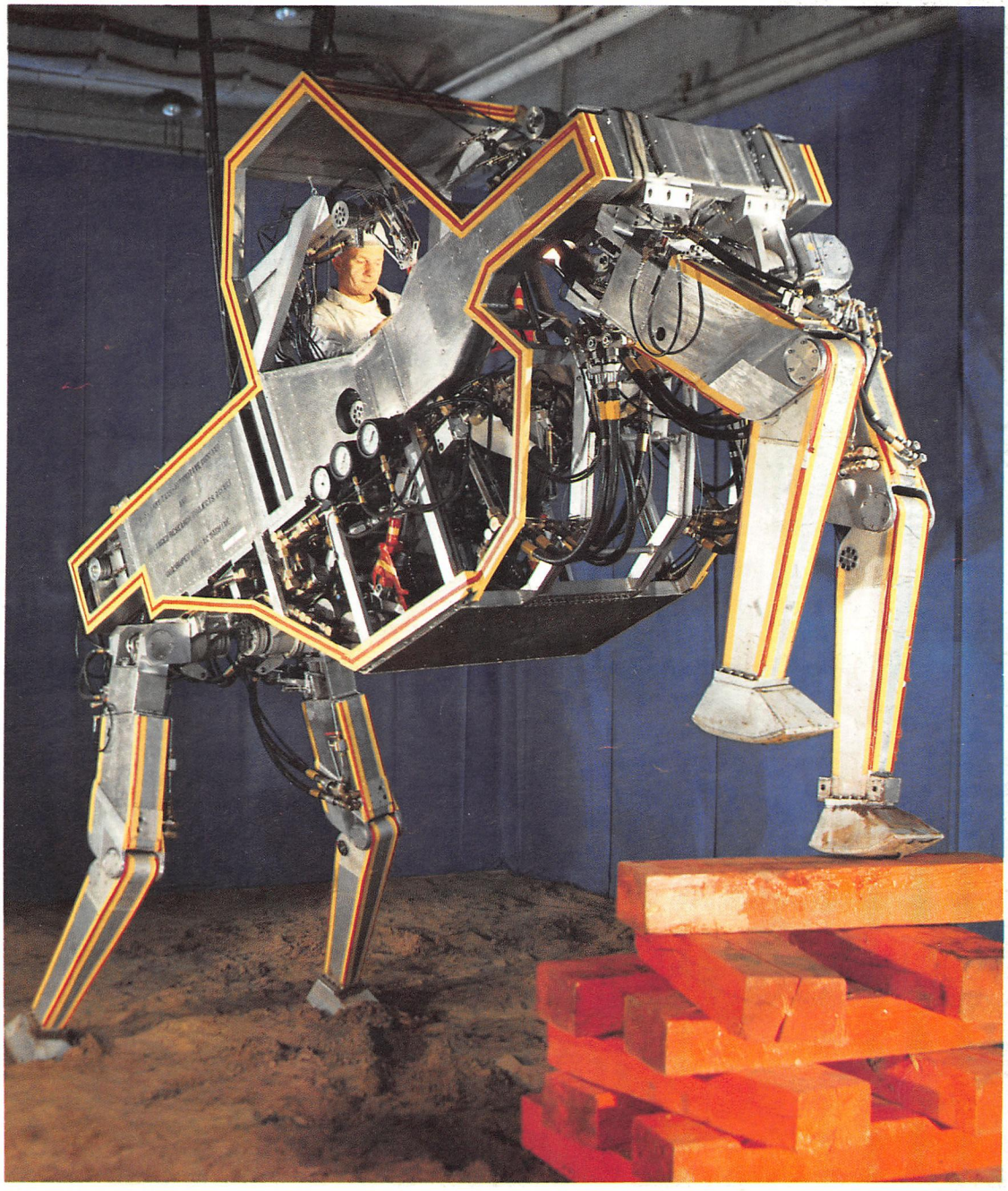
Helping the disabled

Exoskeletons that magnify human strength by a factor of ten could have commercial applications in warehousing and construction. However, similar devices with specifications equivalent or even inferior to the human model have also been developed, for use by the disabled. Mostly these are cumbersome and inelegant devices, but the design could conceivably be refined to become a viable and even preferable alternative to the wheelchair.

An exoskeleton can only amplify existing movement, making it impracticable for use by many disabled people. But the area of prosthetics (replacement limbs) is now starting to overlap with robotics, too. Such research is also called sceptrology, because the Greek word from which 'sceptre' comes means 'staff' and refers not only to a king's staff of power but also to a crutch.

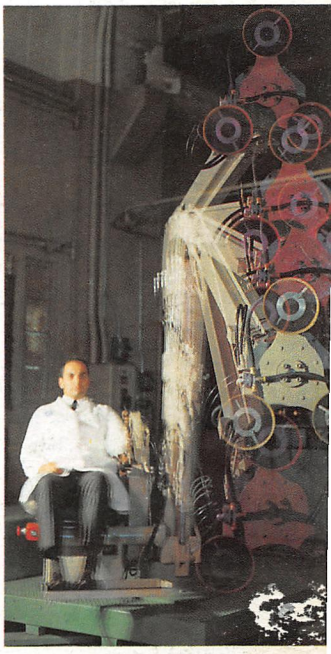
No mechanical construction could emulate the dexterity of the human hand, but some artificial limbs can be applied successfully to a wide range of tasks. Motive power usually comes from rechargeable batteries, or small cylinders of compressed air inside the limb. To deliver a useful force, the construction should ideally be fixed directly to the bone, but this entails passing through the skin, which results in a join that is prone to infection. Scientists now believe that the answer to creating a join between skin and metal or plastic may lie, literally, at their fingertips – the cuticle at the base of each fingernail. What is needed is a transplanted or artificial cuticle that, like the one on each finger, provides an impermeable connection between skin and a hard surface.

Early forms of electromechanical sceptres relied on some artificial form of control, such as the wearer blowing through small tubes. Recently there has been considerable progress in linking the actuators directly to the nervous system – by means of electrical contacts fixed to the skin of the upper arm or leg. Provided that the nerve system is still functioning properly, the artificial arm will respond in the same way as a natural one, albeit with less freedom of movement. It may one day be possible to perform the reverse process, and link touch sensors of the kind developed for industrial robotics directly



The walking lorry was an experimental vehicle developed by the Cybernetic Anthropomorphous Machine Systems division of General Electric, for potential use by the US Infantry. Even with modern weaponry, the mobility of the foot soldier makes him irreplaceable. The walking lorry was intended to provide support for the infantry, particularly with materials handling.

The operator controls the four legs with his own arms and legs. His movements are amplified by the control circuitry, but force feedback is incorporated so that driving the lorry feels somewhat like crawling on all fours.



The Man-Mate (above) is essentially a powerful telechir for manipulating heavy materials. It simulates many of the motions of the operator's arm and wrist while magnifying his strength and reach capabilities. The controls incorporate force feedback, so that the operator can feel the weight of objects. Without this, setting down objects would be difficult – they would either be dropped or forced through the floor!

back into the nervous system and thereby restore the natural sense of touch.

Robot locomotion

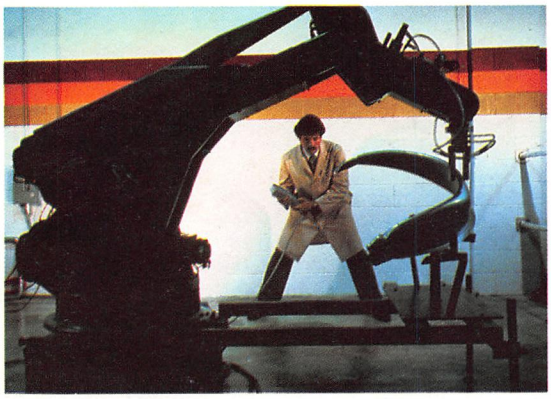
Developments in exoskeletons and sceptrology have contributed surprisingly little to another related field of robotics – locomotion systems, or building robots with legs rather than wheels. The one exception has been the walking lorry, in which the four mechanical legs were linked to the driver's four limbs, using exoskeleton technology.

Contrary to what films might suggest, no one has yet developed a really effective robot biped, so horrendous are the problems of control. Most mechanical walking systems, such as those found on the giant drag-line cranes, are of the quasi-static variety; weight is transferred entirely onto one leg while the other is moved forwards. Humans do not walk in this way, as you will discover if you try to walk very slowly. Instead, we employ dynamic control – continuously adjusting the forces in our legs according to the direction the body is moving, which is detected by sensors in the inner ear. Dynamic control has never been a strong point in robots, although things are improving as microprocessors increase in speed.

One possibility is a uniped robot, such as the experimental 'hopper'. This computer-controlled device is a very good model for learning about dynamic control and locomotion; its action is analogous to using a pogo stick.

If the robot is viewed as a one-to-one replacement for man, then a biped system of locomotion is essential to cope with the same variety of terrain. However, as with so many facets of robotics, for purely commercial applications it is almost always cheaper to redesign the environment to suit the robot than the other way around.

STATIC INDUSTRIAL MANIPULATORS



The idea of the robot worker existed in fiction long before it existed in fact – indeed the word robot was invented by the Czech playwright Karel Capek to describe a human-like machine used as slave labour. Unlike the fictional robot workers, however, the contemporary industrial robot resembles man in function only – not in appearance.

If Isaac Asimov is regarded as the father of robotics, then the father of the industrial robot is George C. Devol, who, in 1954, filed a US patent application for 'Programmed Article Transfer'. Two years later Devol licensed the company that was to become Unimation Inc. – the first business solely devoted to robotics.

After World War II many industries had started to look seriously at automation. The main problem was that each automatic machine had to be designed specifically for one task, which meant that much of the plant had to be replaced whenever there was a change in the products being manufactured. Devol's idea was for an automatic device that could be purchased off the shelf and then programmed to perform the task required. This approach reduced costs and afforded the purchaser considerable protection against obsolescence.

The distinguishing characteristic of these industrial manipulators was that they could learn a sequence of movements and then repeat it reliably and indefinitely. On early models, the sequence was controlled by a rotating drum, similar to that in a musical box, or by an electrical patchboard – with plugs and sockets like the original telephone exchanges. The arrival of the modern digital computer made the creation and execution of even complex sequences into a trivial exercise. Industrial robotics research now concentrates on mechanical performance and on giving the robot senses such as sight, sound and smell.

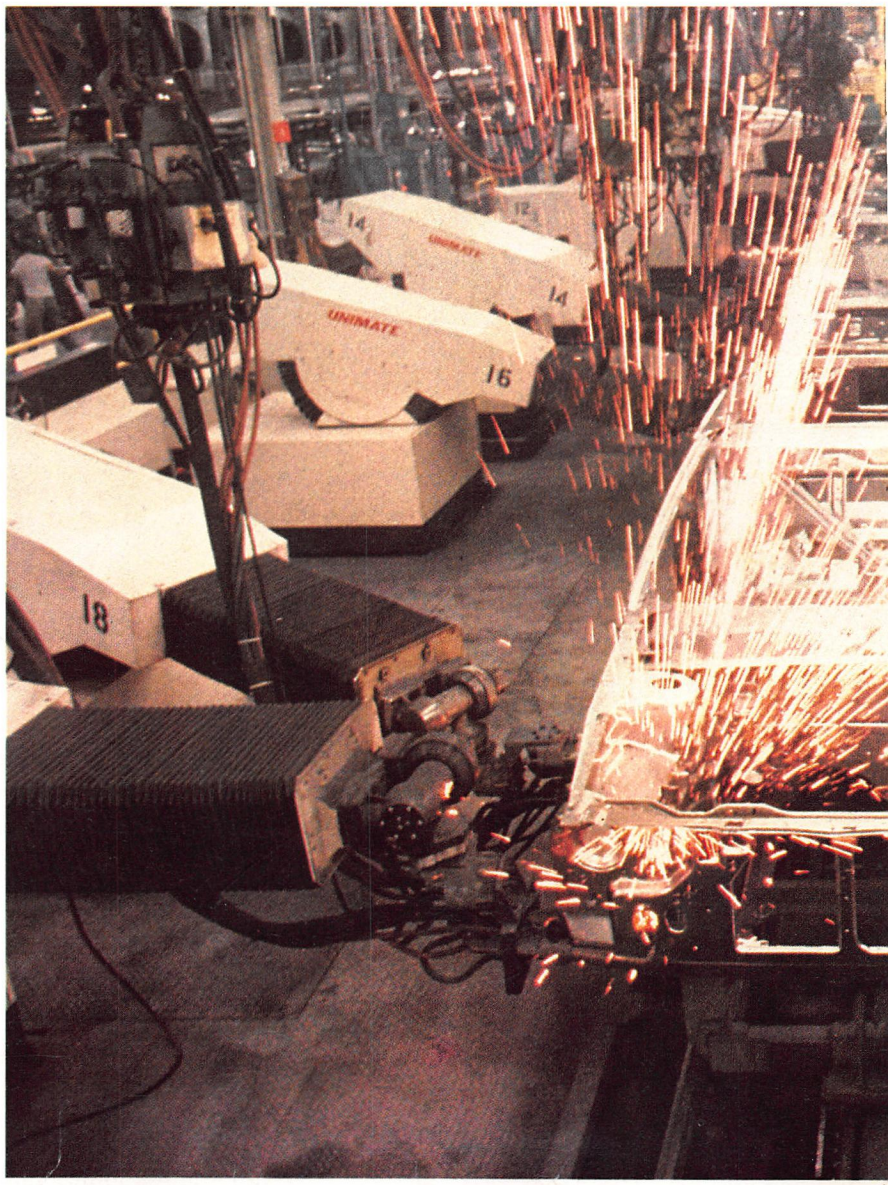
As labour costs soared, the idea of the robot as a one-to-one replacement for a human worker was given more credence. For many applications, a mechanical worker was shown to be a reliable and cost-effective alternative.

Transferring parts

Until recently, however, industrial robots could only be applied to a limited range of tasks. Most are still installed for pick and place applications: picking up objects and placing them somewhere else. This is also called parts transfer. Effectively, the robot is filling in the gaps between other automated devices – for instance, collecting the finished goods from a conveyor belt and stacking them for transport.

Such jobs are boring, tedious and frequently hazardous for humans. In a giant steel press, for example, there may be a 'window' of just a few seconds for the workpiece to be changed before the tool comes crashing down again. A robot can follow a very accurate operation cycle without tiring, and even if it were to go wrong, a broken robot gripper is preferable to a mangled hand.

The robots featured most frequently in the media are really programmable manipulators, like the one shown here (far left). Most resemble the geometry of the human arm, but with both the reach and power extended. Having been programmed once by an operator, they can be left to perform a task indefinitely.



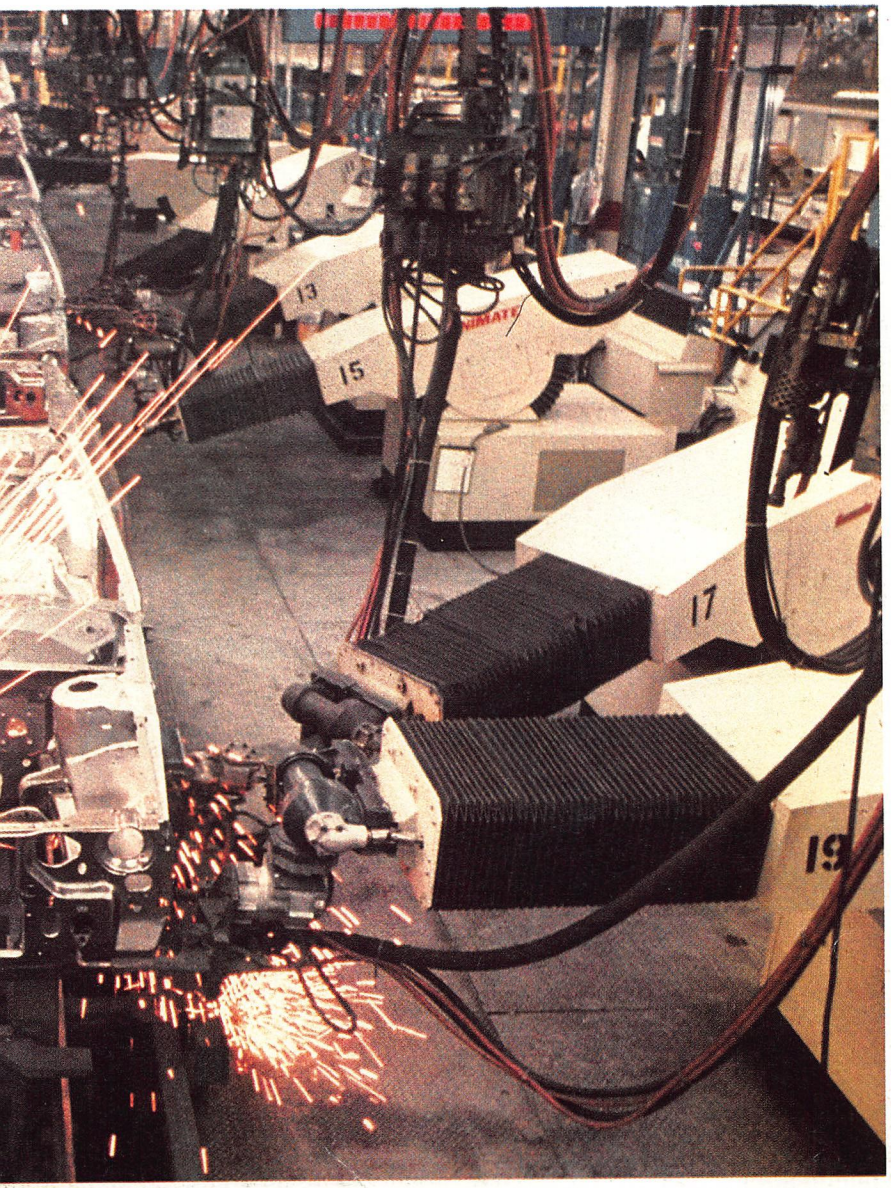
Finishing
The second major application for industrial robots is that of finishing. Paint spraying is perhaps the best-known example of this. The robot arm is, first, physically guided by a human operator through the correct path, while the computer records the movements for programmed operation, and then the arm repeats the procedure automatically. There are many other finishing applications, including sanding, polishing and fettling – removing the excess of 'flash' material from iron castings.

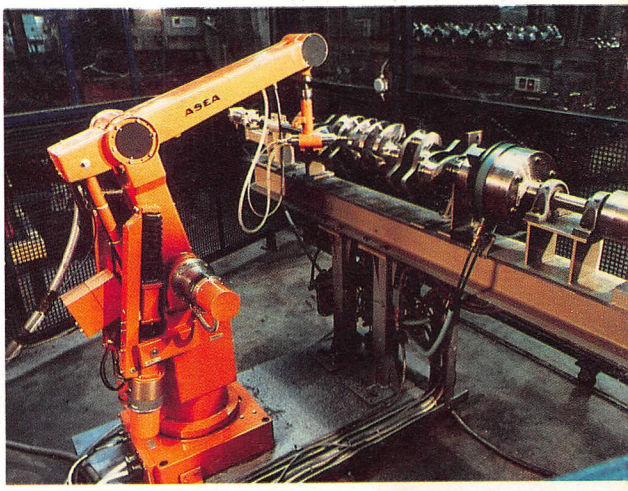
Assembling
The use of robots in assembly is still rare, except for spot welding. Static industrial manipulators and mobile bases can between them put together the entire bodyshell of a car, but the main problem with robots is that they lack the fine sensing apparatus of humans. The finest computer vision system cannot compare with human eyesight, and perception in general is an almost impossibly complex function to model.

The task of inserting a bolt into a hole, which is so simple for humans, is difficult even for the most precise of robots. Our hands are extremely sensitive to pressure, and our brain uses these tiny forces to instruct our hands how to move the bolt. Since robot sensors cannot emulate this, the best the engineers can do is to build some flexibility into the wrist joints.

Checking
Robots have been successfully applied to the inspection of finished goods. A simple vision system is used by one pottery to detect flaws in the glazed pattern, and 'sniffer' robots can detect flaws in a welded structure filled with inert gas (see page 84).

Design
Although there is variation in the shape of industrial robots, most follow the anthropomorphic design of a jointed arm. Some people argue that this is the most effective general-purpose geometry for working in three-dimensional space, others that it is merely a consequence of replacing human jobs on a one-to-one basis.





This Chrysler plant in Missouri (left) shows the extent to which robots are now employed in car production. The range of possible tasks has now been extended from welding and spraying to include fitting windscreens and wheels.

Dedicated automation is losing ground against the new flexible manufacturing systems (FMS). Robots load and unload components from machine tools like this lathe (above), and can then be reprogrammed to produce a new product.

Certainly as industrial automation increases in sophistication, the recognizable human analogies in the design of robots or their environments may well decrease rather than increase. Factories run entirely by robot manipulators needn't be lit, nor do they have to be heated to the level required for a human workforce. Safety considerations need not waste so much space and noise would not be a problem. Moreover, if the goal of robots being serviced by other robots is ever achieved, there is no reason why access by humans should be accommodated at all. If the product to be manufactured is small, like sweets or wristwatches, and the robots are suitably scaled, why shouldn't the whole factory be miniaturized?

EDUCATIONAL ROBOT ARMS

Educational robot arms that plug into a standard home or business microcomputer have been on the market for several years. Mostly, they are purchased by schools, universities and industrial training colleges. Some have found their way into the homes of hobbyists and the increasing breed of robot enthusiasts. Some have even been installed for commercial applications – handling test-tubes in a laboratory, for example.

Two things distinguish the educational robot arm: small size and loading capacity. They are small enough to fit on a table top, with a maximum reach of around 50 centimetres (about 20 inches), and few can lift more than 100 grams ($3\frac{1}{2}$ ounces) – the weight of an apple. Within those boundaries, however, there is considerable variation. Some are designed and constructed by enthusiasts, using balsa wood and string; some come as sophisticated kits; others come ready built and professionally supported with documentation and service agreements. In consequence, they range in price from under £100 to over £2000.

Characteristics of the small robot arm

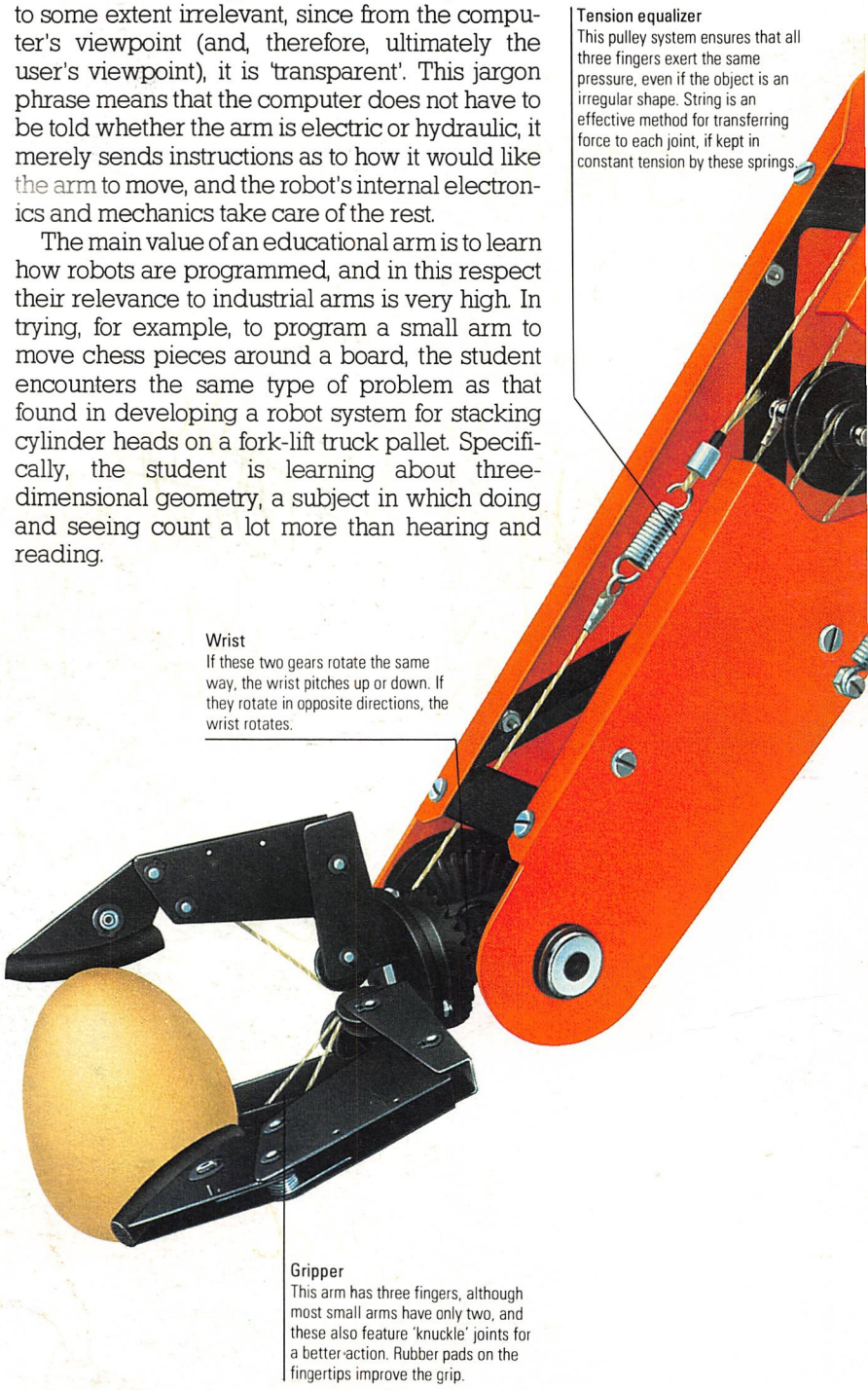
Since the main application for these devices is to learn about the operation of robotic arms in general, it is worthwhile examining the similarities and differences between them and their full-scale industrial counterparts.

In terms of construction and geometry, most educational or small robot arms follow the same pattern as large manipulators, although they usually have fewer independent axes of movement. The end effector may be a simple hook, or an electromagnet for picking up metallic objects. More versatile are the two- and three-fingered grippers, which are scaled-down versions of the professional units. Very few educational arms have the ability to change the end effector (unless you are prepared to design and build them yourself). In contrast, many industrial units can exchange the general-purpose gripper for a power tool such as a drill or sanding disc. (See the section on How Robots Work for more information on these capabilities and the technology behind them.)

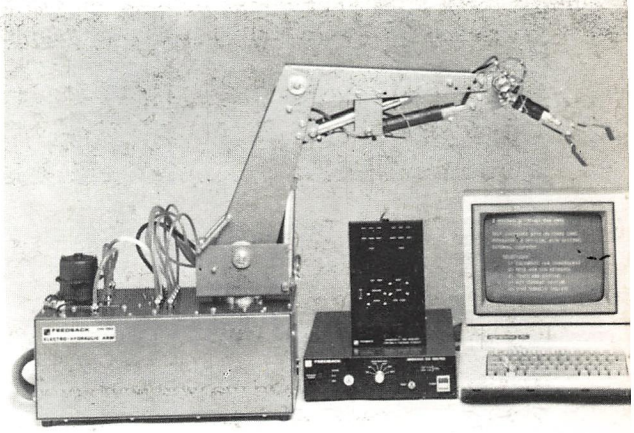
The stepper motor, explained on pages 69–70, is the favoured choice of motive power for such arms, because it can be instructed to turn through a specified number of degrees. But stepper motors are not renowned for strength. Most arms could lift more than their maximum specification, but the programmer could not then rely on the motor turning through the exact number of steps required. The circuitry to convert the instructions coming from the microcomputer into the electrical signals needed to move the motor is usually housed in the static base of the arm, although sometimes there is a separate unit.

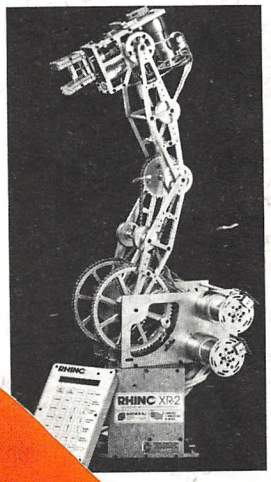
There are educational arms that use other sources of motive power, such as conventional electric motors, hydraulic rams or pneumatics (pressured air), giving them an added degree of realism. However, the choice of motive power is to some extent irrelevant, since from the computer's viewpoint (and, therefore, ultimately the user's viewpoint), it is 'transparent'. This jargon phrase means that the computer does not have to be told whether the arm is electric or hydraulic, it merely sends instructions as to how it would like the arm to move, and the robot's internal electronics and mechanics take care of the rest.

The main value of an educational arm is to learn how robots are programmed, and in this respect their relevance to industrial arms is very high. In trying, for example, to program a small arm to move chess pieces around a board, the student encounters the same type of problem as that found in developing a robot system for stacking cylinder heads on a fork-lift truck pallet. Specifically, the student is learning about three-dimensional geometry, a subject in which doing and seeing count a lot more than hearing and reading.



Robot arm
The Colne Armdroid, illustrated here, was one of the first designed for use with a microcomputer and has been one of the most popular. Its features are common to many other products.





Educational robot arms come in many different shapes and sizes. The Commotion arm (above left) comes in kit form and is driven by servo motors – like the ones used in aeromodelling. The Rhino XR (left) is also electrically driven, and features a large range of add-on devices including a variety of grippers. Feedback Instruments are one of the few manufacturers to have opted for a hydraulically driven arm (above).

Spools
The spools of string are all fixed in a common axis. This allows each of the joints to be moved independently of the others.

Drive belts
Toothed rubber belts gear the rotation of each motor down. Some educational arms use belts throughout, in place of strings.

Stepper motors
With suitable circuitry, a stepper motor can be instructed to turn through a specified number of 'steps' – typically around 7° each. The rotor arm will then be held rigid in the position reached.

EDUCATIONAL FLOOR ROBOTS

A floor robot is probably the most exciting peripheral that can be added on to a home microcomputer, certainly the most educational, yet by no means the most expensive. Some take on a highly technical appearance, others look like furry little animals – reflecting the diversity of possible uses and the age range of their owners.

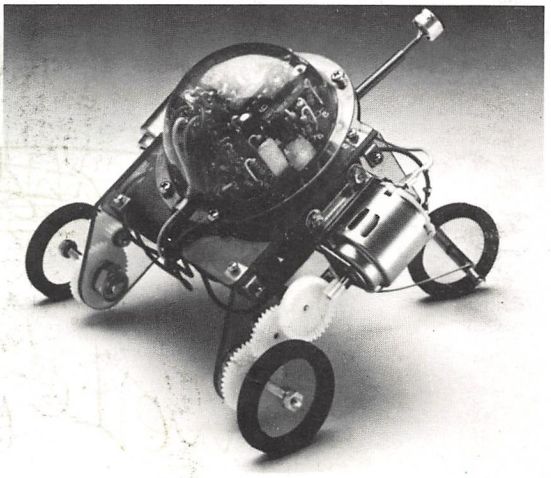
Internally, all floor robots work on the same principles. The link between computer and robot is usually provided by a cable – a kind of electronic umbilical cord. It is possible to eliminate the physical link by using infra-red technology, working in the same way as the channel changer on a modern television set. This gives greater freedom of movement, but requires a line of sight between the robot and the computer at all times.

Two independently powered wheels or caterpillar tracks provide the movement, with trailing wheels or castors to balance the structure. The ability to control the speed of each motor and the exact amount by which each wheel turns is of fundamental importance. By turning them in opposite directions at the same speed, for example, the robot will turn on its own axis. Using the computer programs supplied with the robot, the operator can simply specify the movements in terms of a distance forward or a direction and angle of turn.

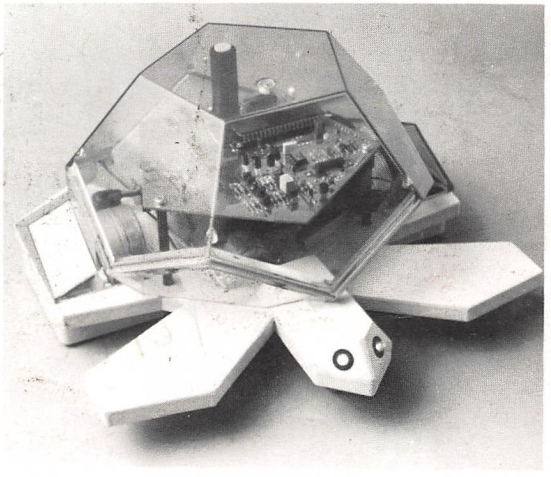
Prices for floor robots range from around £30 to £300. The more expensive models can be controlled with greater precision and feature a variety of extra gadgets. A small speaker, for example, may be programmed from the computer to make sounds when the robot reaches its destination, or even to play music. Flashing lights make the robot appealing to young children.

Attracting the interest of children is an important consideration, since floor robots can make an invaluable contribution to education – even at primary school level. Fitted with a pen between the two wheels, these robots can be instructed from the computer to draw shapes on a large

The Turtle (left) is a dedicated form of floor robot for drawing lines on the floor as directed by the computer, using the LOGO language (see page 179).



The Piper Mouse (below) is one of a range of low-cost robot construction kits. Movement is controlled by means of an ultrasonic receiver linked to a small hand set.

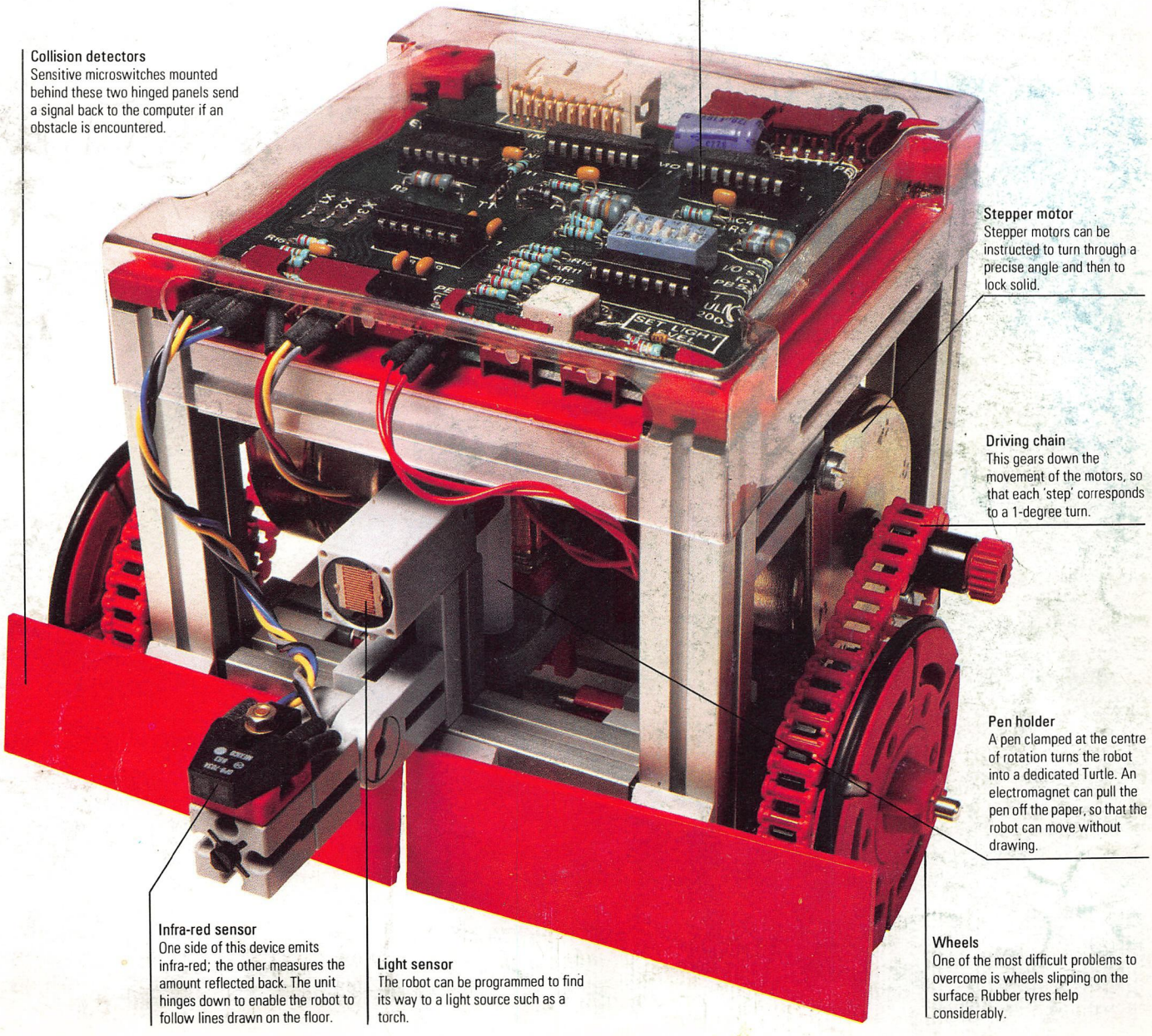


The Valiant Turtle (above) looks more like a real turtle than most of its rivals. It also uses an infra-red link to the computer, in place of an umbilical cable.

sheet of paper. A special programming language called LOGO (see page 179) was developed originally for this purpose and has met with considerable success in teaching elementary geometry and spatial awareness to young children. It is from LOGO that the name 'Turtle' comes, describing a floor robot designed specifically for drawing. Using LOGO, children learn how to build up complex patterns from simple ideas, and the language's main proponent, Seymour Papert, describes the Turtle as 'a device to think with'.

For older children and adults the main value of floor robots lies in learning about robotics and related fields of engineering. Sensors play a more important role here, just as they do in full-scale industrial robotics. Collision sensors will send a signal back to the computer whenever the robot touches a solid object, and this facility can be used either as a safety precaution or to navigate the robot through an obstacle course. The more sophisticated floor robots are constructed so that a whole variety of add-ons can be fitted: grabber-arms, sonar rangefinding for locating objects from a distance of several metres and light sensors for following a line on the floor.

Floor robots have formed the basis of many interesting competitions, including the Micromouse competition, where the device had to find its way to the centre of a large maze constructed from hardboard. Umbilical cords were not allowed here, so contestants had to build the computer on top of the robot.



FREESTANDING DOMESTIC ROBOTS

The two most famous robots in fiction, C3PO and R2D2 from the *Star Wars* films, reflect the two opposing feelings we have about robots. C3PO is the classic android, a mechanical copy of a man and, in some respects, intellectually his superior – perhaps embodying a little of what we fear about being replaced by robots. R2D2, in contrast, plays both companion and servant to his master. Quite dissimilar in appearance and a more practical proposition to build, his functions complement those of humans rather than replace them, and he has all the charm of a household pet.

Real robots, in the R2D2 mould, are now on the market, but the manufacturers have yet to agree on a description for them. They are described as 'self-contained', 'free-roving', 'educational' and even 'domesticated' robots, and their prices range from £1000 to over £3000. Their common factor is that they can all move around under their own steam; powered wheels and heavy rechargeable batteries are hidden in the base. Control is usually provided by an onboard computer, although in some cases there is an infra-red link to a desktop computer instead. The computer is programmed either through a built-in keyboard and screen or a plug-in keypad.

Some have manipulator arms for retrieving small objects, others can relay messages – using a speech synthesizer. Navigation is a major problem; since they are fairly sizeable and weighty, relying on collision detectors alone could create hazards. So most free-roving robots employ ultrasonics, like the automatic focusing systems on some cameras, to measure the distance from nearby objects.

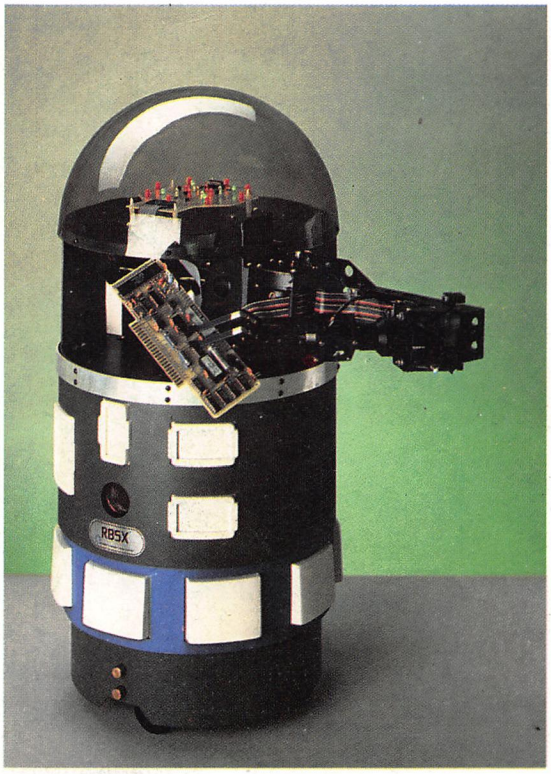
The more technically geared robots, like the Hero 1 illustrated, have slots into which additional electronics boards can be plugged to provide, for example, sensors for heat, or gas or sound. Others are clearly directed at the entertainment market; the Hubot contains a television set, a radio/cassette and a video games player.

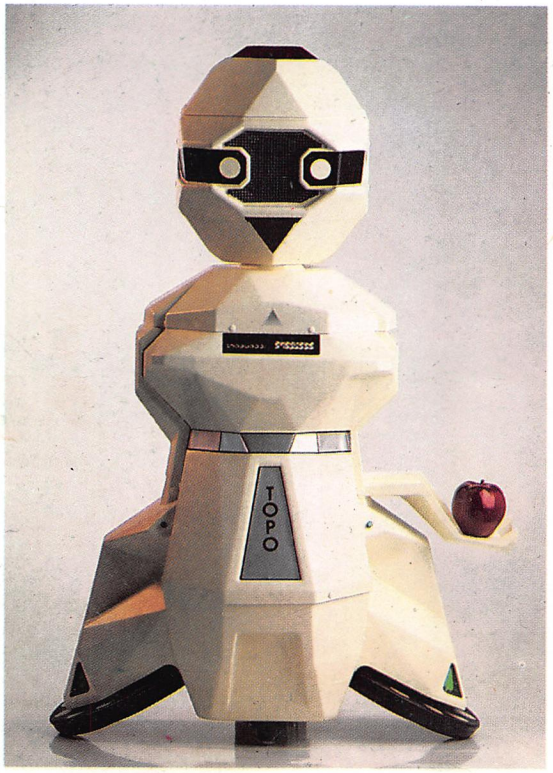
Capabilities

But what can they actually do? According to the brochures they can 'act as a watchdog for burglars', 'vacuum the carpet' or 'fetch a beer from the fridge'. Even if these applications do appeal to you, they are actually quite impracticable using current technology. The robot arm might well be able to carry a can of beer, but it certainly couldn't cope with most fridge doors.

The situation is very similar to the early days of microcomputing, when manufacturers promised that a home computer could 'control the central heating' and 'run your household accounts'. Few, if any, home computer owners pursued these ideas, but the micro nevertheless proved its worth in both education and entertainment.

Viewed in these terms, the domestic robot is a viable idea, at least if the price falls to a more realistic level. For older children and adults, it provides an enjoyable way of learning robotics, electronics and mechanics. For younger children . . . well, it was Isaac Asimov who first introduced the idea of the robot dog.





The functions of the Hubot (below) are slanted towards entertainment rather than education. A television screen takes the place of the face, with the body comprising a video-game machine, radio and cassette recorder. Some pundits describe it as little more than a racked hi-fi system on wheels.

TOPO (left) is manufactured by Androbot, set up by Atari founder Nolan Bushnell. It is controlled from an Apple II microcomputer by means of an infra-red link to a receiver on its head. TOPO can speak in an electronic accent and move around, but that's about all. The fold-down tray can carry small items, but there is no mechanical gripper or arm.

RB5X (far left) more closely resembles the domestic robots seen in films. The panels around the base are collision detectors.

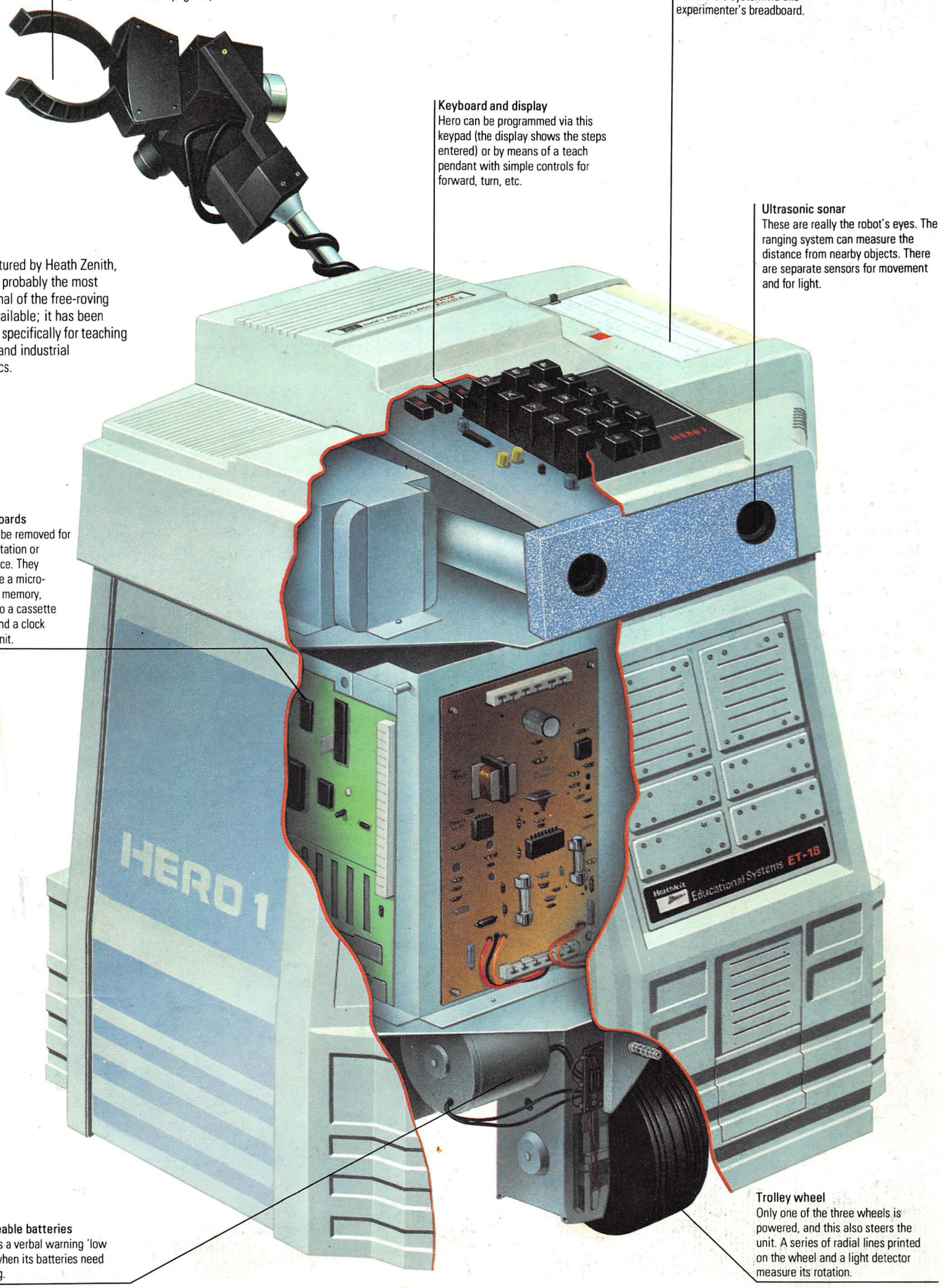
End effector
In addition to opening and closing the gripper, the end effector features five degrees of freedom (see page 66).

Breadboard
Integrated circuits and other electronic components can be plugged into Hero's system via this experimenter's breadboard.

Keyboard and display
Hero can be programmed via this keypad (the display shows the steps entered) or by means of a teach pendant with simple controls for forward, turn, etc.

Ultrasonic sonar
These are really the robot's eyes. The ranging system can measure the distance from nearby objects. There are separate sensors for movement and for light.

Hero 1
Manufactured by Heath Zenith, Hero 1 is probably the most educational of the free-roving robots available; it has been designed specifically for teaching robotics and industrial electronics.



Control boards
These can be removed for experimentation or maintenance. They incorporate a microprocessor, memory, interface to a cassette recorder and a clock calendar unit.

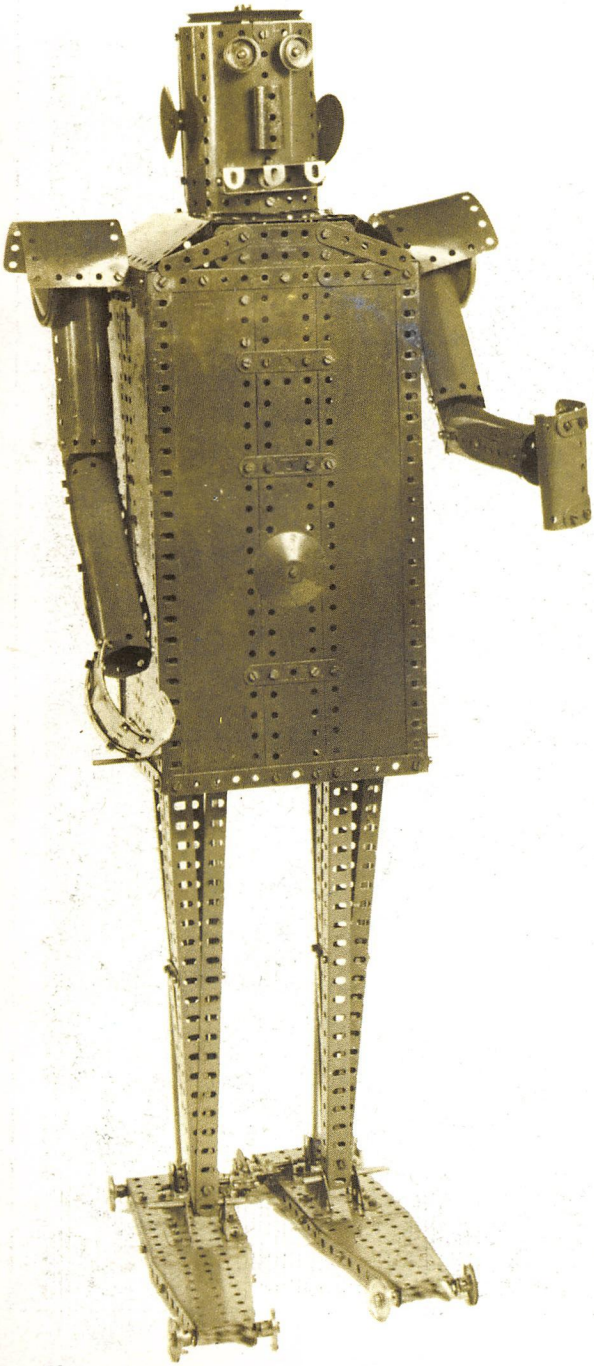
Rechargeable batteries
Hero gives a verbal warning 'low voltage' when its batteries need recharging.

Trolley wheel
Only one of the three wheels is powered, and this also steers the unit. A series of radial lines printed on the wheel and a light detector measure its rotation.

ROBOT TOYS

In the eighteenth century, inventors like Pierre Jaquet-Droz and Jacques Vaucanson were constructing animated mechanical figures, the sophistication of which has not been matched since (see page 11). Jaquet-Droz's writer, for example, could dip his pen in an inkwell and proceed to write in an elegant script *Cogito ergo sum* – Decartes' celebrated proof of existence, while Vaucanson's duck could both ingest and excrete food!

It wasn't until the 1950s that toys were designed to resemble robots in form as well as function, although even at that stage the robot was still nothing more than a fictional creation. Since then, robot toys have proliferated in many shapes and sizes, mostly using the human-like configuration of head, arms and legs as a model. The only other common element is that, until recently, almost all such products played on the sinister side of robots, with menacing expressions and movements backed up by an arsenal of lasers, phasers, rockets and grenades.



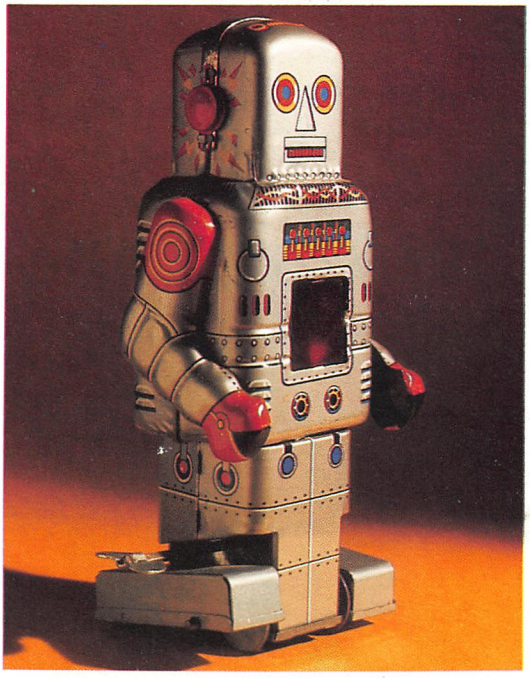
Today this image is fading slightly, or being replaced by more subtle suggestions. The transformer toys from Japan (the largest producer and consumer of both industrial manipulators and toy robots) come packaged as benign saloon cars. But in a few seconds they can be unfolded and manipulated to form aggressive-looking mechanical monsters.

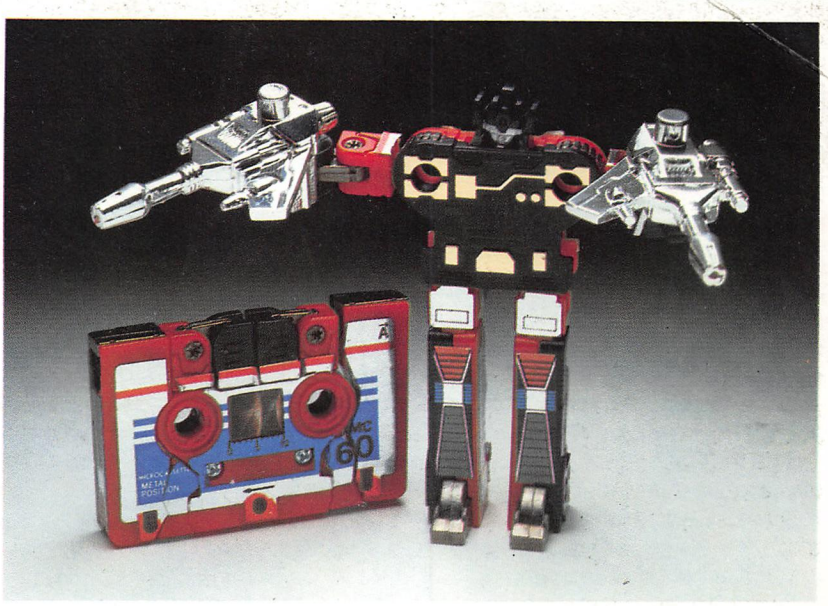
Star Wars can take some credit for introducing the idea of the robot pet, and now friendly toy robots are gaining popularity, assisted by some sophisticated technology that, five years ago, wasn't even available to the space programme. Now you can buy toy robots that can speak, or that can respond to a limited range of spoken commands. In the latter case, the robot will have to be trained to recognize a particular user's voice and pronunciation – all these characteristics reinforcing the pet concept. The ability to allow the robot owner to program a sequence of movements and then have the robot replay it is becoming a common feature, too, although it requires the robot to have an inbuilt microprocessor and some memory. (see page 88).

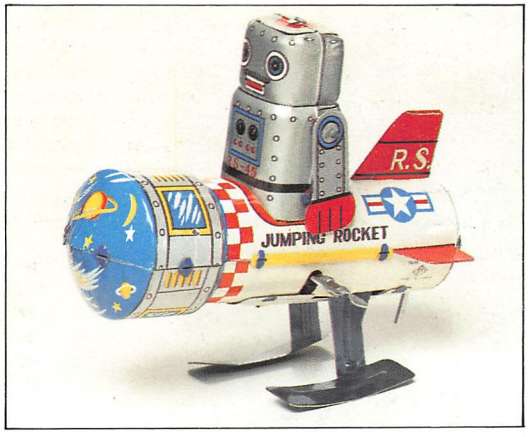
Surprisingly, perhaps, robot toys are very popular with more serious robot enthusiasts. With a little knowledge of electronics on the part of the user, many toys can be interfaced to home computers to increase their capabilities. Moreover, products like Milton Bradley's Big Trak provide a Pandora's box of mechanical and electronic goodies from which quite different models can be constructed. As technology improves and prices fall over the next few years, the distinction between toys and domesticated functional robots will gradually fade.

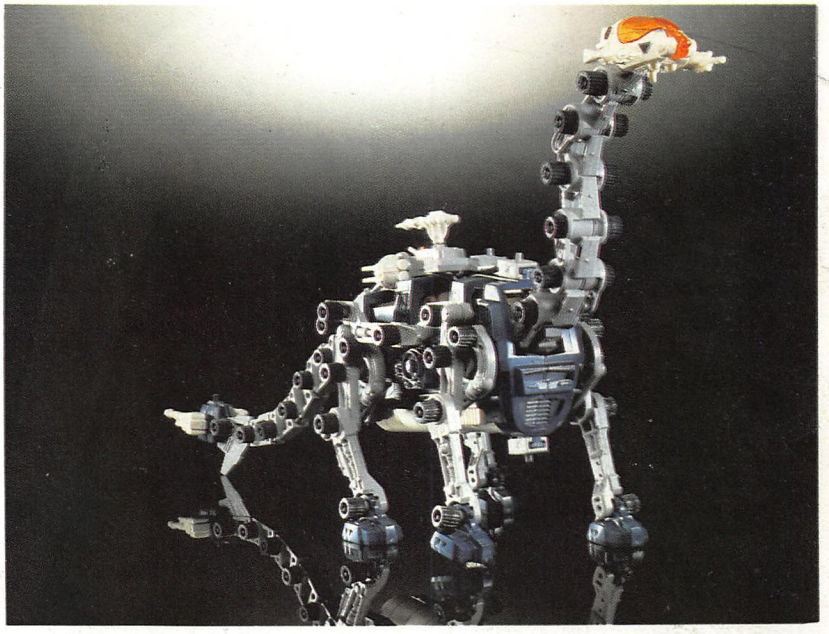
Toy robots have existed since the Seventeenth century, but became very popular in the 1950s, as science fiction writers took up the robot theme. Some of the early examples (below left) are now valuable collectors' items, and many (below right, and nearest column right) are featured in museums. A good example is Comro Inc/Jerome Hamlin's *Bumpy* (bottom, near right column), described as a mobile 'speaking' tele-operated personal robot. Made in 1978, Bumpy appeared in the American Craft Museum's 'The Robot Exhibit' of 1984.

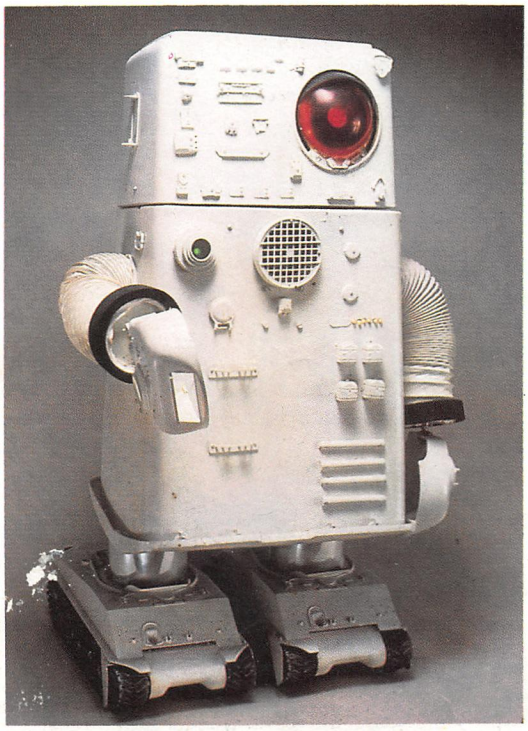
Modern robot toys (far right column) employ much mechanical ingenuity. The Japanese transformer toys (top) take the guise of everyday objects such as audio cassettes or cars. An incredible example of three-dimensional design, they all unfold into menacing robot figures. The Giant Zrk (centre) is the most sophisticated of a range of Zoids. All four legs are powered, and the long neck sways from side to side as it walks. The Robo Armatron (bottom) is more of an educational toy. Its movements resemble an industrial manipulator with five degrees of freedom and are controlled by two joysticks. The objective is to complete a set task in the most efficient manner, each movement being logged on the Energy Level display.

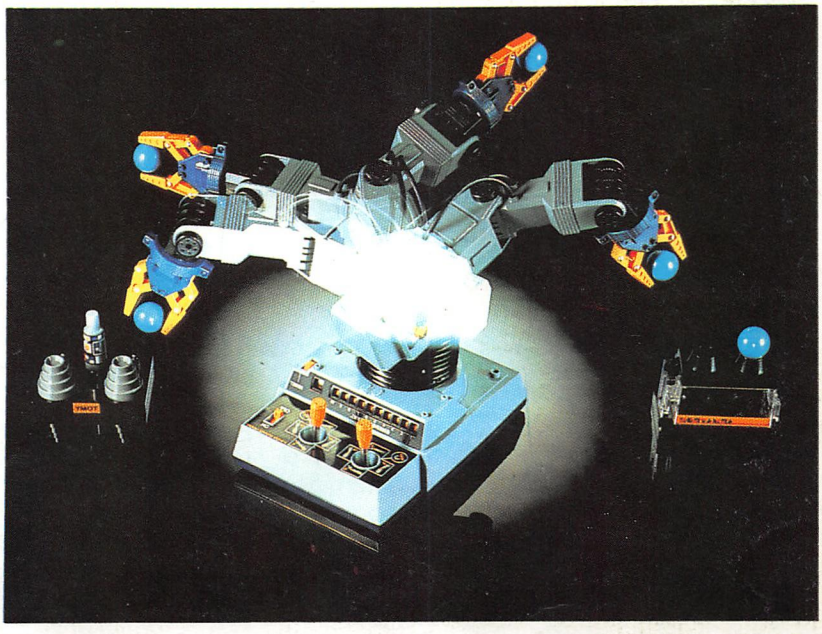





R.S.
JUMPING ROCKET







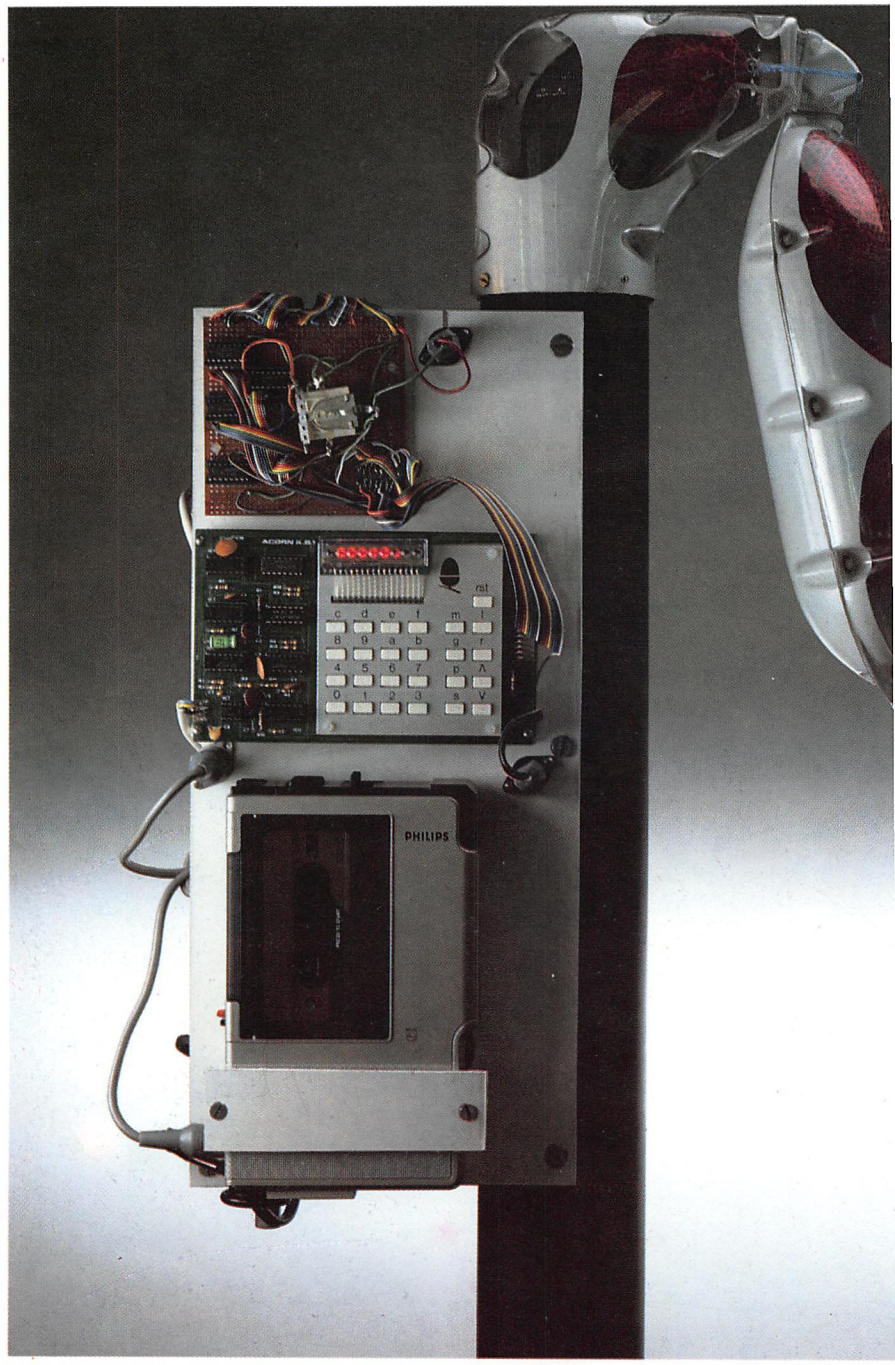
EXPERIMENTAL ROBOTS

With the exception of static industrial manipulators, which have been available off the shelf for over a decade, the majority of the world's robots are of the experimental or prototype variety, rather than mass produced. These devices have been designed and built in universities, schools, industrial research laboratories, garages and even garden sheds.

The market for robots is still embryonic, and no one is quite sure what people really want to buy robots for – especially in the home. Furthermore, most of today's robots simply aren't intelligent enough to be let loose in the real world.

A free-roving robot, for example, whether for domestic or industrial applications, must be able to navigate around many kinds of obstacles. But a typical room is far too complex a place, in terms of the variety of three-dimensional shapes it contains, in which to develop a system of navigation. So the engineer must devise an artificially simple room (called a limited environment) in which the number of variables is drastically reduced. Once the robot has been successfully programmed to operate within this simplified obstacle course, further complications can then be introduced.

Shakey (see page 15) is a good example of an experimental robot designed to work within a limited environment, as is SHRDLU (page 92), although the latter is a computer simulation rather than a physical system. Some of the best navigation algorithms (an algorithm is a procedure or methodology for achieving an objective) have resulted from the international Micromouse competition (page 80), in which contestants have to build a small mobile robot that can find its way through a purpose-built maze, receiving no outside help.



Experimental contests

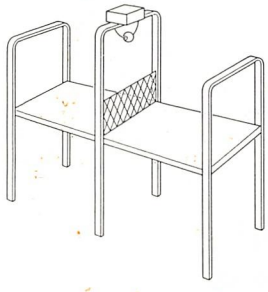
Competitions have proved very fertile ground for advances in robot technology; these advances range from a simple vehicle that can find and retrieve an object from 10 metres (30 feet) away, to voice-controlled manipulators for assembly tasks. At the time of writing, a new contest is being formed that should continue to stretch the robot builders throughout the 1980s.

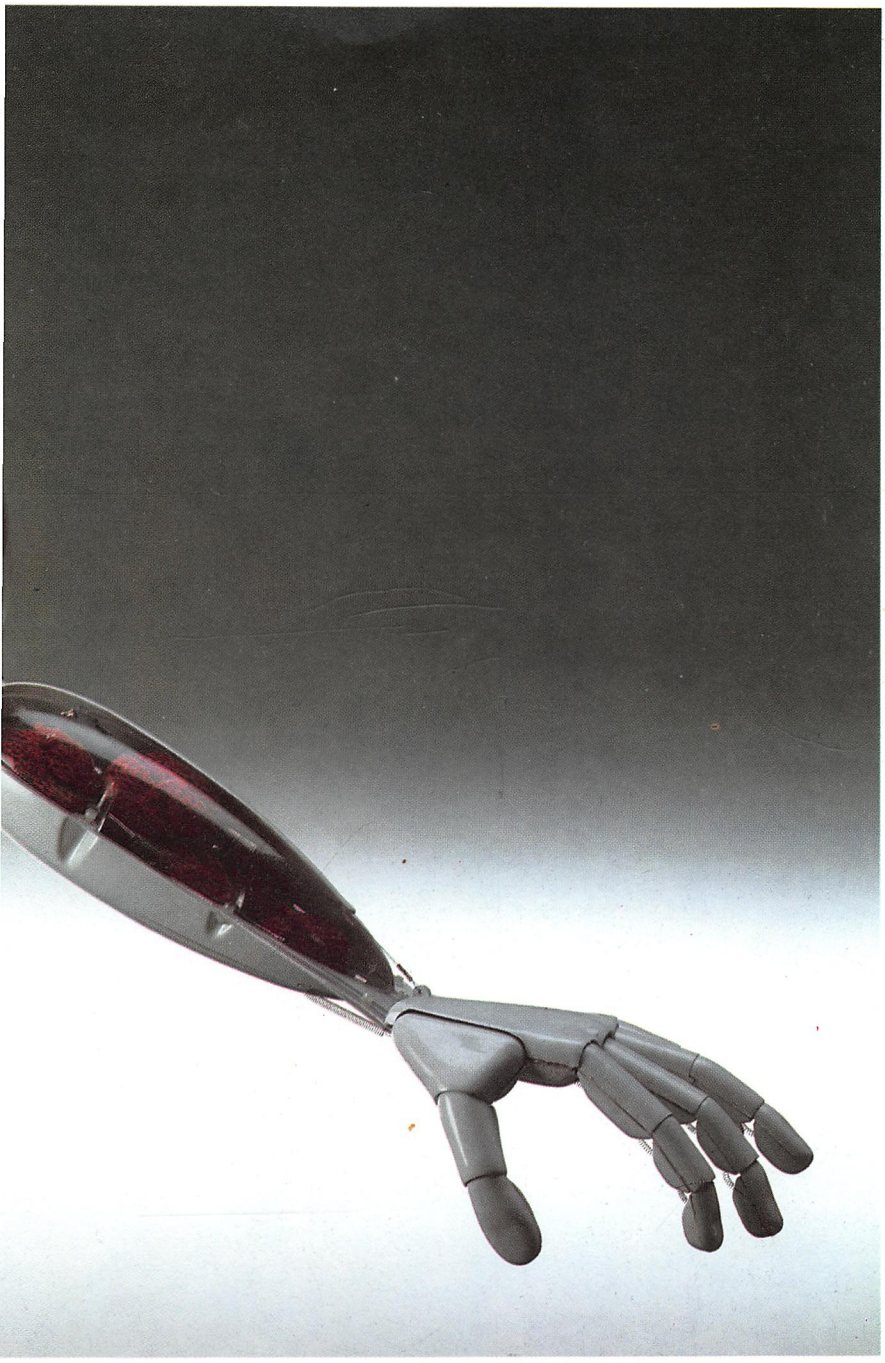
The requirement is for a robot that can play table tennis on a reduced-size table. This activity draws upon one of our most sophisticated functions: hand/eye co-ordination. The robot will need a stereoscopic vision system (or a single eye together with some other form of rangefinding) to track the ball, and a fast-acting arm that can position the bat and deliver an impulse at the correct angle to return the ball.

One solution is to control the whole operation in software, using a very fast microprocessor. However, it now looks as if the best approach will be to emulate the human reflex system. This entails linking the robot arm directly to the electronic eye – using a servo-mechanism – so that the arm places the bat in the path of the ball in a kind of 'reflex action' and only using a computer to make the strategic decisions – such as the type of stroke to play.

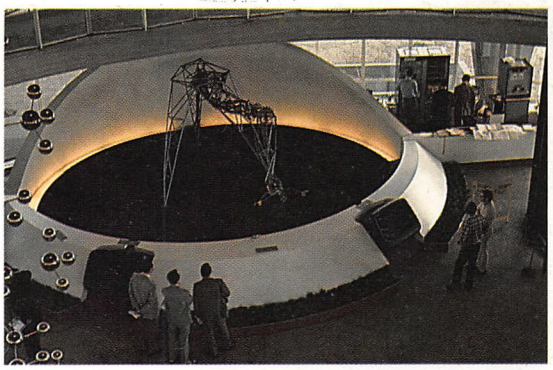
At its conception, the competition's organizers expected that the first entrants would be capable of little more than a single return of service, but that within two years stable rallies between two robots would be commonplace. The rules specify that a rally of twenty returns is automatically won by the defending (non-serving) robot. Beyond that stage, the robots are expected to emulate much of the cunning and strategy of human players, including bluff strokes and spinning.

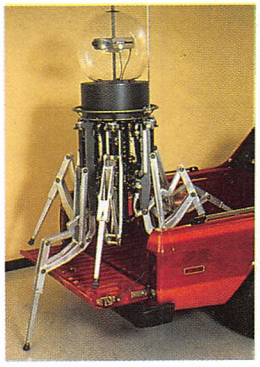
Shown below is the table design for the robot ping-pong contest devised in 1984. The ball is served by a mechanism located directly above the net, which is constructed from transparent perspex. The ball must bounce on the table and pass through the hoop at the end.

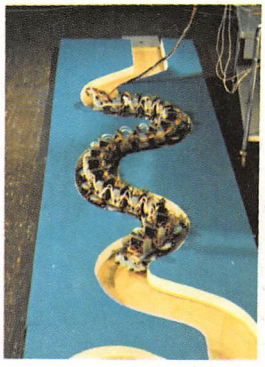




The arm above is based on an experimental system of pneumatic muscles. Air is forced into the muscle bags, which expand but shrink in length. String tendons link the muscles to the bones, resulting in movement of the limbs. The robot was developed by the Original Android Company, in association with the Royal College of Art, to test the viability of having moving mannequins in shop window displays. The microcomputer on the left drives a series of servo valves, which feed pressurized air to the muscles.







The hydraulically operated Senster (top) reacts to the sounds and movements made by onlookers, giving the impression of being alive. Odex 1 (above left) was an experiment in locomotion, showing that a robot with eight legs could get in and out of a pickup truck! The Active Cord Mechanism (above right) relies on tactile sensors to imitate the movements of a snake.

Experimental gains

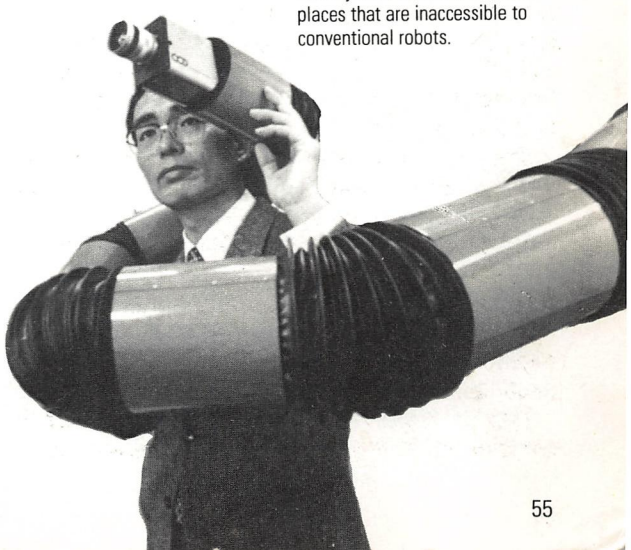
A ping-pong-playing robot may in itself have little commercial importance, but the experience gained in hand/eye co-ordination will have considerable value when applied to automated assembly tasks. Such valuable experience can also be derived from many other experimental robots, particularly in the fields of vision, end effectors and locomotion.

Realistically, there may not ever be a requirement for a robot biped, except perhaps for entertainment value, but there is a real and unmet need for mechanical systems that can climb stairs. Few robots can negotiate outdoor terrain, either, but this restriction will have to be overcome if robots are to play their part on the farm or, for that matter, in a military engagement.

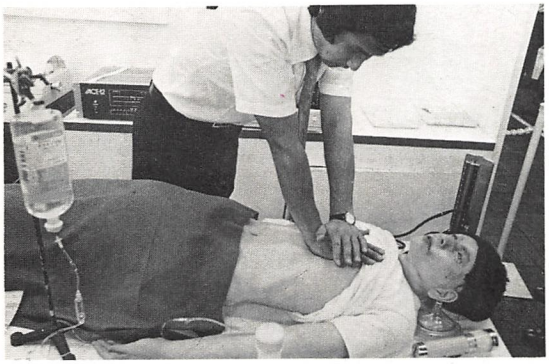
Research departments, left to their own devices, have come up with a panoply of possible locomotion techniques. Some are based on the mammalian system, with two or four legs; some emulate the movements of a snake; some use conventional wheels and tracks; others borrow principles from the hovercraft or submarine. Even if few of these ideas ever make it to market, the experience gained will not be wasted.

Perhaps the most encouraging facet of experimental robotics is that this is one field in which individuals can still make significant contributions. Unlike other emergent technologies, such as microelectronics and biotechnology, robotics draws more upon the traditional skills and pioneering spirit of the inventor than on expensive materials and processes.

This experimental arm features seven joints, and can reach into places that are inaccessible to conventional robots.



PSEUDO ROBOTS



There are devices that look like robots but are really nothing of the kind, and there are devices that look nothing like robots yet which match up to the technical definitions. To complete this tour of the main types and applications of contemporary robots, we shall consider some of these misfits – best described as pseudo robots.

Machines that look like humans

Many people's idea of a robot is still the android – a mechanical being made in the visual image of a human – and this has been reinforced not only by the film-makers but by an increasing number of androids built for promotional purposes. Such 'robots' feature in pop-music videos, television advertisements and exhibitions.

Some of these devices have very little in the way of powered mechanical movement, and few have any form of intelligence or programmability. Nevertheless, the effect can be quite convincing – particularly the characters that hand out brochures at exhibitions and hold conversations with bystanders. Most people are too distracted by the apparent intelligence of the machine to notice the operator standing close by with a microphone and radio-control panel concealed in his hands. Although the androids are the most popular design, promotional robots can also resemble manufacturers' product ranges, from lemonade cans to tomato ketchup bottles.

As the available technology has improved and public expectation increased, so promotional robots have had to become more sophisticated, to the point where some genuinely earn the robot label. A few upmarket clothes shops have replaced their traditional window dummies with animated mannequins, which can be programmed to follow a continuous sequence of movements.

On a more functional level, humanoid robots have been constructed for teaching medical students. A microcomputer simulates the function of various organs, and the body itself has both sensors and electromechanical outputs. Use of the robot gives the students practice at handling emergencies, such as cardiac arrest, where the procedures would be too dangerous to try out on healthy patients.

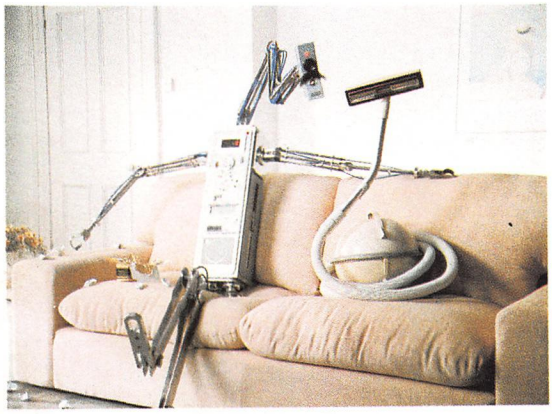
Machines that do a human's work

At the other extreme, an increasing proportion of domestic appliances now contain as much electronic intelligence as a desktop microcomputer. Top-of-the-range dishwashers feature a programming panel, internal electronic sensors and electromechanical output, and they demonstrably replace a human function on a one-for-one basis. The marketing people haven't been slow to recognize the analogy; even versatile food mixers have been sold as 'robot chefs'. Is this really justifiable? Should the term 'robot' encompass all forms of automation from the numerically controlled machine tool to the autopilot on a jet aircraft?

The demarcation between robots and non-robots is really an arbitrary one, and there is little to be gained from trying to create a watertight definition. The idea of a machine made in the image of a man is a good one, but 'image' must be understood in its widest sense, encompassing function as well as form. Some of today's robots did not even exist in people's imaginations ten years ago and, some of science fiction's best ideas have yet to be implemented. This book has shown how the conception of the robot has changed over the centuries. In the next ten years it is likely to change as much again.

The patient receiving emergency treatment for heart failure (far left) is actually a robot. Driven by an external minicomputer, the robot is equipped with a vast array of sensors, and will respond to treatment with changes in its mechanical body functions, such as pulse rate, breathing, pupil dilation and so on. The robot is one of the best ways to train medical students for coping with emergencies.

Robots will soon be appearing in amusement arcades to bring action games off the screen and into the physical world. This robot gunman (left) was developed in the 1960s. You have to shoot the photocell mounted on the sheriff's badge with your light gun before he raises his gun. In the future we can expect to see three-dimensional space invaders, and fantasy adventures where the player interacts with real friends and foes.



Television commercials now make use of promotional robots like the John Cleese robot (above). It was controlled live by someone sitting behind the sofa.

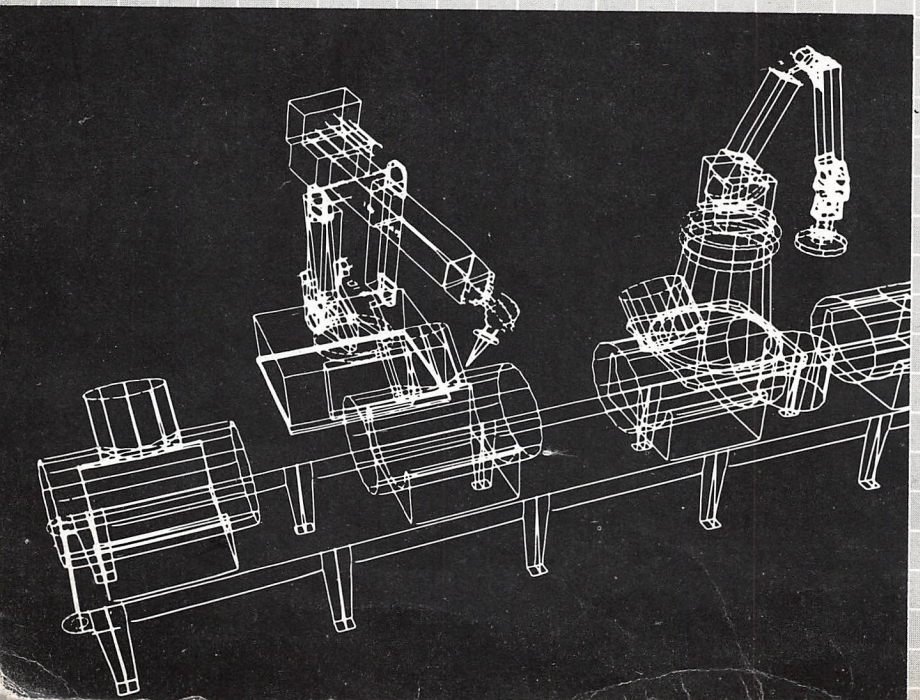
Machines like the Rediffon 767 flight simulator (left) don't look like robots but are more deserving of the title than many promotional robots.

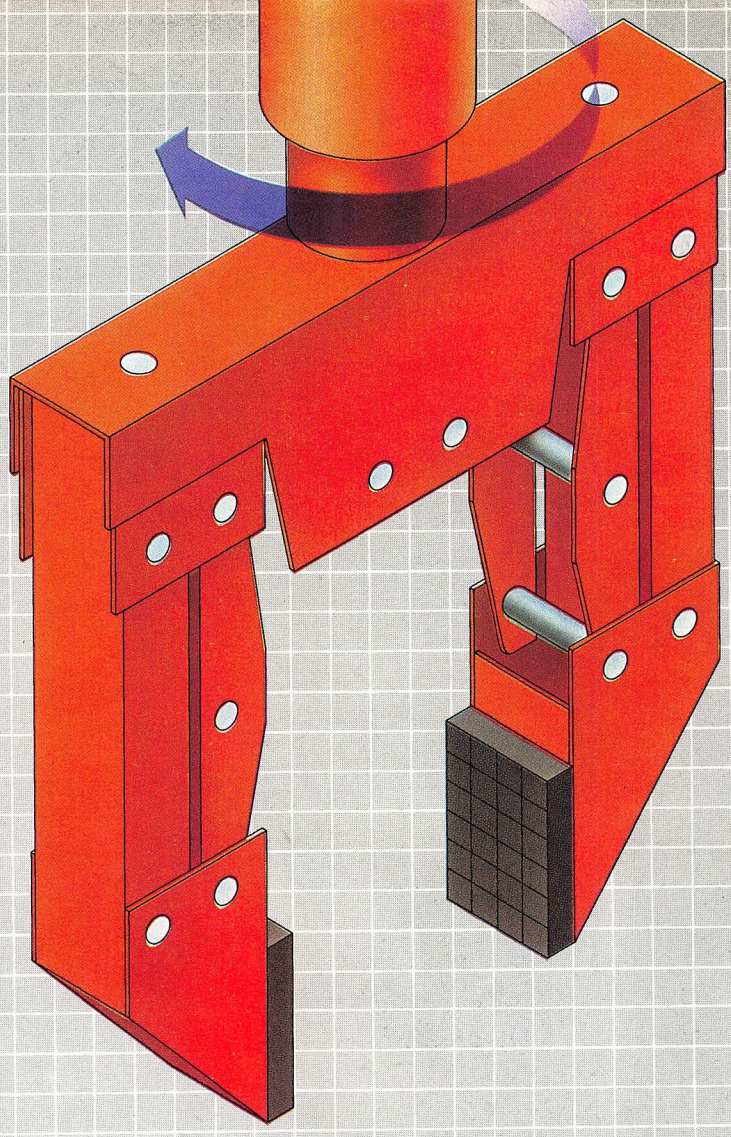
Promotional robots have been employed in exhibitions and shop displays for years. They may look like robots, but in reality, most are simply mechanical models.

The new generation of promotional machines, however, are highly sophisticated. The arms feature a large number of articulations, and the movements are programmable. This one was built by the Original Android Company, as a replacement for the static mannequins used in shop windows. Similar robots are now appearing in promotional music videos and feature films.

PART

3 HOW ROBOTS WORK



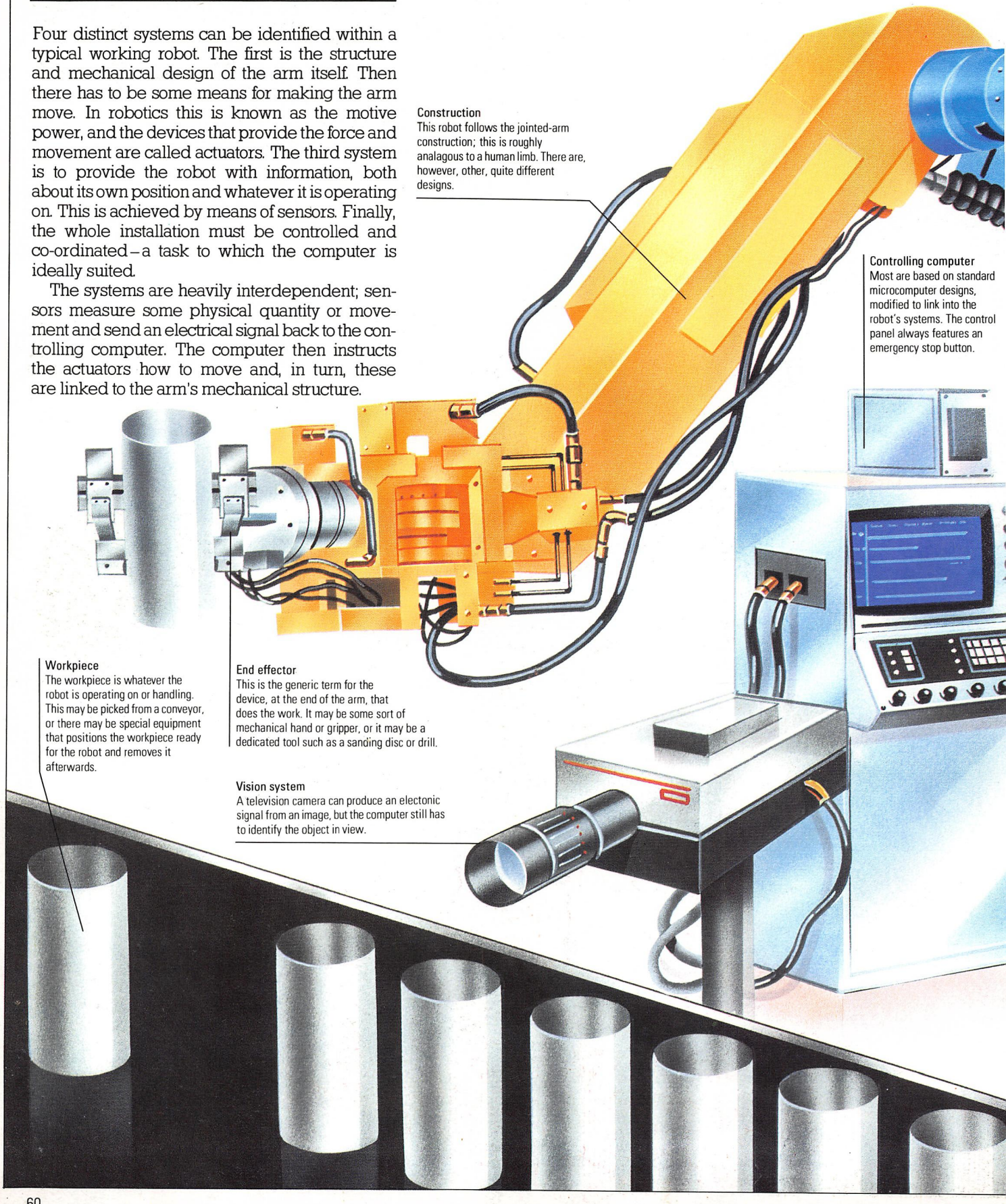


MAIN PARTS OF AN INDUSTRIAL ROBOT	60
TYPES OF CONSTRUCTION	62
END EFFECTORS	64
ROBOT GEOMETRY	66
MOTIVE POWER	68
POSITION SENSING	74
TOUCH	76
SOUND	78
NAVIGATION AND RANGEFINDING	80
VISION	82
SMELL AND TASTE	84
COMPUTER FUNDAMENTALS	86
INTERFACING ROBOT DEVICES	88
ARTIFICIAL INTELLIGENCE	90
INTERPRETING IMAGES	94
PROGRAMMING	96
NEURAL NETWORKS	98

THE MAIN PARTS OF AN INDUSTRIAL ROBOT

Four distinct systems can be identified within a typical working robot. The first is the structure and mechanical design of the arm itself. Then there has to be some means for making the arm move. In robotics this is known as the motive power, and the devices that provide the force and movement are called actuators. The third system is to provide the robot with information, both about its own position and whatever it is operating on. This is achieved by means of sensors. Finally, the whole installation must be controlled and co-ordinated – a task to which the computer is ideally suited.

The systems are heavily interdependent; sensors measure some physical quantity or movement and send an electrical signal back to the controlling computer. The computer then instructs the actuators how to move and, in turn, these are linked to the arm's mechanical structure.



Construction
This robot follows the jointed-arm construction; this is roughly analagous to a human limb. There are, however, other, quite different designs.

Controlling computer
Most are based on standard microcomputer designs, modified to link into the robot's systems. The control panel always features an emergency stop button.

Workpiece
The workpiece is whatever the robot is operating on or handling. This may be picked from a conveyor, or there may be special equipment that positions the workpiece ready for the robot and removes it afterwards.

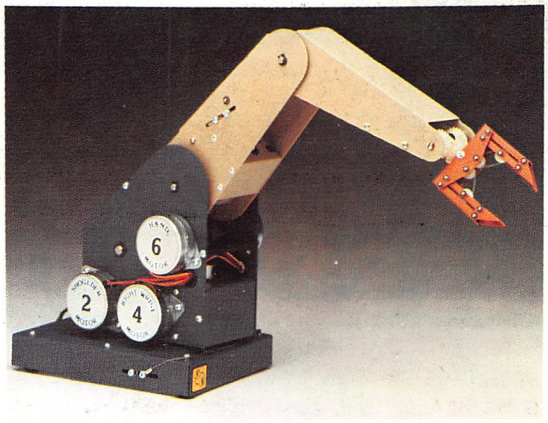
End effector
This is the generic term for the device, at the end of the arm, that does the work. It may be some sort of mechanical hand or gripper, or it may be a dedicated tool such as a sanding disc or drill.

Vision system
A television camera can produce an electonic signal from an image, but the computer still has to identify the object in view.

Position sensors
Even if it has no external sensors simulating touch or sight, each joint in the arm will contain a position sensor telling the computer the angle of the joint. Without position sensors, errors build up, with the result that the end effector will not be where the computer thinks it is.

Actuators
The actuators provide motive power to each movable section of the robot. They may be electrical, hydraulic or pneumatic. In the case of an arm, power will be supplied to the actuators through a heavy-duty cable or pressure hose. Smaller wires carry the control signals from the computer to each actuator. A mobile robot may have to carry its own power source along with it; typically, this will be rechargeable batteries.

Smaller version
Most of the principles on which a large industrial robot operate apply equally well to a small educational arm. A home micro takes the place of the purpose-designed control computer, and the construction is simply scaled down. Some types of actuator do not scale down equally well, so the home robotics experimenter will have a more limited choice of motive power systems. Only in sensors is there a marked difference from industrial robots – low-cost arms seldom incorporate sensors as standard.



Programmer
A programmer is currently needed to instruct the computer every time a new task has to be learned. In the future, and especially in the design and manufacture of new cars, the computers used in the design office may well be able to program the manufacturing robots directly.

Teach pendant
The hand-held teach pendant features buttons for flexing or extending each joint. The computer will then 'learn' the movements instructed by the operator and repeat them continuously.

TYPES OF CONSTRUCTION

Robot limbs, unlike their human and animal counterparts, vary not only in size and proportion, but also in their construction. The jointed-arm design springs to most people's minds when robots are mentioned – perhaps because it most closely resembles our own anatomy – but as the illustrations on the right show, this is just one of four popular designs.

The reason for such variety is partly historical and partly functional. If you were developing a robot purely for retrieving components from a shelf racking system, the Cartesian construction would suggest itself. If the robot was intended to service several machine tools, the most economical layout would be a circle, with a cylindrical or polar robot at the centre. If, however, the robot must reach into awkward spaces – often the case with paint spraying or spot-welding – the jointed-arm design offers many advantages. Each manufacturer of industrial robots favours one type, reflecting their own background and the applications in which they specialize.

Whereas the pivoting joint is copied from nature, the telescopic extension forming the basis of three of the designs has no natural counterpart. Though nature provides some excellent models for construction, motive power and sensing, the robot engineer must never fall into the trap of thinking that they are the only solutions.

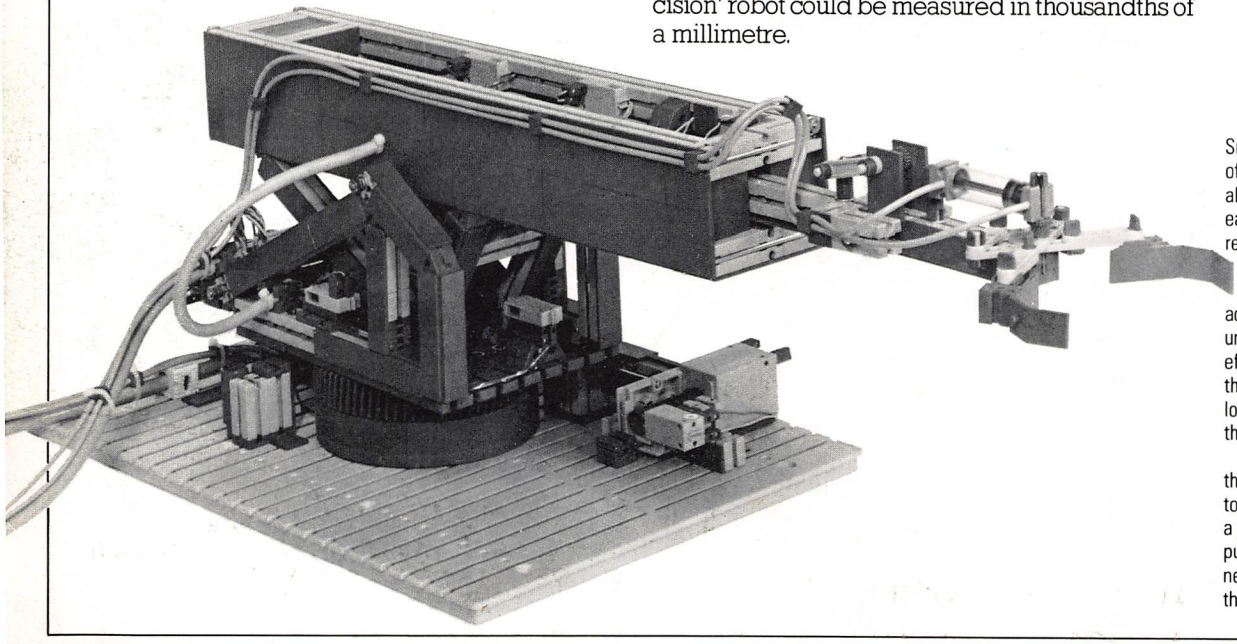
Specifications

In addition to its method of construction, an industrial robot's specifications will include its working envelope, strength (sometimes called its maximum loading), accuracy and repeatability. The working envelope is the volume – the three-dimensional space – that can be traced out by the robot's end effector. The shape of the envelope may be quite irregular, because each joint and movable section will have limits of travel, and will be quite different for each type of construction. It is frequently more economical for a manufacturer to rearrange his workpieces to fit a standard robot working envelope than to design a special-purpose robot.

Despite their comparatively large size, many robot arms are surprisingly weak and would provide a human with little competition at arm wrestling – were such a contest not inadvisable on safety grounds. It is true that some robots can lift half a tonne, but for many others a maximum loading of 10 kilograms (22 pounds) is typical. In detailing the specifications of a robot arm, the manufacturer must state the worst case; as with the human arm, lifting capacity decreases as it is extended.

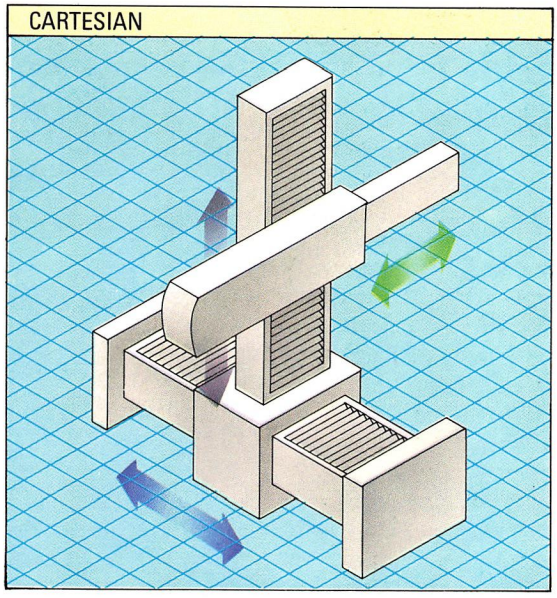
Furthermore, robot arms are notoriously inefficient. Most are very heavy, and much of the motive power is therefore 'wasted' in overcoming the inherent inertia. It is the momentum of the moving arm itself, rather than the useful force it can deliver, that necessitates so many safety procedures. Replacing the conventional steel structures with light materials such as carbon fibre yields better results, but adds considerably to the cost.

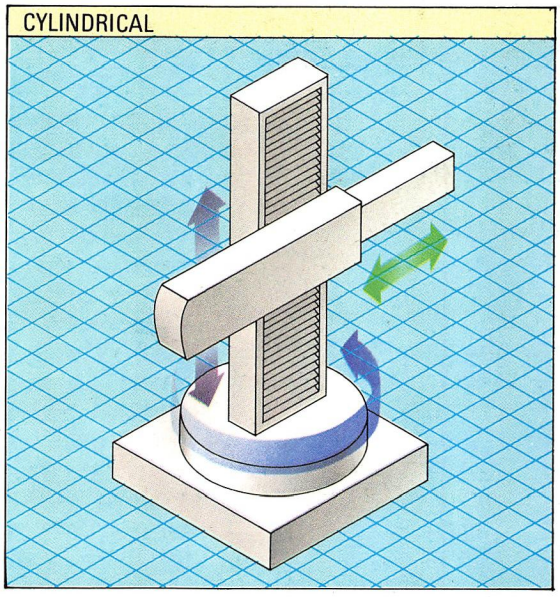
The more accurate an arm is, the closer the end effector will be to the position specified by the controlling computer. Repeatability is a related but more useful measurable capability. If a robot is programmed to repeat a sequence of movements, by how much will the position vary each time it returns to the same point in the cycle? A heavyweight robot may well be able to repeat to within a millimetre of the original position each time, while the repeatability of a low-power 'precision' robot could be measured in thousandths of a millimetre.

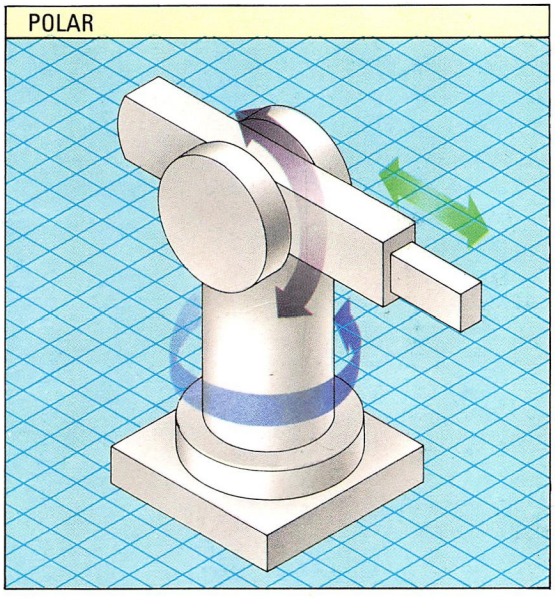


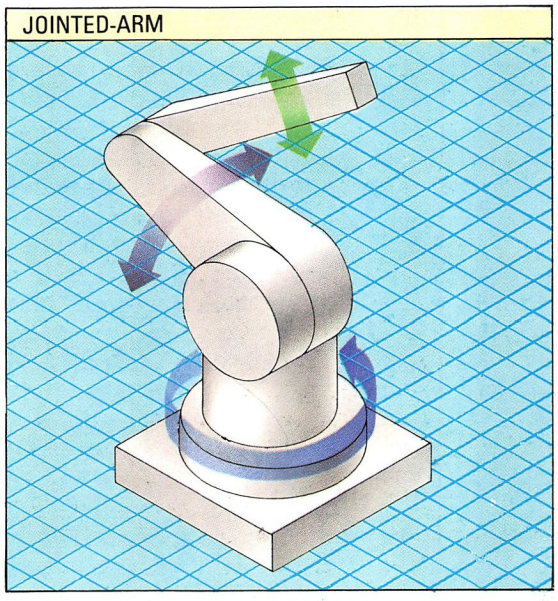
Small robot arms can follow any of the designs featured opposite, although the polar system is the easiest to implement. The main reason for this is weight distribution. The heaviest parts of any robot are the actuators – the motive power units. The robot will be more efficient if it doesn't have to lift the actuators in addition to the load and if they are as close to the centre of rotation as possible.

In a polar design, the arm's three actuators can be close together. To achieve the same for a jointed arm, a series of push-rods and strings would be needed to transfer movement to the joints themselves.









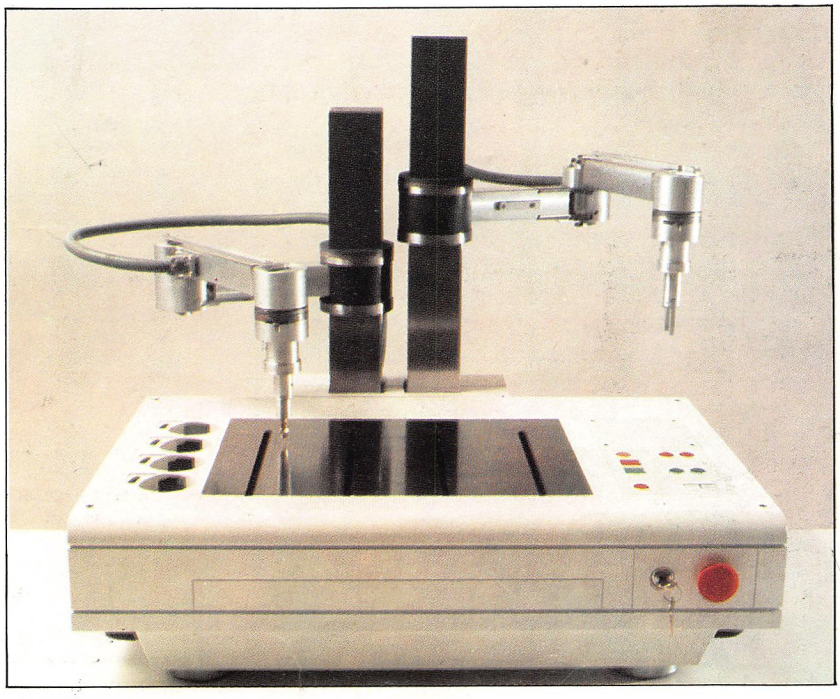
Most industrial robot arms fall into one of four types of construction. Each robot pictured here has three axes of movement, shown by the coloured arrows. Each movement may be rotational – one part pivots around another – or linear – one part slides along another or extends telescopically.

The Cartesian design features three linear movements, and takes its name from Cartesian co-ordinates, in which every point is defined as a distance along, across and upwards from a point of origin. Cartesian robots are sometimes referred to as XYZ robots – the letters signifying the three axes of movements. The working envelope, which is the volume that can be accessed by the end effector, will be box-shaped.

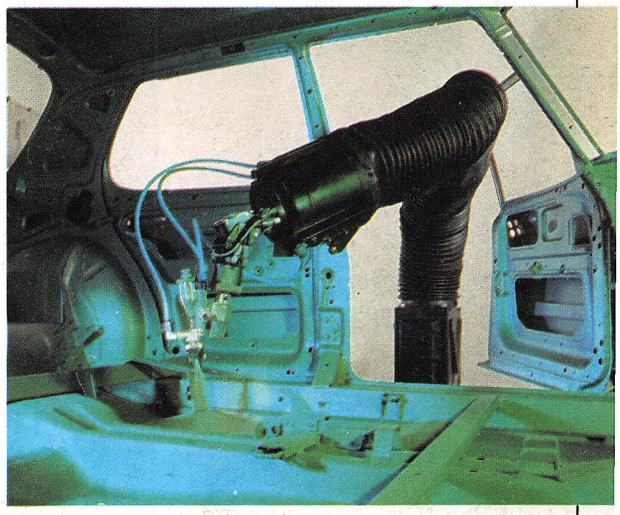
The cylindrical robot replaces one linear movement with a rotational one at the base, giving a working envelope shaped like a cylinder.

The polar design uses polar co-ordinates to specify any position in terms of a rotation at the base, an elevation angle and a linear extension for the arm.

The jointed-arm (properly called a revolute design) uses only rotational joints to reach any position and is the most versatile.

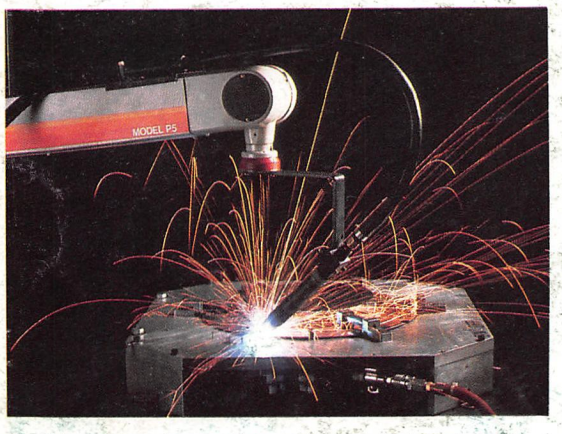


The Yes-Man (left) is intended for light assembly-line work, where it can work alongside human operators. After much research, the designers concluded that, as with humans, a two-armed approach worked best!



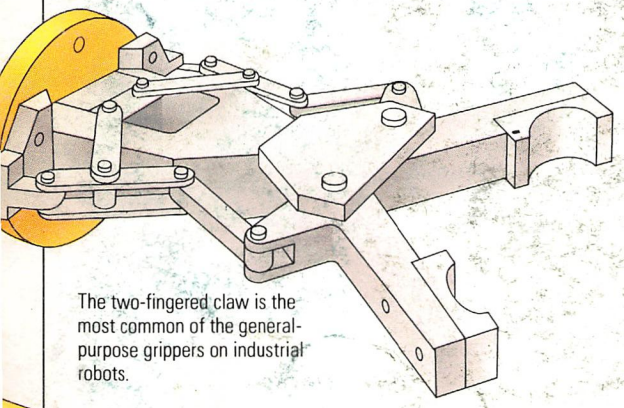
The versatile spine robot (above) doesn't fall into any standard design category. It is constructed from metal discs interlinked by push-rods, and has the advantage that it can reach into very awkward spaces.

END EFFECTORS

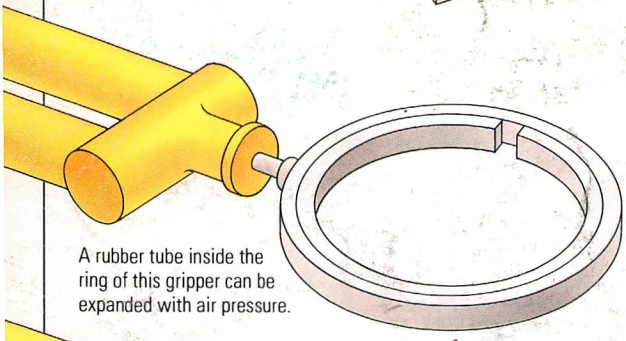


Specialist tools, such as for arc welding, can be fitted directly to robot arms in place of more general-purpose grippers.

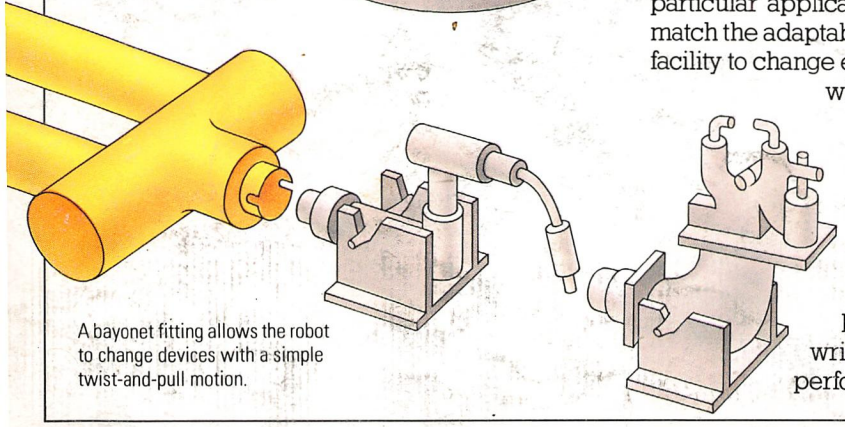
Illustrated below are examples of end effectors found on industrial robots. Some robots have the ability to select one of several tools from a rack, which gives them a considerable advantage.



The two-fingered claw is the most common of the general-purpose grippers on industrial robots.



A rubber tube inside the ring of this gripper can be expanded with air pressure.



A bayonet fitting allows the robot to change devices with a simple twist-and-pull motion.

Many experts believe that an electronic equivalent to the human brain is a more attainable goal than a mechanical copy of the human hand. The similarities that exist between the construction of a robot arm and our own limbs are certainly not in evidence when we examine the end effectors.

Robot arms generally feature one of three types of end effector: the general-purpose 'claw'; grippers designed to handle a very specific type of object; and the working tool. Most industrial robots are used for materials handling – anything from transferring test tubes between experiments to stacking beer barrels. These, and the small number of robots used for assembly work, feature grippers or claws. Robots that perform a process like paint spraying or spot-welding employ specialist tools fixed directly to the end of the arm.

The most common form of general-purpose gripper has just two fingers, like a pair of tongs; those used to handle tiny delicate objects resemble tweezers. Generally, grippers have rigid fingers, shaped slightly to cope with round or square objects. Where there are three fingers, they may be identical and equally spaced, or there may be a distinguishable 'thumb' opposite two fingers. Hands with more than two fingers must be very carefully designed so that each digit exerts the same pressure on the object, irrespective of its shape. Sometimes this is achieved by building spring-loaded 'knuckle-joints' into each digit. Although four- and five-fingered robot hands have been attempted, none has yet made it into commercial production.

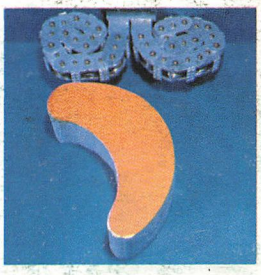
Some general-purpose grippers bear no resemblance to the hand – for example, the tentacles shown on the far right. Another ingenious approach uses a large bag of iron filings, which is dropped onto the object. An electromagnet then 'freezes' the bag solid, making the bag take on the shape of the object and grip it hard. When the magnet is switched off, the bag can be used again on another shape.

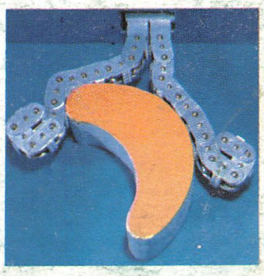
Current technology, however, cannot match the strength, lightness, flexibility and control of the human hand. Does this really put the robot at a disadvantage? A device designed specifically to grip food tins will outperform the hand in that particular application. And though no robot can match the adaptability of the hand, many have the facility to change end effector completely – either when the robot is reprogrammed for a new task or, in some cases, while it is in operation.

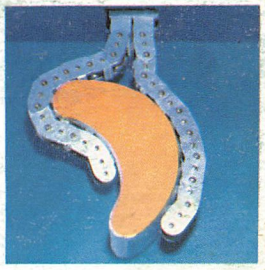
One field in which the hand remains unbeaten is in assembly tasks, where tactile feedback is as important as dexterity. Robot designers have found that giving the wrist some elasticity improves performance, for example when

This general-purpose robot gripper (above), developed by Hitachi, incorporates touch sensors that enable it to handle very delicate objects – including an unboiled egg. The sensors indicate the size, shape and pressure required to grip the object. It is claimed to have a sensitivity approaching that of the human hand. (Picture courtesy of Hitachi Europe Gmbh.)

The 'soft gripper' (below) will grasp irregularly shaped objects firmly but gently and uniformly. The tentacles are made from chain links, inside which are pulley wheels. A thin cord is wound around each pulley and, when tension is applied from an external motor, they unwind around the object to be grasped. When the first link makes contact with the object, the next one starts to unwind, because the pulley wheels at the tip of the tentacle are smaller than those at its base.



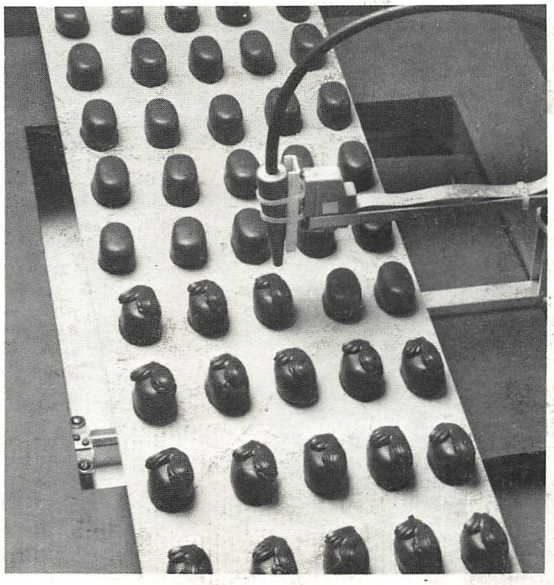




trying to locate a bolt into a hole, but there is still a very long way to go.

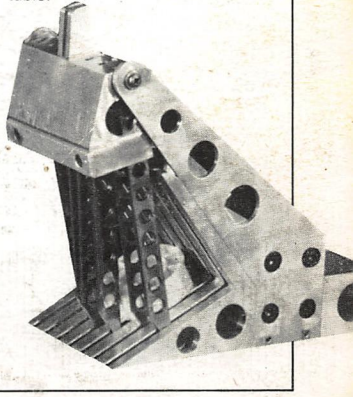
It is easy to adapt the general-purpose gripper to more specific tasks by reshaping the claws and fingers to fit the object. Suction and electromagnetism can also be equally effective as means to grasp large or smooth objects, from sacks of grain to domestic appliances.

When it comes to handling tools, the robot has a considerable advantage because the device can be affixed directly to the mechanical wrist. This increases the precision with which it can be manipulated, the reliability and the strength. Some of the drills and sanding discs that robots manipulate would be far too heavy for humans to support for long periods. However, robots are good at handling some of the lighter devices too; these include spot-welding pincers, glue guns, paint sprayers and nozzles for injecting the jam into doughnuts.



A small robot arm (left) is used to pipe patterns onto chocolates moving along a conveyor. The end effector is simply a nozzle.

This seven-fingered robot hand (below) is designed to pick up irregularly shaped objects from a table.



ROBOT GEOMETRY

One of the most important specifications of a robot arm is the number of degrees of freedom it has, because this governs the range of movements it can perform. The number of degrees of freedom is the number of independent axes of movement – in effect, the movable joints and, therefore, usually the number of motive power units.

For a robot arm to have a three-dimensional working envelope, it must have at least three degrees of freedom. Each degree of freedom may be linear, as with a telescopic extension, or rotational, as with a pivoting joint. The four designs shown on the previous page will generate differently shaped envelopes, but they demonstrate that any combination of linear and rotational movements can be arranged to cover three-dimensional space.

Three degrees of freedom will position the end effector anywhere within its working envelope, but if control over the direction from which the object is to be grasped is needed, then further degrees of freedom are necessary. The ideal is three for the arm and a further three for the end effector (not including the opening and closing of the jaws), totalling six. This enables any object in the working envelope to be grasped by the end effector from any desired angle.

Many industrial robots manage with just four or five degrees of freedom, but some models can offer the purchaser the choice of three to six. Adding degrees of freedom generally reduces both the strength and the precision of the robot because of the small amount of play introduced at each joint. Where possible, the workpiece is usually redesigned so that the robot's gripper does not need to have the full range of movement.

It is often said that the human arm and wrist have six degrees of freedom altogether, but in fact the total is seven. The one usually overlooked is that the upper arm can rotate within the shoulder socket, as well as move in two directions. This extra freedom is very useful for reaching around awkward obstacles, as there is a choice of several ways for reaching the same point.

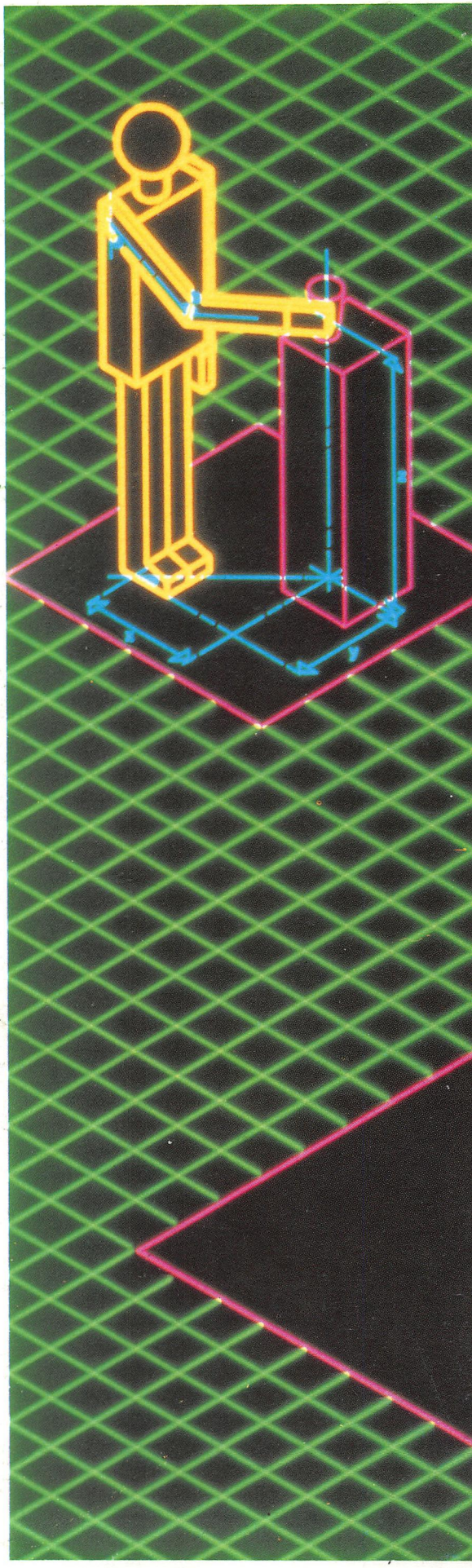
Obstacle avoidance is a particular problem for industrial robot arms. It is not sufficient merely to specify that the end effector move an object from point A to point B; the programmer must ensure that no part of the robot's structure hits any objects within the envelope, such as the conveyor. Nor must the robot foul itself, and manufacturers usually build in programs to prevent this.

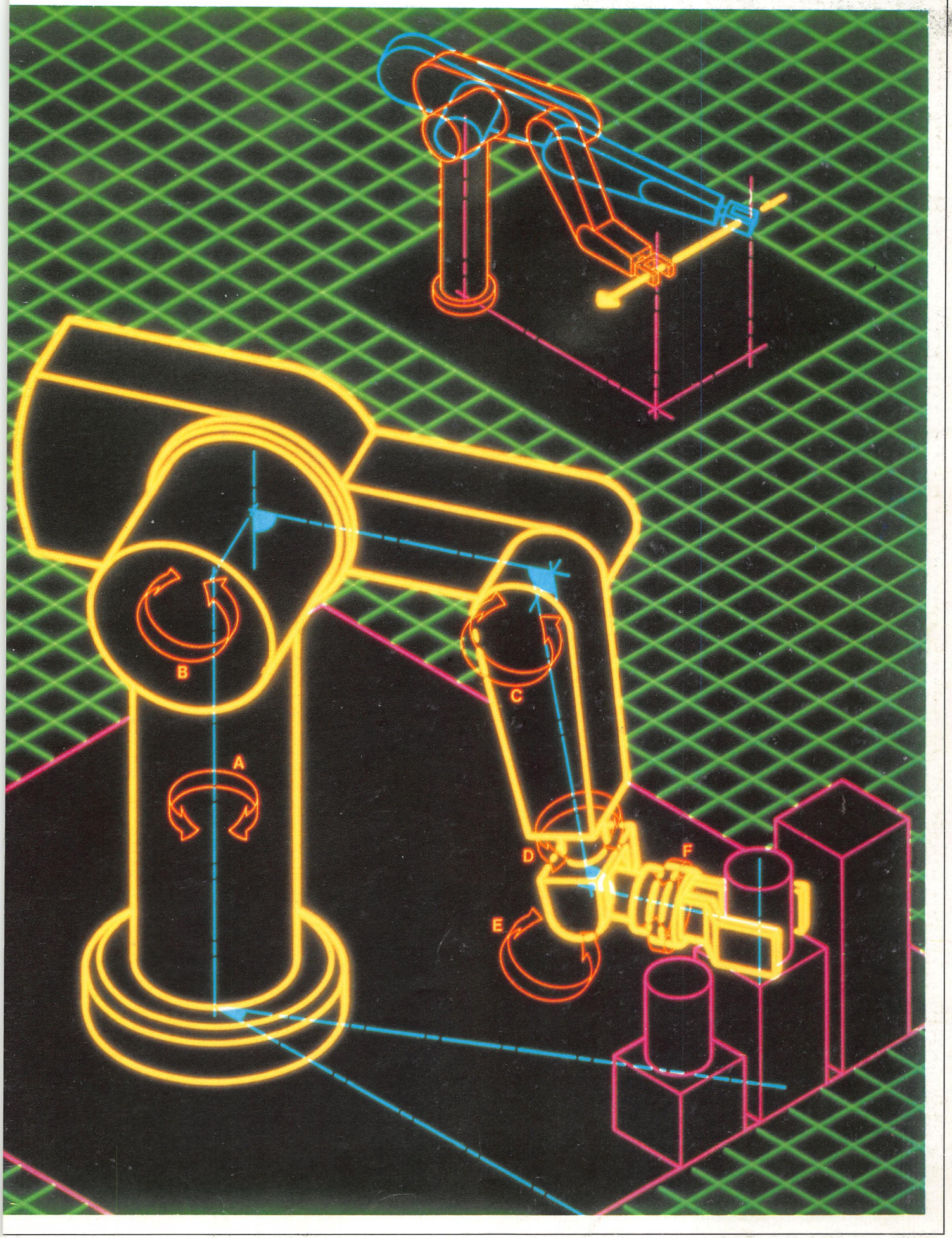
Large robot installations are sometimes simulated entirely on computers before they are built. The computer handles all the conversions between different types of co-ordinates, and can assist in the design of ancillary equipment, such as conveyors for feeding objects to the robot.

We are used to specifying the relative position of objects in Cartesian (XYZ) co-ordinates (nearest diagram), in other words: a distance along, across and up or down. Unless the robot follows the Cartesian design, these measurements will have to be converted into appropriate values for each of the joints – a very difficult exercise in three-dimensional geometry, complicated even further by wrist movements.

The joints and members of a jointed-arm robot (centre) are given anthropomorphic labels: waist (A), shoulder (B) and elbow (C). The elbow joins the upper arm to the lower arm, and the wrist describes all the joints between end effector and lower arm. The three movements of the end effector are by convention called yaw (D), pitch (E) and roll (F), from the movements of a ship in rough seas.

Continuous-path applications (far diagram), such as arc welding, rely heavily on mathematics. Even moving the end effector in a straight line is not as simple as it may sound. Powering any single actuator in a jointed-arm robot will cause the end effector to trace out a curve; so, making the arm follow the line of the seam will involve all of the joints moving simultaneously, but at different speeds.




A
B
C
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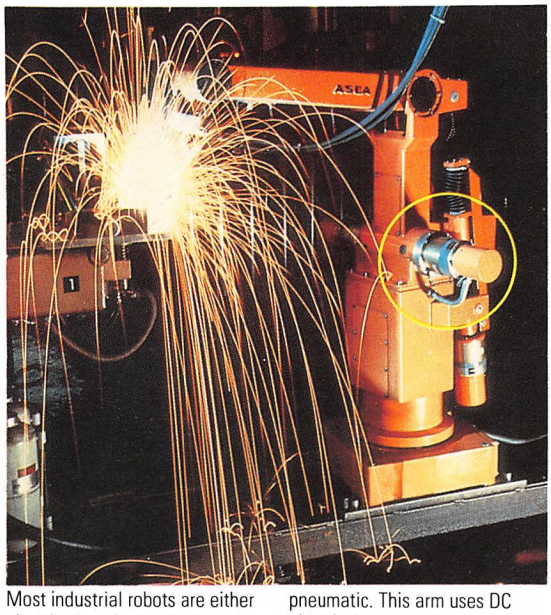
E
F

MOTIVE POWER



Most industrial robots are either electrically or hydraulically powered, and a few are pneumatic. This arm uses DC electrical servo motors, seen here protruding from each joint.

DC motors

Most of the electric motors we encounter, from toy racing cars to food mixers, are direct-current or DC motors. A battery is a source of direct current and will power such a motor directly. Mains electricity provides alternating current (AC) – the current in the wire changes direction fifty times every second – but a rectifier circuit can convert it back to DC for driving the motor. AC motors do exist and could be connected directly to the mains, but it is difficult to alter the speed at which they run or to accelerate from standstill.

The DC motor is a very suitable source of motive power for both static and mobile robots. The motors are manufactured in a wide range of sizes, are easy to control and the source of power to drive them is readily available in an industrial environment. More than half of all industrial manipulators use DC motors.

However, there are several inherent disadvantages resulting from the difference in movement between a DC motor and the robot it powers. The DC motor spins around an axis several hundred times a minute; a robot elbow may only rotate through, perhaps, 160 degrees at the most. The DC motor turns at high speed but with little torque (that is, turning force); a robot arm moves at relatively low speeds but needs very high torque to lift heavy objects. Finally, although it is possible to control the motor's speed very accurately, it is impossible to stop the spindle at a specified position; whereas position control on a robot is of fundamental importance.

The first two difficulties can be overcome simply by gearing the motor down. The power in a shaft equals the speed of rotation multiplied by the torque. By reducing the speed of rotation using a gearbox and maintaining the power, the torque will increase proportionately. That is why you get better acceleration in the lower gears on a car. For robot applications, the speed of the motor must be geared down by at least a hundred to one. This could be achieved using a whole series of simple gear reductions, but that inevitably introduces some loose play (backlash) which would be disastrous at the end effector. The answer lies in the harmonic drive, an ingenious gear reduction unit, used in the majority of robot arms driven by DC motors (see below right).

The problem of position control can only be overcome using feedback – measuring the results of an action and feeding this information back to the device controlling the action. A position sensor fitted inside the robot joint constantly measures the angle of that joint and sends an electrical signal back to the circuit driving the motor. As the arm approaches the specified position, the controller will reduce the speed of the motor.

One of the nice features of DC motors, from the robot designer's viewpoint, is that any increase in the load (i.e. the force) applied to a motor will cause it to draw more current. By this means, the controller can detect when the gripper has made firm contact with the object to be grasped, or when a limb has reached the limit of its travel.

Stepper motors

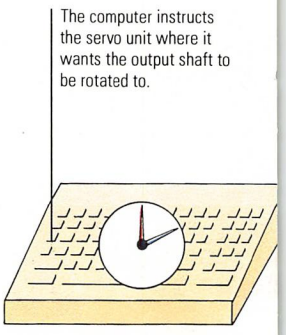
In some ways, the stepper motor is the robot engineer's dream come true. Unlike a conventional DC motor, where the output shaft simply spins, a stepper motor turns in small and very precise steps. If a motor features 12 steps per revolution, then each movement will be exactly 30 degrees. Top-of-the-range devices have as many as 240 steps per revolution – equivalent to just 1.5 degrees for each increment.

Powering a stepper motor, however, is not simply a matter of connecting the terminals to a battery. Special electronic circuits are needed outside the motor to control its movement; the size of these circuits has been reduced over the years so that they can now be purchased on a single silicon chip. The control chip links directly to a computer, allowing the programmer to specify the number of steps through which the motor is to turn each time, and this is the principal advantage of the stepper motor.

Stepper motors are used in many applications where movement must be controlled precisely – for example in numerically controlled machine tools where the workpiece is moved through fractions of a millimetre. They can be found inside computer printers, both in the paper advance mechanism and for moving the print head itself.

Servo motor

A DC motor on a robot arm without feedback would be useless. Very often, the control circuitry, motor, gearbox and feedback-measuring device are built into one unit – called a servo motor. Large servo motors form the basis of much factory automation, and small ones can be found in some model aircraft. A schematic diagram of the operation of a servo motor is shown below. The characteristic closed loop is clearly visible.



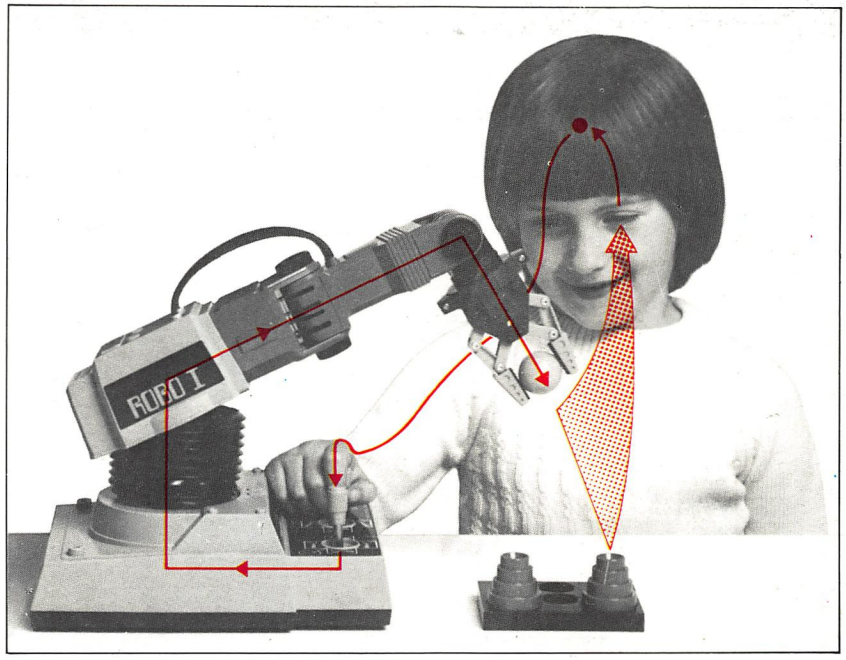
The harmonic drive

For use on a robot arm, a DC motor must be geared down by at least 100 to 1 in order to reduce the speed and increase the torque (turning force). Most electrical robots use the harmonic drive, an ingenious gearing mechanism developed in the USA, and used on the Apollo lunar rover to power its four wheels independently.

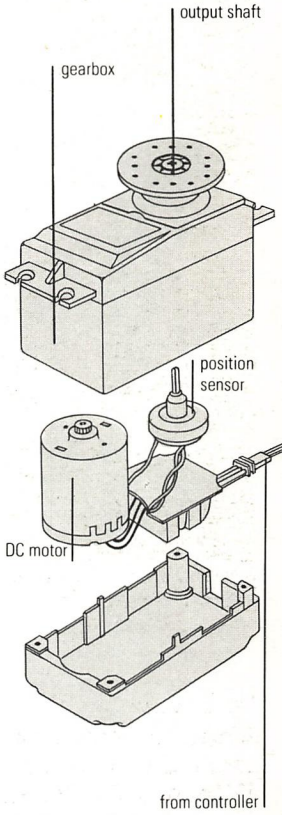
Using just three components, the harmonic drive can achieve a reduction of up to 320 to 1. The biggest advantage over conventional gears, however, is that a large number of teeth are meshed together at any one time. This increases the useful strength of the joint and substantially reduces backlash – the degree of loose play that results from most gear systems.

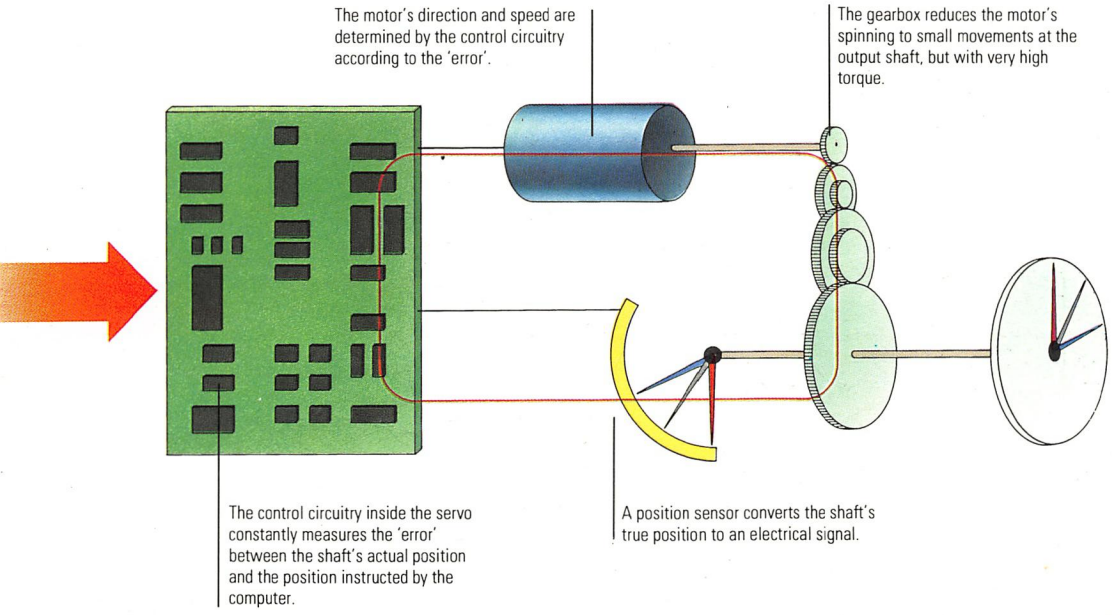
Feedback: closed-loop control
The principle of feedback is to measure the output or effects of a system and feed this information back to the controlling device.

All systems using feedback contain a *closed loop*, around which information flows. The girl playing with the toy robot arm (right) is using feedback through her eyes and brain. The closed loop is shown in red: the hand moves the lever which results in movement of the robot. The 'error' between the end effector's actual position and the goal is measured by the eye and transmitted to the brain. The brain uses this information to compute the next action, and sends directions to the hand. If the child were to wear a blindfold, the system would become an *open loop* and it would be very difficult to place the ball in the correct position.

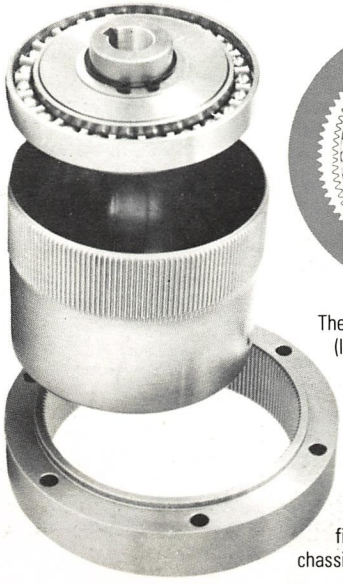


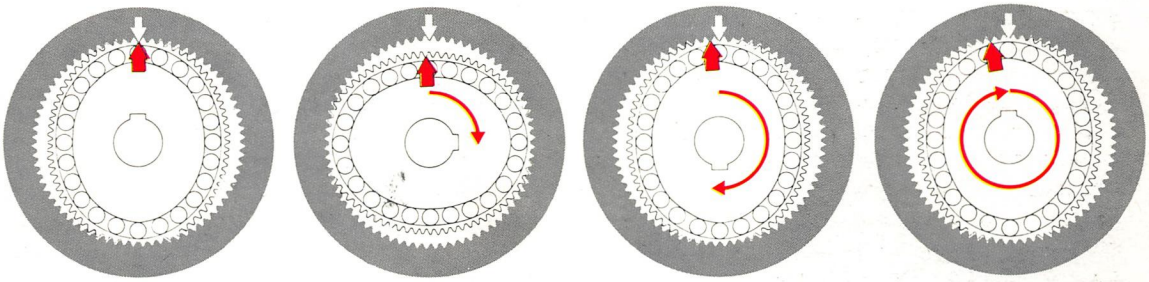
Small servo
The matchbox-sized servo motors that are used to move the control surfaces on a radio-controlled model aeroplane employ the same principles as the large servo units in industrial manipulators.



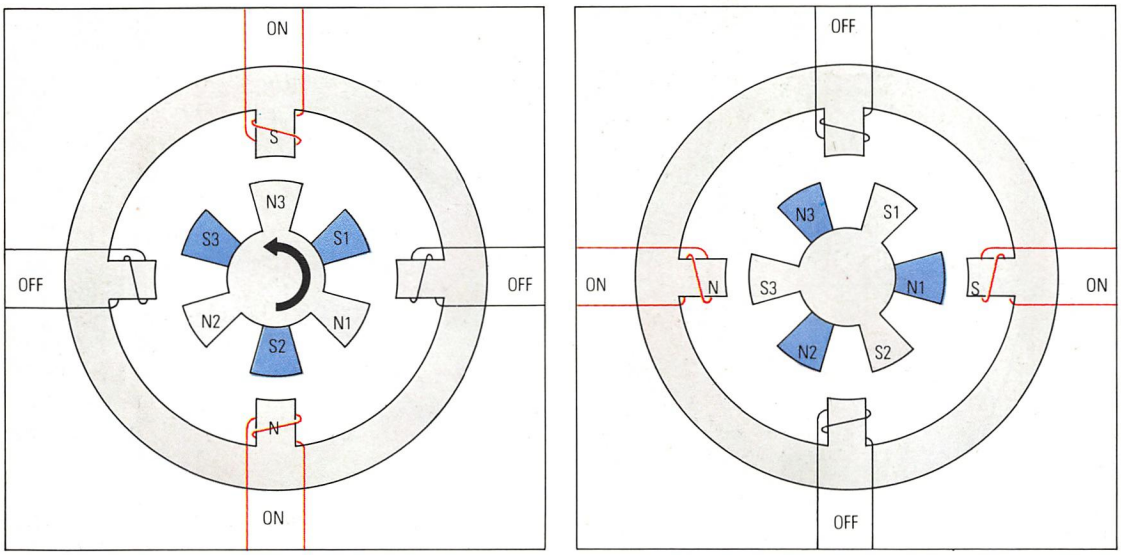


The output shaft turns through, typically, 120 degrees, but with such high torque that it cannot be stopped using finger pressure. Interfaces now exist to connect these servos directly to a microcomputer, providing an excellent base for home-constructed robot devices.





The dismantled harmonic drive (left) shows the three components. The *wave generator* (top) is oval shaped, with a smooth surface, and is connected to the motor shaft. The *circular spline* (bottom) has teeth on the inside and is fixed to the robot's chassis. The output of the drive is connected to the *flexspline* (middle), made from thin flexible metal, which sits between the other two components. The exterior of the flexspline has teeth that mesh with the circular spline. The inside is smooth, so that as the wave generator is turned the flexspline will distort in shape. The flexspline typically has two less teeth than the circular spline **(1)**. As the wave generator starts to rotate clockwise **(2)**, the zone where the teeth engage moves with the wave generator. Because the flexspline has two less teeth than the circular spline, when the wave generator has turned through 180 degrees **(3)** the flexspline will have had to turn gradually anticlockwise by one tooth to keep up. By the time the wave generator has made one complete revolution **(4)**, the flexspline will have regressed by two teeth from its original position. The same thing happens for each revolution. The direction of turning is therefore reversed. The actual reduction ratio depends on the number of teeth on each spline.



The rotor in a stepper motor is constructed from several permanent magnets with north and south poles. The stator (that is, the fixed part) is wound into a series of electromagnets, which can be switched on and off. In the left-hand diagram, the two activated electromagnets hold the rotor rigidly in the position shown. In the second diagram, the original windings have been switched off and the other pair activated. This pulls the rotor round by one step, and holds it rigid in the new position.

Stepper motors also provide the motive power for most low-cost robot arms and floor buggies. For these applications 'steppers' can be operated in open-loop rather than closed-loop mode (see previous page), because they move so accurately. One of the costliest components of a closed-loop system is the encoder or positional sensor to provide the feedback information. So, because they don't need these devices, steppers can bring down the price of a robot.

Steppers have other advantages. Using chains or other gearing mechanisms, the steps of the motor's spindle can be converted into a useful unit of movement. For example, some floor robots are designed so that one step on each motor moves the buggy forward by one millimetre.

For applications that demand high torque, however, stepper motors lose accuracy and are less economical than DC motors. This is one of the reasons why steppers aren't generally seen on industrial robots. The torque supplied by a motor has to be measured in two ways. The dynamic torque is the turning force that it can deliver to, say, a robot arm joint when the arm is actually moving. The holding torque corresponds, in this case, to the rigidity of the joint when it has stopped moving.

When the power is turned off there is very little holding torque and the spindle on a small stepper motor can be turned using finger pressure, although it will still only turn in steps. With power applied, it takes considerably more effort to turn the spindle – unless the instructions are coming from the control chip. Nevertheless, if a torque greater than the holding torque is applied, the spindle can still be moved by one or more steps unknown to – because not instructed by – the control chip and, therefore, unknown to the computer. In commercial applications this could have disastrous consequences. Incorporating a position feedback sensor would solve the problem, but there is then no economic advantage over using a DC motor.

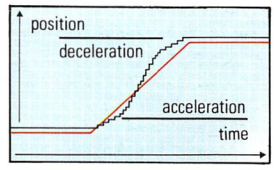
The phenomenon of missed steps is far more likely while the arm is moving than when it is stationary, particularly when it picks up a heavy object. This is why the quoted lifting capacity of most educational arms is so low – often 100 grams ($3\frac{1}{2}$ ounces) or even less.

Acceleration and deceleration

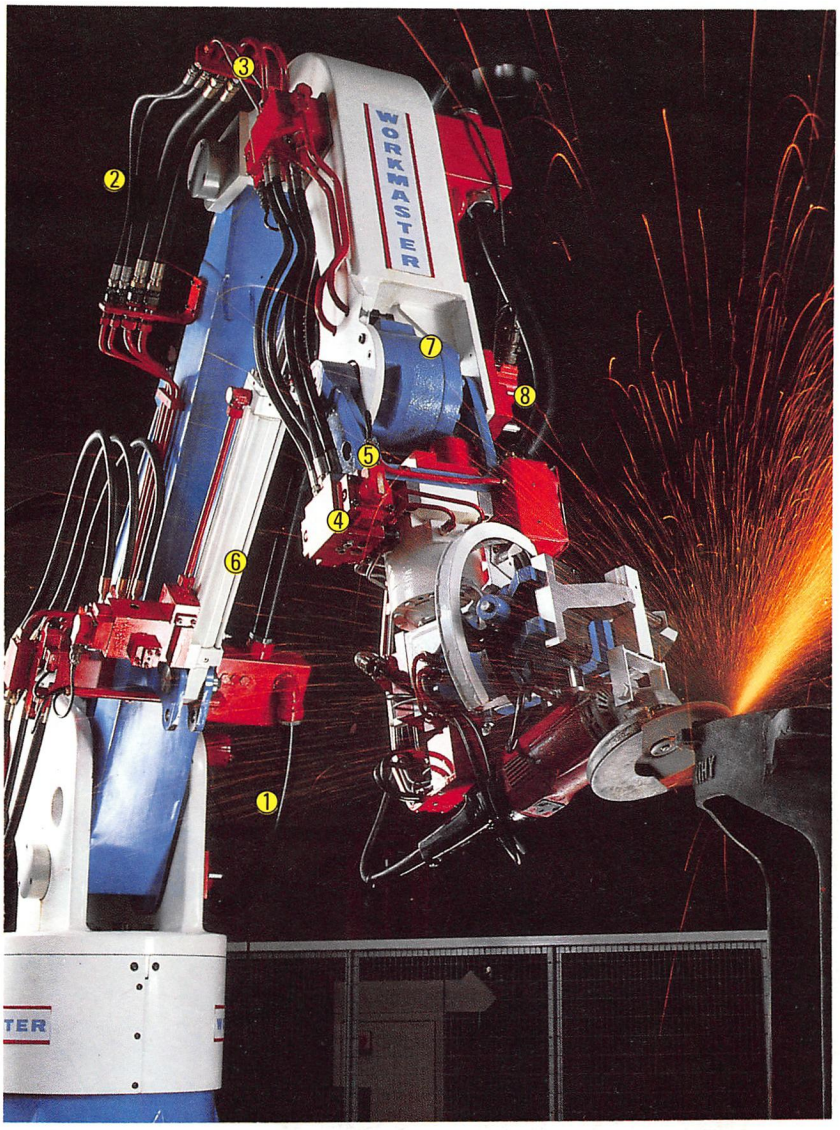
The speed at which a stepper motor turns, which is usually measured in steps per minute, can be specified accurately. The control chip interprets the speed requested by the computer into a series of electronic pulses delivered to the motor's windings. Unlike a DC motor, it is not possible to set the motor to the intended running speed and wait for it to accelerate. Instead, the speed (also called the step rate) must be gradually increased to the desired value.

Equally, the stepper must be put through a proper programme of deceleration, carefully calculated so that the spindle stops in the correct position. Specifying too large a jump in the step rate will result in the motor stalling or overrunning; either way steps will be missed out. Engineers refer to this situation as a loss in pulse-to-step integrity. The greater the load on the motor (i.e. the greater the mass of the object being moved), the slower the acceleration and deceleration must be.

Acceleration and deceleration control is not confined to robots based on stepper motors. When an industrial robot arm moves a distance of, say, a metre, nine-tenths of the distance will be traversed at high speed, whereupon the motors will slow right down for the last tenth. Better control can be achieved at lower speeds, but there is a second motive for slowing right down at the end of the movement: reducing the momentum of the arm. Even if the device was accurate to within half a millimetre, it would still be highly undesirable for an object weighing half a tonne to hit a stationary workpiece at the robot's typical speed of 50 centimetres (20 inches) per second.



A sudden change in the speed of a stepper motor (black line) will either cause a stall or cause steps to be missed out. Instead, the stepping rate must be gradually increased (red line), and then decreased to stop the rotor at the desired position.



The Ajax Workmaster (above), capable of lifting half a tonne, shows the components of a hydraulic system. Pressurized fluid is supplied through a heavily protected tube (1) from an external compressor. Flexible hoses (2) and rigid pipes (3) distribute it to the joints. Servo valves (4) control the pressure of the fluid inside the actuators, by means of electrical signals (5) from the computer. A linear actuator (6) is used to flex the elbow, with three rotary actuators (7) inside the wrist joints. Position sensors (8) send electrical signals back to the computer indicating the current angle of each joint.

Hydraulics

The word hydraulics comes from the Greek *hudraulos* – a musical organ driven by water power. We use it to describe any system where mechanical power is transmitted through a liquid under pressure.

The braking system on modern cars operates hydraulically. The brake pedal pushes a piston within the master brake cylinder, and this forces the brake fluid (usually a form of vegetable oil) along a pipe. At the far end, the oil enters the slave cylinder in the brake unit, moving the piston that is directly connected to the brake shoes. Hydraulics relies on the fact that liquids are virtually incompressible.

As a means for transferring mechanical force and movement from one place to another, the hydraulic method offers several advantages. Firstly, the linkage is flexible; the hydraulic hose can be routed around obstacles more easily than a direct mechanical linkage, and it permits limited movement between the master and slave parts of the machine. Secondly, because it avoids the power losses associated with converting electrical power into mechanical movement, it is highly efficient. Furthermore, when you brake a car, the brake shoes travel only a fraction of the distance moved by your foot, but with considerably greater force. So the third advantage of hydraulics is this 'leverage' effect to increase the useful force at the slave end.

Hydraulics is therefore the favoured source of motive power for heavy-duty industrial manipulators – the ones employed in moving heavy objects rather than just wielding a paint gun. We are used to seeing hydraulically operated excavators digging up the roads, and these are very similar to large robot arms, but with just four degrees of freedom.

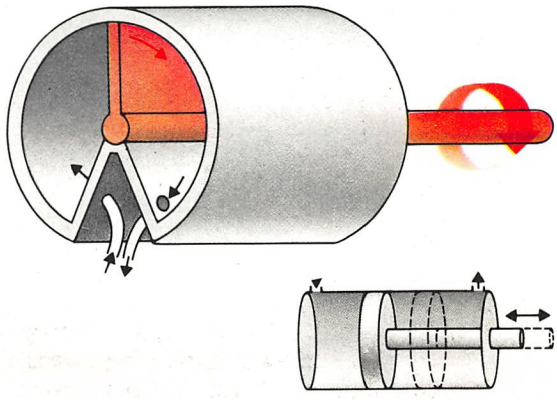
The system employed is rather different from that of a car brake. A large compressor, driven by an electric motor or combustion engine, delivers fluid at a constant pressure (several thousand times atmospheric pressure) through one pipe. At the robot end, smaller supply lines connect this pipe to each actuator, which may be linear or rotary (see diagrams) according to the construction of the robot.

Between the supply line of pressurized fluid and the actuator is an electrically operated valve, called a servo valve, which is linked to the control computer. When a joint is to be moved, the computer opens the servo valve, which releases pressure into the actuator.

There are several problems associated with hydraulics, quite apart from the need for an expensive and noisy compressor next to the robot. The seal between the fixed and moving parts of an actuator is made to a very high tolerance, but there will always be a slight leakage of oil at each joint, because of the high pressures.

Safety, too, is a major issue – what would happen if the supply hose, which is very well protected, were to be ensnared and severed by the robot? Many systems are designed to be fail-safe, ensuring that the arm instantly locks up and there is no possibility of a heavy load crashing to the floor.

A severed hose, however, is very unlikely. More probable is an electrical failure, so even the small servo valves must be designed to spring closed if there is a power cut. This again locks the actuators solid until power is reapplied. The inertia of a heavy arm moving at high speeds makes all industrial robots potentially dangerous, and the track record of hydraulic arms is as good as any other type.



Hydraulic actuators
A linear actuator (bottom right) is like a conventional piston inside a cylinder, the output shaft extending telescopically. A rotary actuator rotates a vane within a circular casing (top right), like a one-paddled water wheel.

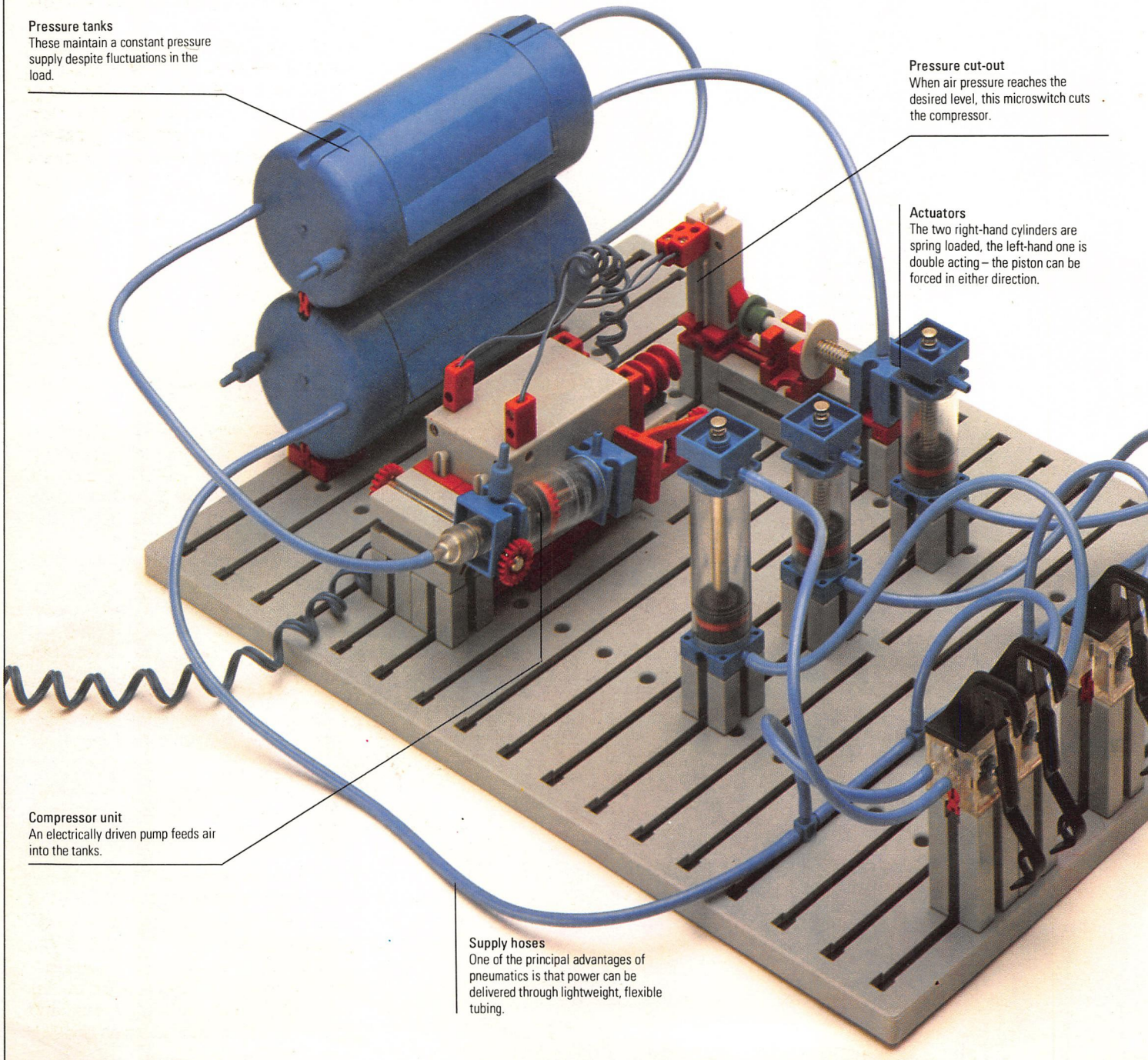
Pneumatics

A pneumatic machine is one that is driven by air pressure – the word comes from the Greek *pneuma*, meaning breath or air. The mechanical power usually originates from another source, typically an electric motor, but the air transmits the power to where it is needed.

In a pneumatic system, the fluid itself is considerably lighter than in a hydraulic one, and because it operates at lower pressures the components of the system can be constructed from lighter materials. The cost is lower, too, because the seals between cylinders and moving pistons don't need to be so precise. A pneumatic system can't deliver nearly the same forces as a hydraulic system, but it is still an attractive proposition for robotics.

There is, however, a major drawback. Unlike liquids, gases are highly compressible. This may be advantageous in some applications, for example those that require the end effector to be slightly elastic, but it is generally quite a hindrance. Specifically, it makes precise control of movement very difficult. It means that, in a

These two pneumatic systems are made from Fischertechnik parts and could easily be constructed by a home robotics experimenter. They also serve as a good demonstration of the principles of operation and the components found in an industrial pneumatic robot.



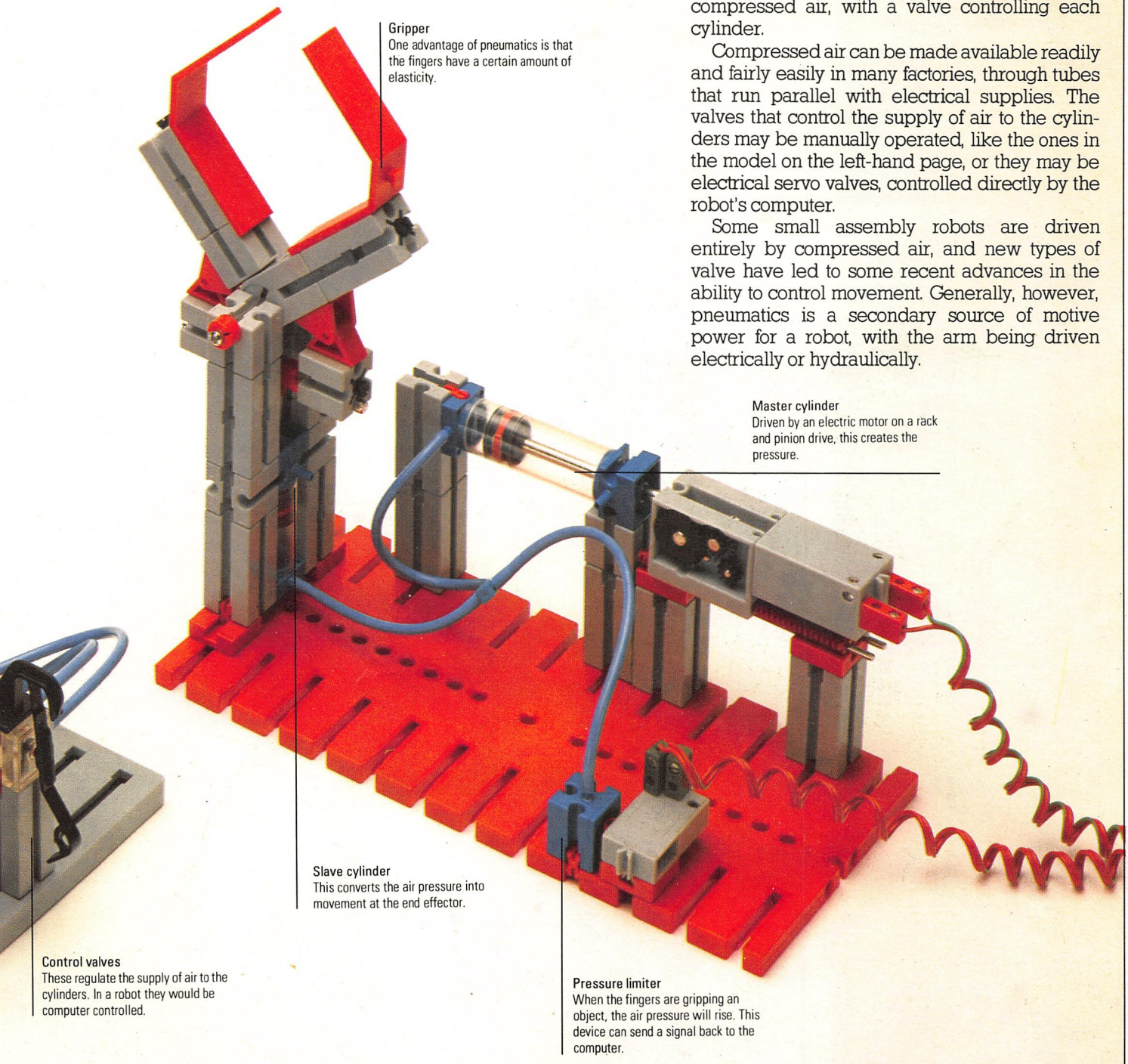
pneumatic system, the amount that, say, the forearm moves will depend on the load it is bearing, and when that load is released the arm will spring upwards.

Pneumatics is therefore mainly used where linear control of movement is unnecessary, for example in a gripper that has only two positions: open and closed. Pneumatics is also commonly used in the ancillary automation equipment that accompanies a robot installation, for positioning objects.

Some pneumatic systems closely resemble hydraulic ones, as is illustrated by the model on this page, and have a master cylinder and a slave cylinder like a car braking system. More often, however, there will be one central source of compressed air, with a valve controlling each cylinder.

Compressed air can be made available readily and fairly easily in many factories, through tubes that run parallel with electrical supplies. The valves that control the supply of air to the cylinders may be manually operated, like the ones in the model on the left-hand page, or they may be electrical servo valves, controlled directly by the robot's computer.

Some small assembly robots are driven entirely by compressed air, and new types of valve have led to some recent advances in the ability to control movement. Generally, however, pneumatics is a secondary source of motive power for a robot, with the arm being driven electrically or hydraulically.



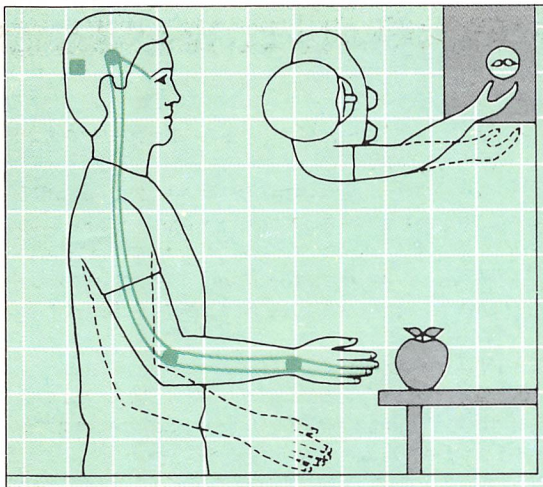
Gripper
One advantage of pneumatics is that the fingers have a certain amount of elasticity.

Master cylinder
Driven by an electric motor on a rack and pinion drive, this creates the pressure.

Slave cylinder
This converts the air pressure into movement at the end effector.

Control valves
These regulate the supply of air to the cylinders. In a robot they would be computer controlled.

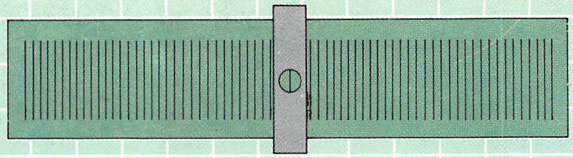
Pressure limiter
When the fingers are gripping an object, the air pressure will rise. This device can send a signal back to the computer.

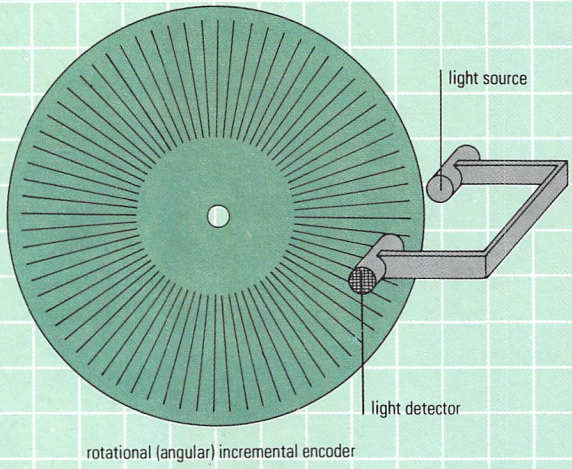


Sixth sense

Proprioreception is the name given to our ability to sense the position of each of our limbs. Special nerves communicate the state of each muscle back to the brain. We use this 'sixth sense' most when deprived of sight.

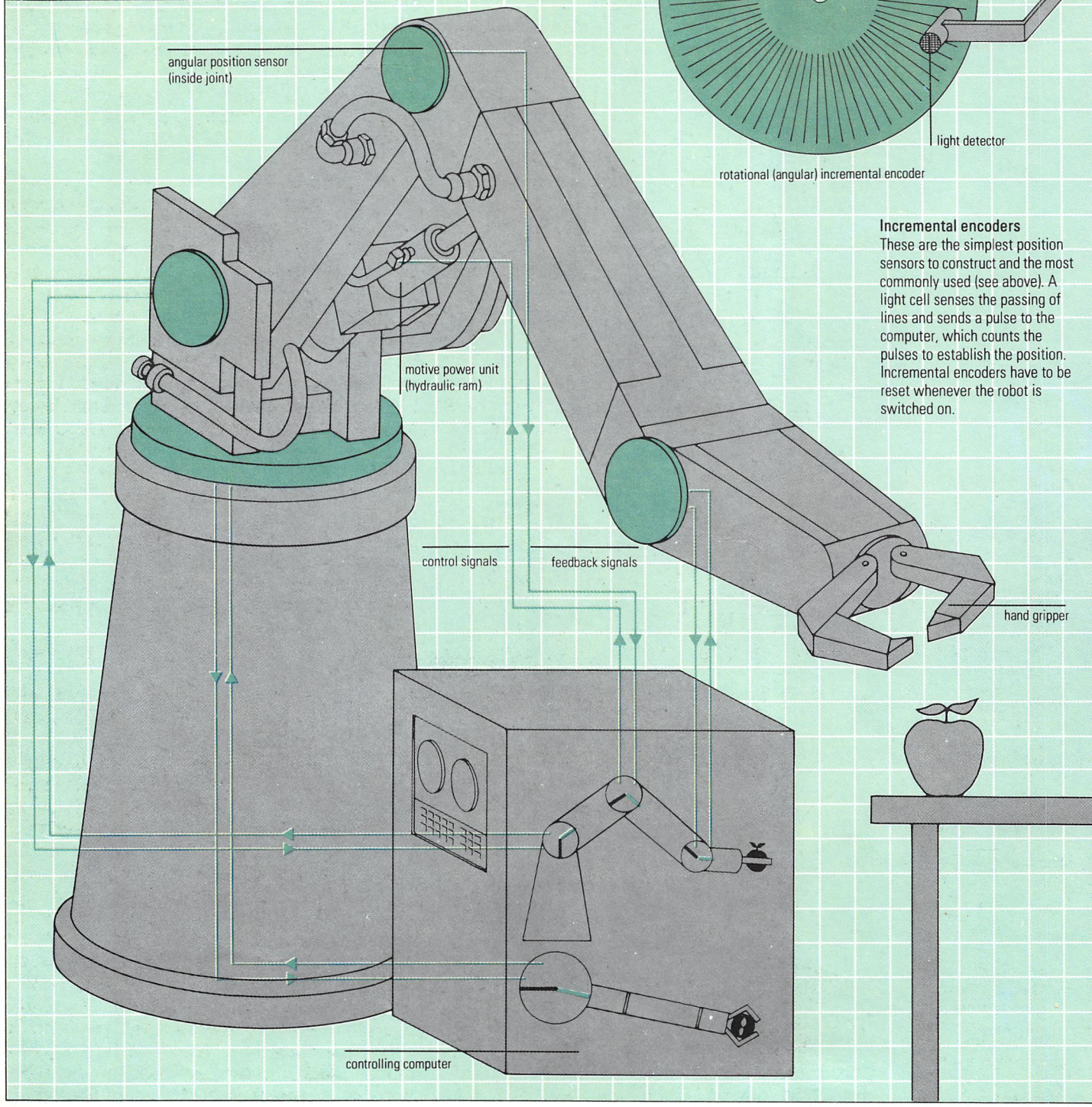
Position sensors mounted in the joints of an industrial manipulator (below) communicate the angle of each joint back to the control computer. It can then calculate how far the end effector is from the target, and send movement instructions to the motive power units.





Incremental encoders

These are the simplest position sensors to construct and the most commonly used (see above). A light cell senses the passing of lines and sends a pulse to the computer, which counts the pulses to establish the position. Incremental encoders have to be reset whenever the robot is switched on.



POSITION SENSING

When we reach out to pick up an object, we don't have to think about the movements involved. But the subconscious part of our brain is doing a great deal of work. Information concerning the relative position of the hand to the object is arriving constantly from the eyes and, from this, the brain is able to derive the appropriate messages to send to the muscles.

Remove the sense of vision by applying a blindfold and the operation becomes more difficult for us, but not impossible – particularly if we have practised several times. Now the brain isn't simply reproducing the sequence of impulses to every nerve that it used before, when we could see the object; this would not be nearly accurate enough. In fact, the brain can sense the position of every joint in the body, and it adjusts each muscle until it senses that the joints are in the same position as when the object was successfully grasped before. This is called proprioreception and is as valid a sense as touch, smell, taste, sight and sound. Proprioreceptor nerves communicate the state of each muscle back to the brain.

Proprioreception is even more important to robotics. Comparatively few robots have any sense of vision, yet they must be able to position the end effector accurately. Robots driven by DC motors have the position sensors built into the servo units. On other types, the sensors may be mounted inside the joints and be separate from the motive power units.

A position sensor converts the angle of a joint or the extension of a telescopic section into an electrical signal. Analogue position sensors are simpler to construct, though digital sensors are more commonly used, because of greater accuracy.

Analogue sensors

The volume control on your hi-fi is a form of analogue sensor. An electrical contact is moved over a piece of resistive material such as carbon; the more you turn the knob, the less material is incorporated into the circuit and the greater the output. If a piece of this material is fixed to one part of a moving joint and the electrical pick-up to the other, then any change in the angle or extension of that joint will change the voltage fed back to the computer.

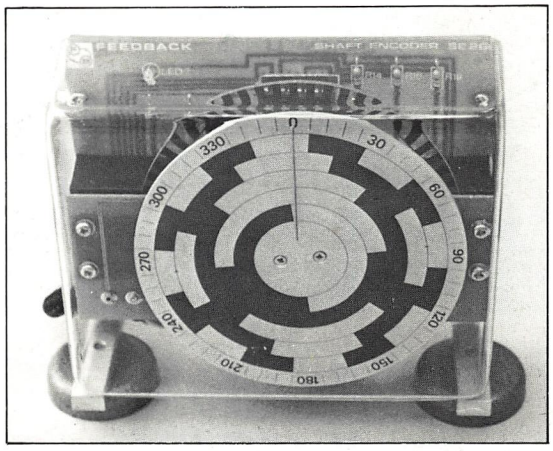
Digital sensors

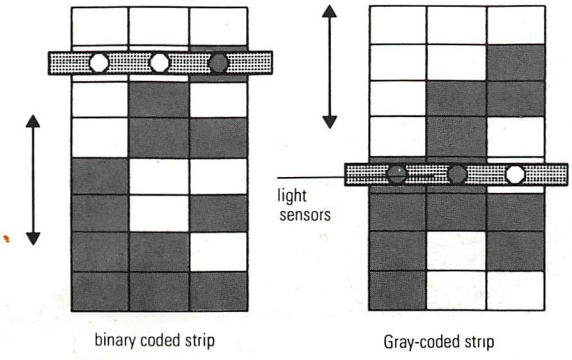
On the simplest form of digital position sensor, one side of the movable joint features a series of marks, and the other a device for sensing the presence or absence of a mark. These marks could be physically engraved onto a surface and detected by a pick-up similar to a record-player needle, or they could be bands of electrically conducting material interspersed with insulating material. The most popular technique is to print black marks on a white background and detect them with a light-sensitive device. There is no physical contact and hence no wear and tear.

Most digital sensors are incremental encoders. A simple circuit counts the marks as they move past the photocell. When the robot is first switched on, the arm is programmed to move to a known position with all the joints fully retracted. The electronic counters are all reset to zero, so that the computer can then convert any relative movement into an absolute position.

Gray code

An absolute encoder works differently, and doesn't require resetting, because the marks are printed in the form of a code, read by several photocells, each possible position having a unique code. The binary code might seem ideal, as computers work in binary, but there is a snag. If the arm came to rest on the join between two codes, each individual photocell might read the value on either side. In binary, several bits may change between two positions. The sensor could end up giving a reading that was nothing like the code for either position. The reading would then be meaningless or wildly inaccurate and would have disastrous consequences. So, Gray code is used. This looks similar to binary, but only one bit ever changes between two adjacent positions. On a join, the sensor has no option but to give a reading that encodes one side or the other, because no more than one bit can be in error.





Absolute encoders
The three position sensors shown on the right are absolute encoders – one angular, for mounting in a rotational joint, and two linear, for measuring telescopic extensions. A wheel or strip is printed with a black-and-white code, which is read by a bar of light-sensitive cells. The code is designed so that each position of the wheel or strip results in a unique pattern of 1s and 0s (ONs and OFFs) from the cells. The robot's position can always be read directly; the computer doesn't need to keep track of previous movements.

The problem with using the binary code (near right) for absolute encoders is that, should the arm stop on a join between two positions, a very inaccurate reading could be given, because on some joins, all the bits change their value.

The Gray code (far right) is more suitable for encoders, because only one bit changes between any two adjacent locations. The light cells will always therefore read the correct code either for one side of the join or the other.

TOUCH

As with all our senses, we take touch for granted. The fingertips are so sensitive that a blind person can read a page of braille with ease. A craftsman's hands can detect the tiniest flaw in a piece of glasswork or polished wood. At the same time, human skin must be able to withstand considerable forces without breaking.

Currently there is no such thing as a robot skin, either biological or electronic. The closest equivalent is a new type of flexible plastic film that creates a voltage in response to pressure. It is so sensitive that it 'feels' sound waves – a sheet pasted to the wall acts as a microphone – but the film has yet to be employed on commercial robots.

Touch sensors

Robots are therefore given a sense of touch by means of physically discrete sensors, mounted at strategic points on its structure. Mobile robots invariably feature collision detectors around the base unit; if contact is made with an unexpected object, the control unit will slam on the brakes. Some of the experimental robot mice designed for maze solving (see page 80) have featured delicate whiskers for feeling their way around the walls. In the case of a robot arm, touch sensors are usually mounted only on the end effector, to facilitate the grasping of objects.

There are four aspects to touch sensing: proximity, contact, pressure and identification. Each has a different application and uses different technology.

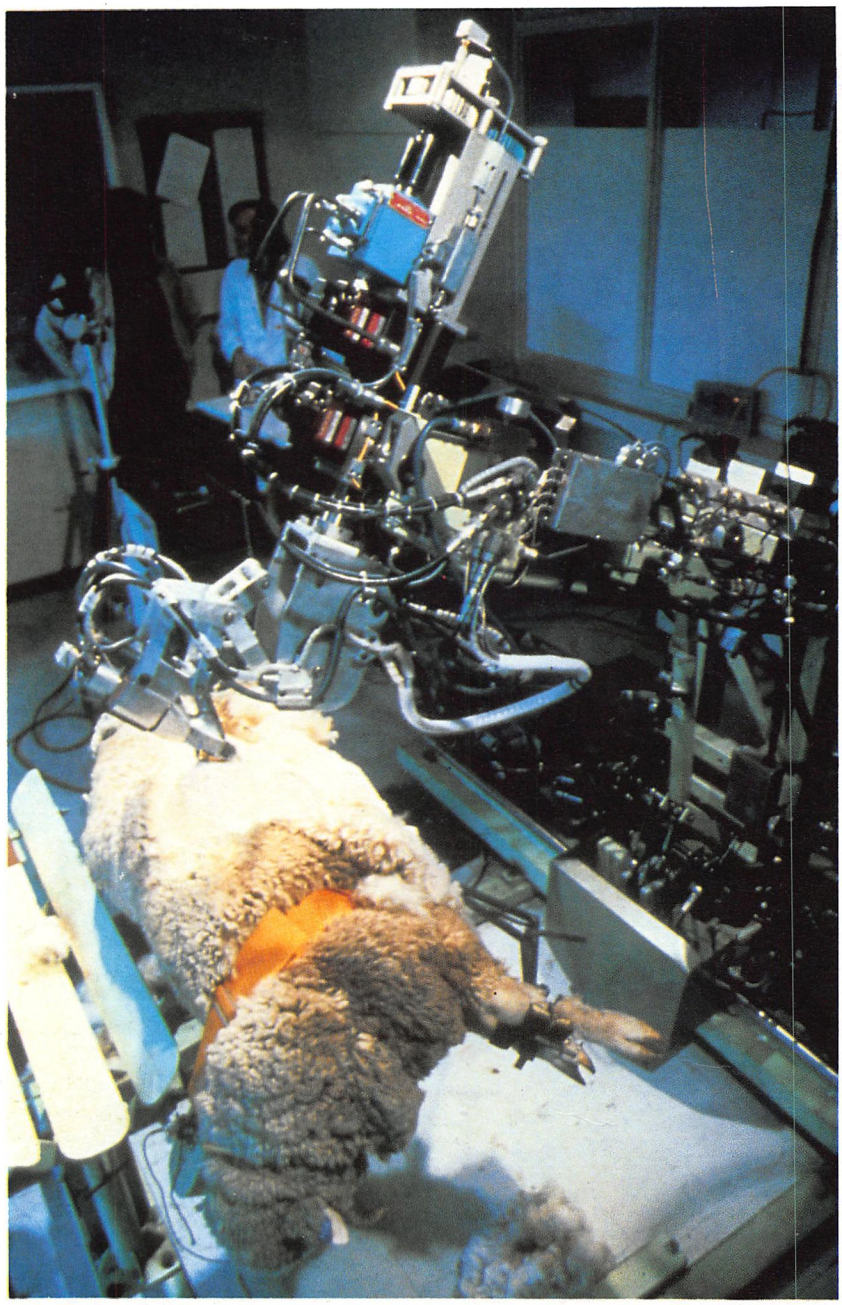
Proximity detectors advise the robot controller that the end effector is nearing an object, or vice versa. Most such devices employ light; either the object breaks a lattice of light beams just in front of the gripper, or a low-powered laser is projected onto the surface of the object, and the level of reflected light is read by a photo detector. Proximity detectors seldom have a range of more than a few centimetres, but they can sometimes be used in place of a full vision system for picking up irregularly shaped items.

Contact detectors have only two output states, indicating whether there is or isn't an object in contact. They are often constructed from simple electromechanical switches, called microswitches, which require very little pressure to close the contacts. An alternative is the magnetic reed relay, where the contacts close when a bar magnet is brought close enough.

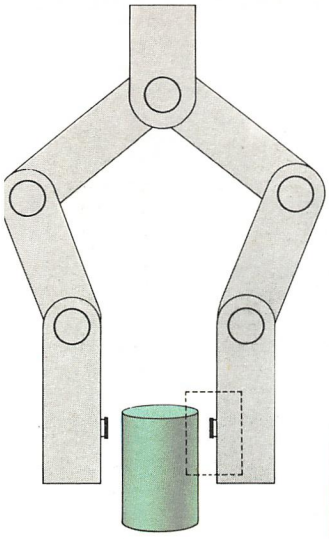
Pressure detectors give an electrical output proportional to the pressure applied. They are therefore analogue rather than digital sensors (see page 75). A piezo-electric crystal forms the basis of most pressure sensors. The molecular structure of this type of crystal is such that when it is deformed under pressure an electrical charge builds up, and this can be measured by mounting the crystal between two metal plates. Incidentally, if the process is reversed, and a voltage applied to one of these crystals, it will temporarily deform in shape. By pulsing the voltage at a high frequency, the crystal will produce sound vibrations – and this is used to advantage in alarm wristwatches.

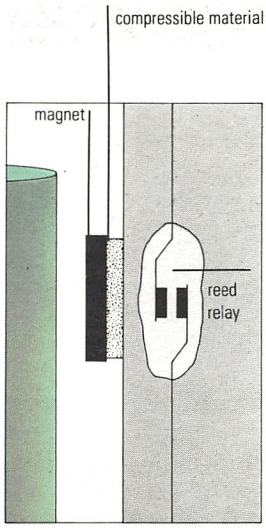
The strain gauge is a device used by engineers to detect tiny amounts of strain (stretching) in steel structures. By mounting strain gauges on the inside of a robot's grippers, the computer can measure the amount by which they bend when an object is grasped and thence calculate the pressure applied.

Touch sensors for the identification of the object

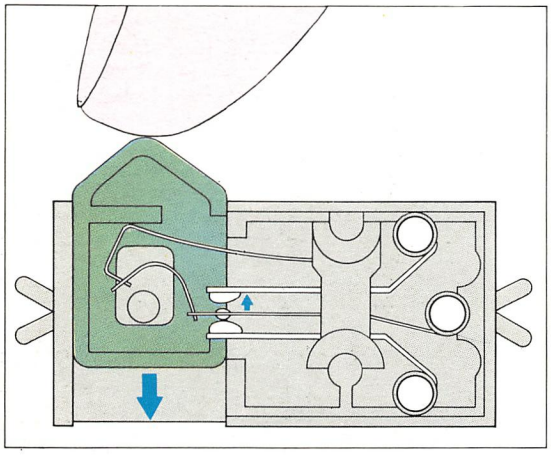


This robot for shearing sheep was developed for the Australian Wool Corporation. Although slower than a skilled human (the robot takes 15 minutes), the robot can continue shearing indefinitely; this makes it economical on very large flocks. The control computer incorporates a software model of a standard sheep in its memory, but the robot's shearing head features touch sensors to measure variation from the standard and adjust the position accordingly.



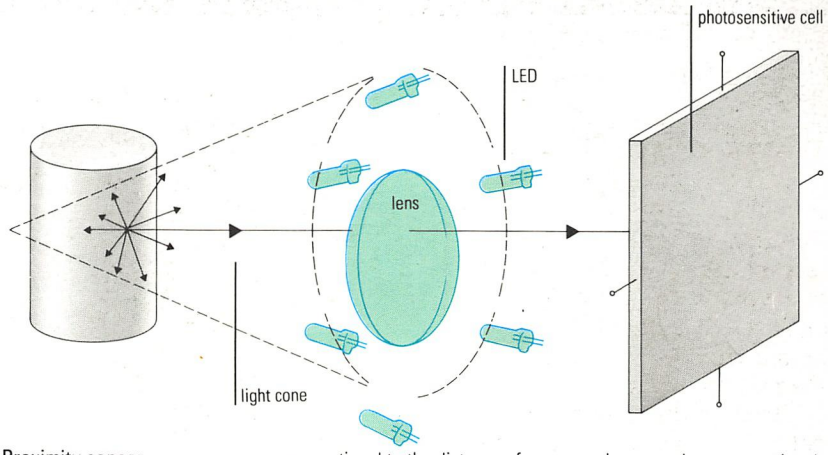


Reed relay
Built into the robot fingers are miniature reed relays, each containing two contacts that can be made to close magnetically. A small bar magnet is mounted on foam rubber and, when the fingers exert pressure on an object, the magnet moves closer to the relay, closing the contacts.

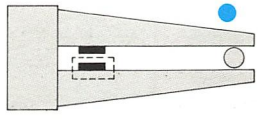


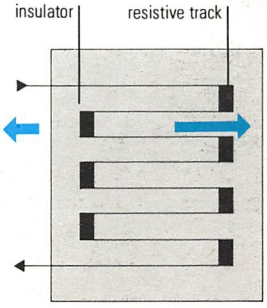
Microswitch
A microswitch is a conventional electrical switch that can be operated by very light pressure, or a minute movement or both. The one shown here features three outputs; normally, the lower two are connected, but when the button is depressed the upper two connect instead. The central contact is mounted on a very fine leafspring, which actually moves less than a millimetre.

Microswitches like these can be used as crude forms of touch sensors, and for collision detectors on mobile robots.



Proximity sensor
A ring of light-emitting diodes (LEDs) projects a cone of infra-red light a few centimetres in length. If an object cuts that cone, a spot of light will fall on its surface, and the size of the spot will be proportional to the distance of the object from the cone's apex. A lens, mounted inside the ring of LEDs, focuses the reflected spot of light back onto an infra-red-sensitive cell (on the right of the diagram), which produces a voltage proportional to the light intensity and, therefore, to the size of the spot. Proximity sensors like these are used when robots have to handle very delicate objects.



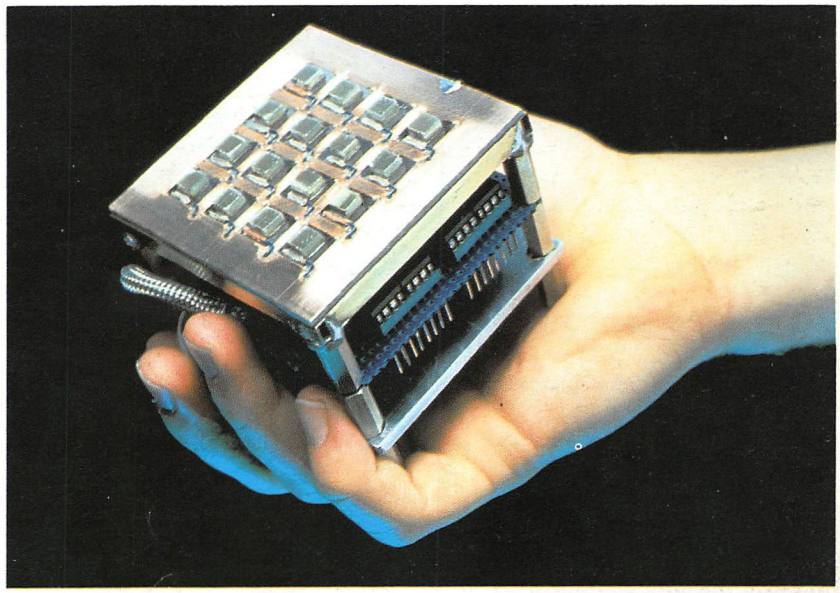


Strain gauge
This type of touch sensor outputs a voltage proportional to the force exerted by the fingers on the object. Even metal grippers flex slightly under stress, and strain gauges mounted on the fingers can measure that deflection. A strain gauge, shown on the right of the above diagram, is a zig-zagging track of resistive material printed on a plastic sheet and stuck firmly to the metal. Even a tiny amount of strain will increase the length of the track, and therefore change its electrical resistance.

being grasped are still experimental. By arranging a number of sensors in an array, it is possible to determine the overall shape of the object. Measuring the surface texture is more difficult. For relatively smooth surfaces, such as on a component turned in a lathe, the texture of the machined surface can be read by drawing a stylus (like a record-player needle) across it and recording the voltage patterns.

As well as the quasi-static applications of grasping an object, touch sensors could also be used for dynamic control. With touch sensors, a robot arm could follow the line of a car body very accurately and dispense a sealant solution along the joints. The same result could be achieved using robot vision, but at greater expense.

The most extreme example of dynamic control is the robot sheep shearer. Touch sensors mounted on the clipper head must detect the shape of the sheep – which, although strapped in a harness, will still be moving – and also stretch the skin to prevent folds from building up. The sheep shearer is one of the first examples of traditional skills and crafts being replaced by a robot.



Shape detector
This is an experimental touch sensor designed to detect not only the presence of an object, but also the approximate shape. It consists of a square array of conventional touch sensors, all connected into a microprocessor, which estimates the three-dimensional shape from the pattern of signals produced. The sensors themselves are piezo-electric cells, which produce a voltage proportional to the pressure applied.

SOUND

Few jobs rely on the sense of hearing: tuning pianos or car engines are the best examples of those that do. One car manufacturer actually uses a small robot arm, equipped with two microphones as its end effectors, to trace the noise sources in a test-bed engine.

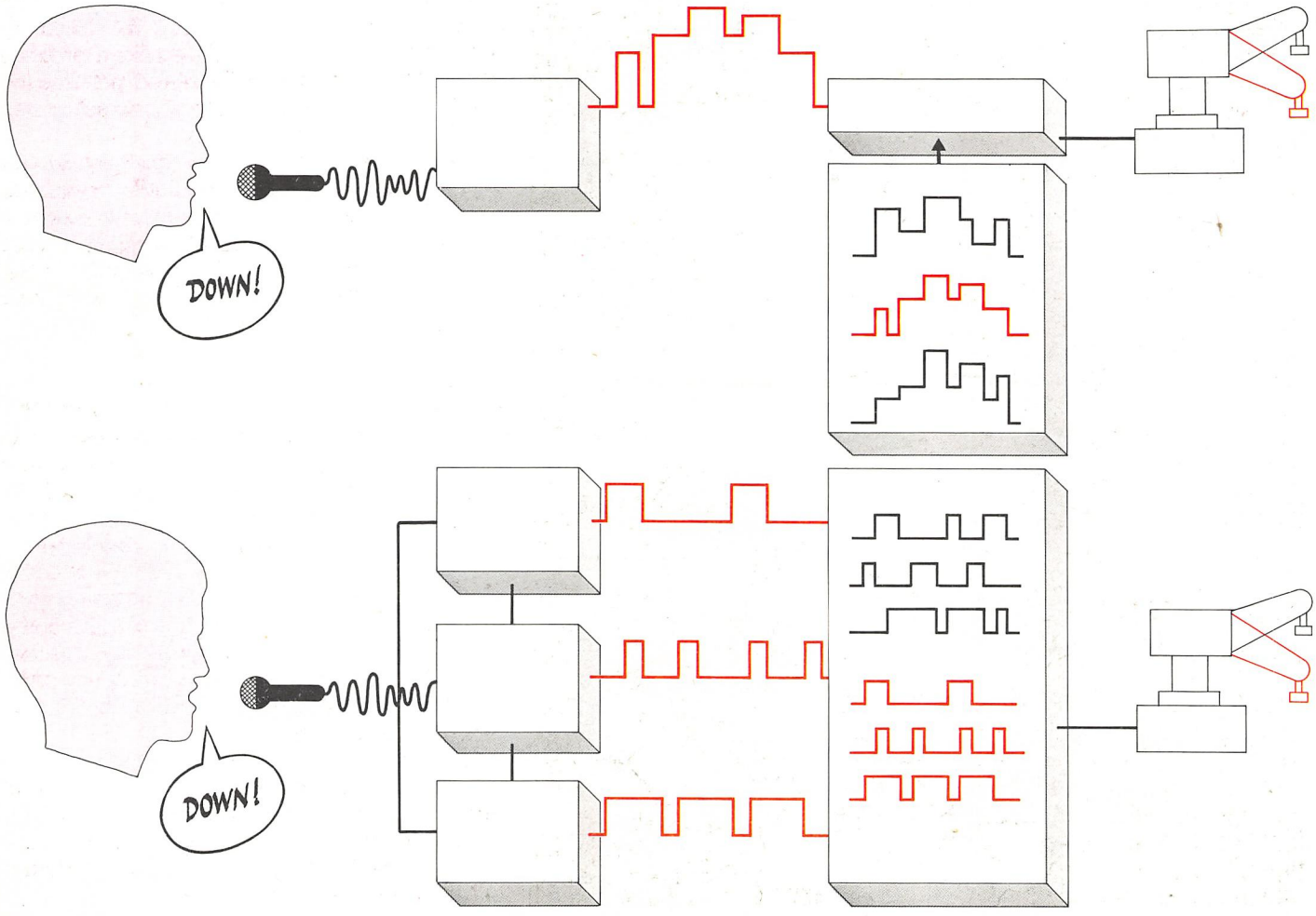
Speech recognition

The main incentive for equipping robots with 'ears' is to imitate another human capability – that of receiving instructions verbally. If a robot could be taught a procedure just by speaking to it, then almost anyone could program it for simple applications. Furthermore it would make feasible complex interactive applications in which a human and robot work alongside each other. The robot performs the heavy or repetitive tasks in an assembly, while the human uses his skills of perception and dexterity and prompts or instructs the robot verbally.

Inputting speech to a computer requires only a microphone – to translate the sound waves into electricity – and an analogue-to-digital converter circuit (see page 87) – to convert these continuous signals into the discrete lumps processed by a computer. The problem lies in interpreting the resulting patterns of data.

Most electronic speech-recognition systems operate under three major constraints. Firstly, they must be trained to the voice of only one particular operator (although this process takes just a few minutes). Secondly, words must be spoken with a small but definite gap in between them; very few systems can cope with normal continuous speech. The concept of the computerized typewriter that can accept dictation on a par with a good secretary is very appealing, but in reality the only prototypes to come close to this performance cost hundreds of thousands of pounds.

Thirdly, at any one time, most speech recognition systems can recognize only a small number of words, typically 64 or less – a rather limited vocabulary. The list of words the robot or computer is expecting, however, can be changed virtually instantaneously – usually by loading a new 'dictionary' from the computer's disks into its main memory. Thus, for example, after hearing 'wrist', the robot knows that the next word must relate to wrist movement, and can load into its memory a new list of expected words related to that subject.



Two different techniques of voice recognition by computer are shown here diagrammatically. The upper example requires less hardware, but is slower in operation. The sound signal from the microphone is converted into a binary pattern by an analogue-to-digital (A/D) converter. Stored in the computer's memory is a binary pattern for each allowable command. The processor looks for the closest match using the same techniques as visual pattern recognition (see pages 94-95).

In the lower example, hardware circuits extract features from the sound signal, including voiced sound, fricatives and silence. The processor compares these features with a list of similar features for each allowable command. This list is more compact than the full digitized signal and is therefore faster to scan.

Tomy (below) is a voice-controlled robot, yet is sold as an inexpensive toy. It can be trained to respond to eight spoken commands for moving and gripping with its arms.

Matching patterns of sound

The computer must then compare the received sound, converted to a pattern of data, with stored patterns in its memory. Using a matching procedure, it will assign a score to each of the words that this pattern could possibly be, according to how sure it is of a match. The word with the highest score is printed on the screen, giving the operator the chance to correct it if necessary. The best speech recognition systems achieve a correct match on 99 per cent of the words spoken.

An alternative to performing the entire pattern-matching exercise in software is to use dedicated electronic hardware to extract some characteristic properties from each spoken word. At the simplest level, speech can be broken up into three components. Voiced sounds, such as the vowels, originate in the throat. Fricatives, like s, t, f and c, are produced at the front of the mouth. The third type of sound is a short period of silence between syllables. These features can be extracted electronically using sound filters, which work in a similar manner to the bass and treble controls on a hi-fi system. By identifying the key features in this way, each word can be described (i.e. stored in memory) in a much more succinct form. The computer then has to do much less processing when it compares the spoken word with each of the entries in its limited dictionary.

Aural image processing

The techniques of pattern recognition for sound waves are broadly similar to those used in two-dimensional visual image processing (see pages 94–95). A spoken word can be displayed on a video screen in the form of a sonogram – a complex-looking pattern of waves that records how the volume of the sound varies over the duration of the word. In theory, the incoming sonogram could simply be placed like a template or a tracing over each of the stored patterns (all this happening electronically of course) to see which has the greatest overlap.

The problem is that even a single speaker can never produce one word identically twice. The word may be spoken slightly faster, or louder or at a different note. So the speech recognizer must identify and match up the key features of the sonograms, rather than simply look at areas that overlap.

Equipment

Professional speech recognition equipment costs thousands of pounds, but it is now possible to purchase versions that are considerably less powerful for home computers for less than £100. You can even experiment with building your own; a microphone linked to an analogue-to-digital converter is the only hardware needed. But you will need to be a very competent programmer. A program written in BASIC could take hours to recognize a single word, so the only effective solution is to use machine code, which is considerably faster in operation but more difficult to write.

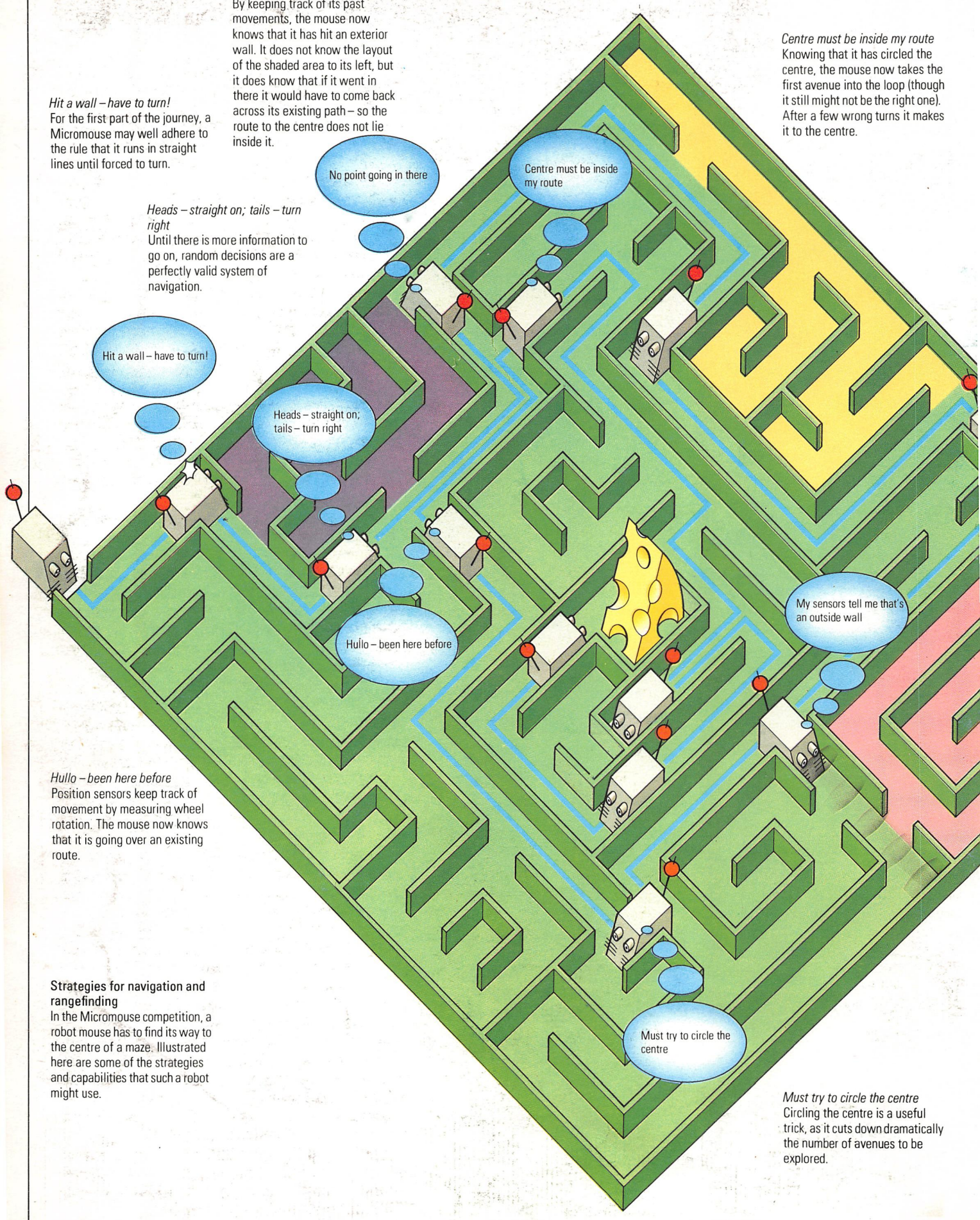
Speech recognition systems that can recognize any speaker and words spoken in continuous sentences and that possess a dictionary containing all the words used in normal conversation are still some years off. But there is now no doubt among researchers that they will happen.

Hit a wall – have to turn!
For the first part of the journey, a Micromouse may well adhere to the rule that it runs in straight lines until forced to turn.

No point going in there
By keeping track of its past movements, the mouse now knows that it has hit an exterior wall. It does not know the layout of the shaded area to its left, but it does know that if it went in there it would have to come back across its existing path – so the route to the centre does not lie inside it.

Heads – straight on; tails – turn right
Until there is more information to go on, random decisions are a perfectly valid system of navigation.

Centre must be inside my route
Knowing that it has circled the centre, the mouse now takes the first avenue into the loop (though it still might not be the right one). After a few wrong turns it makes it to the centre.



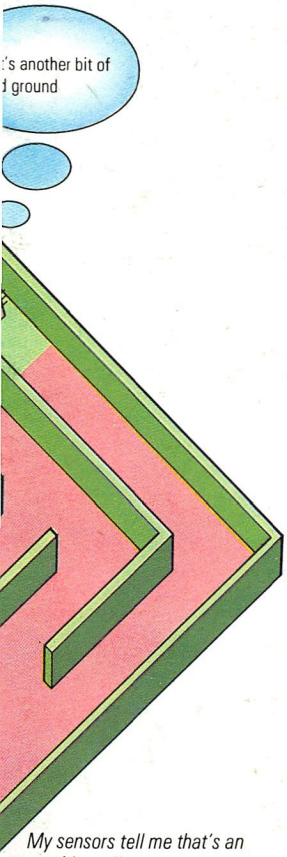
Hullo – been here before
Position sensors keep track of movement by measuring wheel rotation. The mouse now knows that it is going over an existing route.

Strategies for navigation and rangefinding
In the Micromouse competition, a robot mouse has to find its way to the centre of a maze. Illustrated here are some of the strategies and capabilities that such a robot might use.

Must try to circle the centre
Circling the centre is a useful trick, as it cuts down dramatically the number of avenues to be explored.

NAVIGATION AND RANGEFINDING

That's another bit of dead ground
Again, the mouse calculates that it is beside an exterior wall, and is able to write off the shaded (yellow) area behind it. Use of techniques like these speeds up the search.



My sensors tell me that's an outside wall
If the mouse is equipped with rangefinding sensors (such as ultrasonic sonar) it can measure how far a passage runs without traversing it.

For a mobile robot to navigate its way through a series of obstacles effectively, it needs another 'sense'. It must be able to detect objects at a distance, not just when it makes contact with them. This ability is called rangefinding.

Humans rely on two systems for identifying our position relative to the environment. The first is stereoscopic vision. Presented with a left and a right image, the brain must identify which parts of one correspond to the other – even if it doesn't necessarily recognize the object itself. From the relative position of each object against the background in the two images, the range can be inferred. The range of nearby items can be calculated from the angle at which the eyes must converge to focus on them, but this is not the way that stereoscopic vision generally works.

Optical rangefinders based on the angle of convergence method can be constructed, but are rather too delicate for use on most robots. Attempts to model the brain's system of stereoscopic vision on a computer are still experimental, but could be in commercial use within a couple of years. In the meantime, robot engineers must employ other methods, such as acoustics.

In fact humans also rely on acoustic rangefinding to confirm the evidence of the eyes. Most environments are full of ambient noise such as footfalls or conversation, and the brain is constantly reading the reflected sound from walls and floors. That is why many people experience temporary disorientation when they enter a sound-deadened room such as a recording studio or an anechoic chamber. By using amplification for a training period, some blind children have learnt to use sound as an effective means of navigation, to the point where they can detect an open door or a staircase from several feet.

On a robot, audible sound is generally replaced by ultrasonics (sound with a frequency well above the audible spectrum), because such a system is less susceptible to interference from extraneous noise. The robot emits a short ultrasonic burst at regular intervals and can calculate the range of the nearest object from the delay in the returned echo. The ultrasonic transmitter and receivers, sometimes comprising the same unit, may be mounted on the front of the robot or on a rotating head unit to perform a 360-degree sweep.

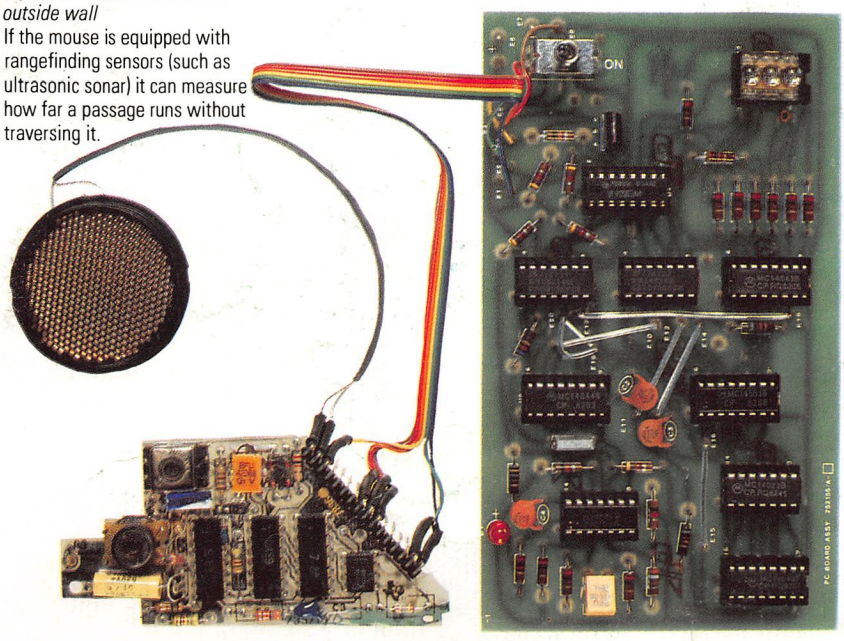
The main alternative to ultrasonics is low-powered microwave radar, which works on a radio wavelength of just a few centimetres. In addition to rangefinding, this can also be used to measure relative movement the speed of approaching objects or the speed of the robot relative to stationary obstacles. This facility is particularly useful in avoiding collisions between multiple mobile robots.

Movement detection relies on the Doppler effect; a wave reflected from a moving object will return at a higher frequency if the object is moving towards the detector, and a lower one if it is moving away. This is why the sound made, for instance, by an approaching ambulance siren is different from that of a receding one. The change in frequency is proportional to the relative velocity of the two objects.

Once rangefinding has been solved, navigation becomes a computational problem. The onboard computer has to compare the readings from the sensors with its own internal map; this is how a cruise missile functions. Alternatively, the robot may be programmed to explore the environment and to build up its own map in memory. The robot will need to keep a very accurate record of its movements, and all the time it will be calculating the optimum routes between key points in the environment for future reference. A really sophisticated system will make educated guesses at what is behind some of the larger obstacles and will avoid exploring unnecessary areas.

Some of the most interesting experiments with navigation algorithms can be seen in the Micromouse competition. Entrants have to construct a self-contained robot mouse, with its own power supply and onboard computer, that can find its way to the centre of an unknown maze.

Ultrasonic sonar is one of the most common means by which robots measure the distance to obstacles. The system shown here was developed by Polaroid for their auto-focus cameras, but it is used on many robots. The transducer (gold colour) emits a short click. The sound waves hit the obstacle, and when the echo returns the transducer sends a signal back to the control board, which measures the time delay. A processing board calculates the actual distance from this time delay, and then displays it as a number, or passes the information to the robot's computer, which then instructs the robot where to move to.



VISION

To most people, sight is their most cherished sense, even though there are others that we might find it harder to function without. Few robots possess the sense of sight, and that is partly why their current range of applications is so limited.

Light cells

As with sound, converting a light image into a form that can be processed by computer is simple. A light-sensitive cell produces electrical signals in response to light. Active cells generate electricity – and are used to provide power, for example, for space satellites. Robot light sensors are passive; electrical power has to be supplied to them, but the intensity of light governs the size of the current passing through them. These light-sensitive resistors have many applications outside robotics, such as in the light meters built into modern cameras.

Single light cells are often mounted on the front of educational floor robots so that they can be programmed to follow a line or seek out a light source. Very cheap vision systems have been constructed by amateurs, by mounting a sensor at the end of the tube, and scanning this tube horizontally and vertically using servo motors. The process is slow and inaccurate, but an entire image can nevertheless be built up in the computer's memory.

Cameras

For serious applications, a complete image must be captured at one go. One solution is to use a conventional television camera, with a special interface to convert the output signals into a digital pattern that can be stored in the computer. These interfaces have been used extensively in industry, but can also be purchased to work with home computers.

The charge-coupled device, or CCD camera, achieves the same result in one stage and is therefore faster and cheaper. A CCD is a miniature array of light-sensitive cells integrated onto a crystal of silicon less than a centimetre square. If the visual image, properly lit, is reduced and focused onto the surface of this special kind of integrated circuit (chip), the result will be an electronic pattern of 1s and 0s, corresponding to the light and dark parts of the image. CCD arrays can break the image down into as many as 512×512 picture cells (called pixels), yet the whole camera may be no bigger than a matchbox.

A CCD array looks like a conventional integrated circuit with the top removed. Interestingly, it has been discovered that if the top is removed from early types of dynamic RAM chip (used for memory in some home computers), they behave similarly to a CCD array, although with less precision and reliability. A dynamic RAM chip stores information as a series of tiny electrical charges, and light falling onto the surface causes the charges to leak away. Initially, all the locations are charged to the voltage corresponding to a 1, and the light areas will change to 0 as the image is exposed. Low-cost vision systems for educational robots consist of little more than a dynamic RAM chip with a lens in front and a simple interface to a home computer.

Grey levels

A system that classifies an image merely into areas of black and white is called a two grey-level system. The threshold is the dividing line; any part of the image darker than the threshold will be read as black and lighter ones as white. Changing the length of time for which the image is exposed to the camera has the effect of altering the threshold, and it is important to choose a threshold that best distinguishes the objects to be viewed from their backgrounds.

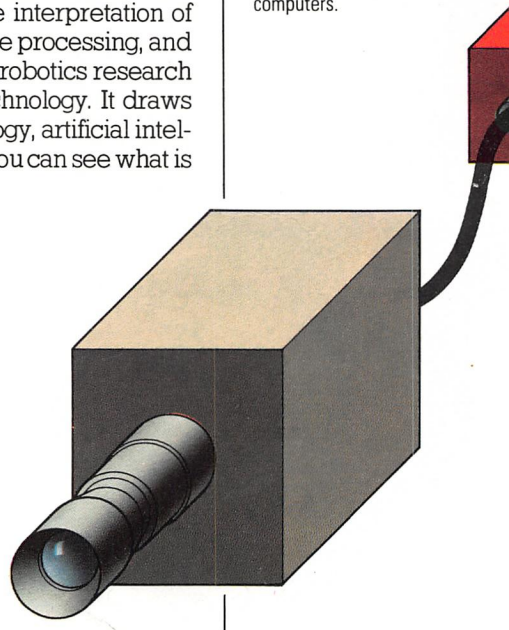
More sophisticated systems classify an image into four, eight or even up to 256 different grey levels; the last is practically indistinguishable from a conventional black-and-white television picture. The number of grey levels is one of the main specifications of a robot vision system, together with the resolution – the number of points into which the image is divided, such as 256×256. For applications in which the robot is identifying shapes against a background, two grey-levels will suffice; more are needed when it comes to recognizing solid, three-dimensional objects.

As with speech recognition, the difficulty with giving sight to robots lies in the interpretation of what is seen. This is called image processing, and is probably the subject of more robotics research than any other aspect of the technology. It draws on the fields of biology, psychology, artificial intelligence and mathematics, and you can see what is involved on pages 94–95.

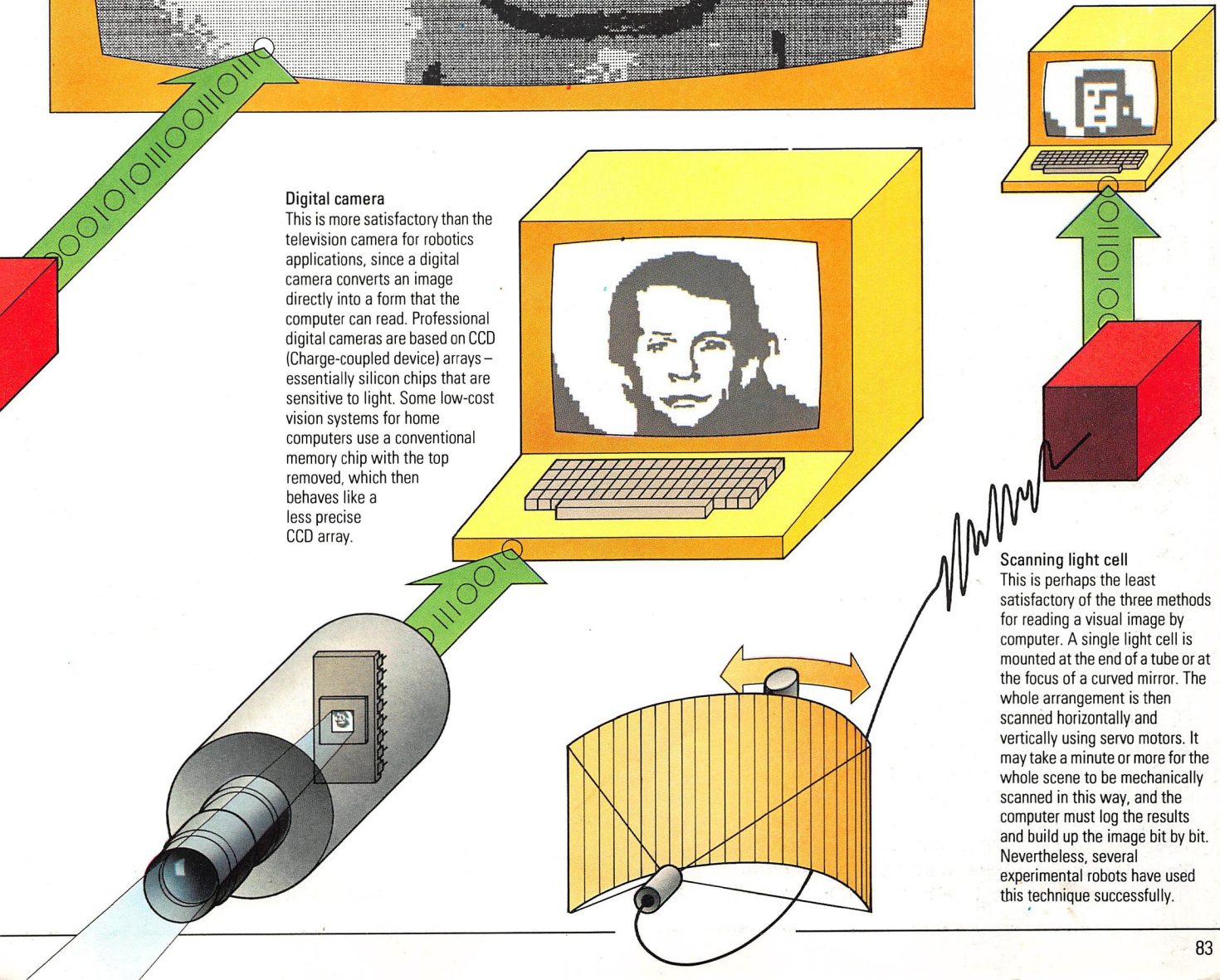
Electronic eyes
For a robot to be able to see, it requires some system for converting a light image into a pattern of 1s and 0s that it can store in its memory. Shown here are three of the most popular methods.

However, converting the image into electronic form is an easy exercise compared with interpreting what is seen. This subject is dealt with on pages 94-95.

Television camera
A conventional black-and-white television camera converts an image into electrical signals in analogue form (see page 87). For a computer to process the image, the analogue signal must be digitized and stored as a pattern of binary 1s an 0s in a block of the computer's memory. The computer can then display this information on its own screen, or process the data to determine the nature of the object in view. Television-camera interfaces can be purchased for many home computers.



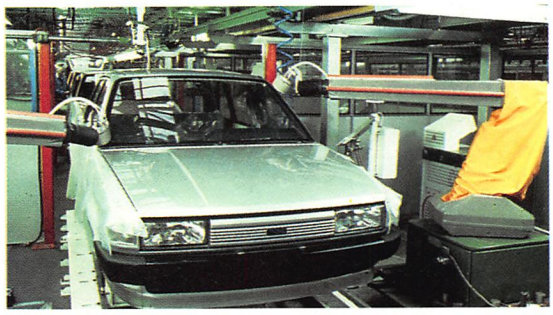
Shady character
These pictures of the author were produced with a conventional television camera interfaced with a home computer and a dot-matrix printer. The left-hand picture shows four grey levels, but the same system can work to two or eight shades. If the computer's output is connected to a colour monitor, each grey level will be displayed as a different, but quite arbitrary colour. This has little value except that the levels are easier to distinguish. The above image shows seven grey shades as white, yellow, cyan, green, pink, red and blue.



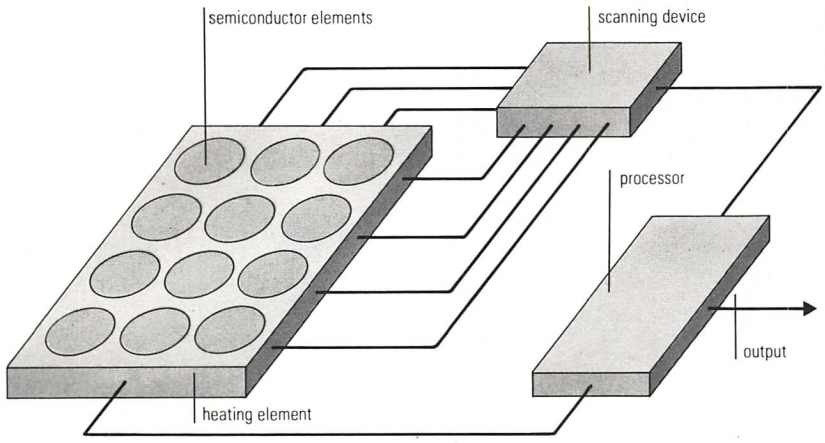
Digital camera
This is more satisfactory than the television camera for robotics applications, since a digital camera converts an image directly into a form that the computer can read. Professional digital cameras are based on CCD (Charge-coupled device) arrays – essentially silicon chips that are sensitive to light. Some low-cost vision systems for home computers use a conventional memory chip with the top removed, which then behaves like a less precise CCD array.

Scanning light cell
This is perhaps the least satisfactory of the three methods for reading a visual image by computer. A single light cell is mounted at the end of a tube or at the focus of a curved mirror. The whole arrangement is then scanned horizontally and vertically using servo motors. It may take a minute or more for the whole scene to be mechanically scanned in this way, and the computer must log the results and build up the image bit by bit. Nevertheless, several experimental robots have used this technique successfully.

SMELL AND TASTE



On a car production line the chassis is filled with an inert gas and 'sniffer' robots search for leaks, indicating a bad weld.



The most sophisticated robot noses (above) can detect half-a-dozen different gases. An array of semiconductor elements is mounted on a heating element – the conductivity of each element varies with the gas concentrations present. The processor reads the elements through a scanning device, and solves a set of simultaneous equations to work out which gas is present.

Of all man's senses (and incidentally we have many more than five if you count pain, temperature, balance and position), smell and taste are the least understood. It is difficult to pinpoint the difference between the two even in animals, but the generally accepted definition is that smell (properly: olfaction) detects airborne particles of the smelt substance, while taste (gustation) is restricted to physical contact with the substance or a solution of it. These senses have been the last to have been added to a robot, perhaps because our knowledge is so limited but also because there is less application – in commercial terms.

It is known that smell and taste depend on chemical reactions; only volatile substances – those in which molecules can escape into the atmosphere – give off scent. Chemoreceptors in the appropriate sense organs react with these chemicals and send nerve impulses back to the brain, but the nature of the reaction is not understood. Surprisingly, there seems to be little correlation between the structure of the molecules and their odour.

Smell in humans and animals is an extremely sensitive function and can, as well, result in the most vivid of reactions. Human beings can distinguish some four thousand scents, but it is not known whether these are independent reactions, or whether there are only, say, ten basic odours mixed in different proportions. Some experimenters have claimed to be able to reproduce any taste using just four components – sodium chloride, sucrose, oxalic acid and quinine hydrochloride – in different proportions, to simulate the four basic tastes of salt, sweet, sour and bitter.

Because we haven't yet mastered the technique of creating artificial sense organs from living cells (and this may anyway be seen as undesirable from a moral viewpoint) a robot nose would have to be constructed using solid-state electronics. In other words, we are restricted to silicon-based rather than carbon-based technology. Luckily, some semiconductor materials react to the presence of a range of combustible gases (hydrogen, methane and so on), provided that they are maintained at a high temperature by a heating element.

Applications

Fortunately, the detection of unwanted combustible gases is one of the prime uses for a robot nose, in an industrial environment. Devices sensitive to concentrations expressed in parts per million have already been achieved, and while this is still crude compared with the human smell function, these devices can perform a useful task.

The detection of scents – odours with very weak concentrations – is still only experimental. One company in the USA is trying to develop a sentry robot for patrolling state penitentiaries. The promised specification includes an olfactory sensor capable of detecting the scent left behind by human beings – a very faint trace of ammonia.

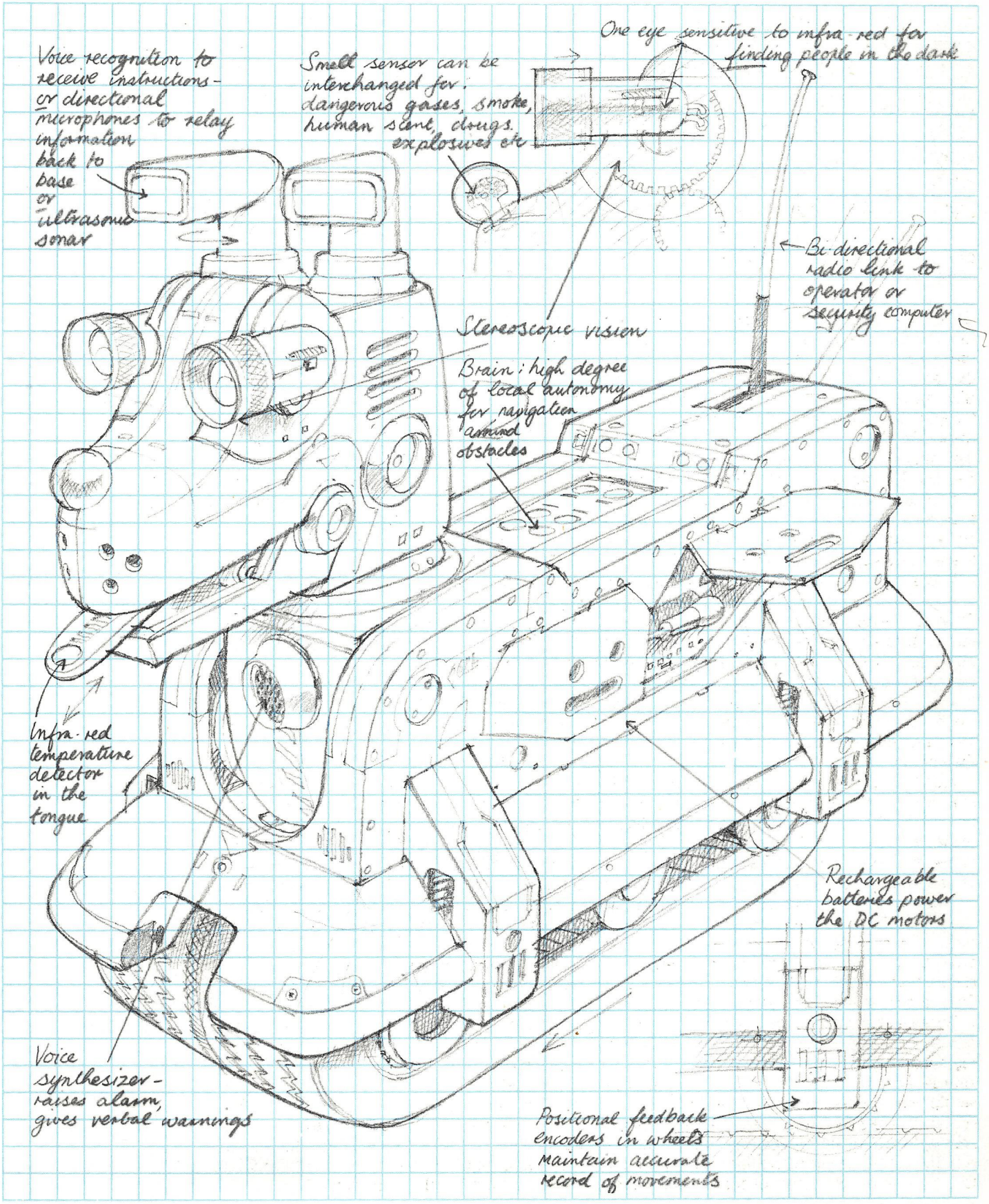
For a moment, sentry robots must rely on other sensors, some of them related to smell. Firefighting is a more immediate application than policing, and one that would be applicable to industrial and domestic markets. A patrolling robot could detect fire by a number of means, and it would probably require confirmation from at least two independent sources of detection before taking action such as applying onboard fire extinguishers or sounding an alarm by remote control.

Ways of detecting fire could include a thermistor, a solid-state electronic device for measuring temperature, or an infra-red camera that can see heat at a distance just as a television camera measures light. Flames are an abundant source of charged particles and these can be detected, as can smoke particles that interrupt a beam of light passing from a light source to a light cell.

But should the robot nose ever acquire the sensitivity and range of the human organ, the possible applications are virtually limitless. Robots are used in the food industry, so why not for testing the taste and smell of the finished goods instead of just the appearance? Could we even end up with robot winetasters?

Senses for robots
This blueprint for the robot tracker dog of the future incorporates not only a sophisticated sense of smell, but also most of the other types of existing robot sensor. Coupled with a powerful onboard computer, this gives the robot dog a high degree of autonomy; it is well able to cope, on its own, with different environments and complex applications.

This robot does not exist as yet, but an autonomous sensing device like it is certainly a possibility. Several companies are developing robot sentries for use by the military, and for such applications as prison patrol.



COMPUTER FUNDAMENTALS

The computer is the ideal means for controlling the operation of a robot; it is the electronic 'brain' that co-ordinates the mechanical body. It can handle information coming from several sources at once – from the operator's keyboard and from each of the sensors. It can process information at a very fast rate in comparison with the robot's movements, and it can drive several outputs simultaneously, corresponding to the robot's joints. It is also very easy to modify or exchange the program used by the computer to process the information whenever a new application is needed.

Some industrial robots can be driven by the same computer that a firm uses for its accounts department, but most now come with their own dedicated computer. The principles of operation, however, are the same for all computers – including low-cost home micros that can be used for robotics experiments.

All information inside a computer is handled as groups of 'bits'. A bit is a binary digit and can take on only two different values: 1 or 0. Any value can be represented as a group of bits using the binary system, which works to base 2 instead of our normal (decimal) base of 10. The table shows some binary values. Binary numbers can be added and multiplied very easily by a computer.

Eight bits make one byte, and 1024 bytes equals one kilobyte or Kbyte. 1024 is a convenient number to express in binary form: it is 2^{10}. A 64-Kbyte micro therefore has 65,536 (1024×64) bytes of memory – and this is a measure of the sophistication of the programs it can run.

Computer system
The components of a computer system are essentially the same, whether the computer is a £1000 micro or a million-dollar mainframe. Shown right is a typical home computer with its casing and keyboard removed.

PCB (printed circuit board)
The PCB is simply a stiff piece of card, drilled with tiny holes into which the 'legs' or pins of the 'chips' (properly called integrated circuits) and other components are inserted. The board is printed with copper tracks, which provide the interconnections between the components. A larger computer may contain several PCBs slotted into a rack.

CPU (central processing unit)
This microprocessor (or chip) is the heart of the computer. The Z80 and the 6502 are the names of the two most popular CPUs in home computers. The CPU executes the program that has been typed in. It performs all the maths and logical manipulation, but it cannot store any information.

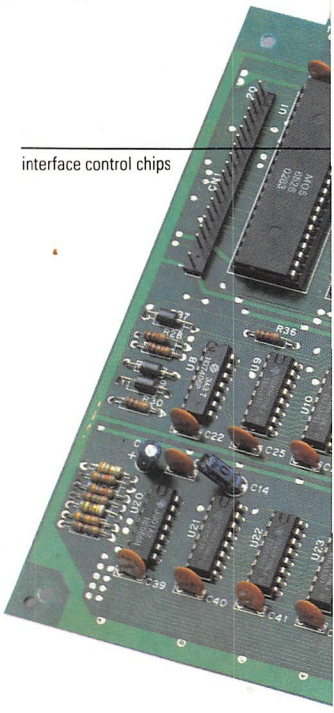
RAM (random access memory)
RAM is the part of the computer's memory where the program and all the data that the CPU needs to have available to run that program are stored. The CPU can read a value from a part of the RAM, alter it and store it back again. The more RAM a system has, the more sophisticated the programs it can run. There are usually several RAM chips in each computer.

ROM (read only memory)
ROM, like RAM, is computer memory in chip form, but its contents have been fixed by th manufacturer. Unlike RAM, the contents of ROM are not lost when the computer is switched off. The CPU can read the values stored in ROM, but can't alter them – hence the name. ROM is therefore used to store data and programs that are always needed by the CPU.

Power socket
Any significant variation in the voltage supplied to the computer would result in errors. Circuits are therefore always included to 'smooth' the power supply, and to convert the mains voltage to the level required by the chips.

Interfaces
The interfaces permit a computer to be linked with other devices. These may be computer peripherals, as listed opposite, or robot devices like those shown overleaf. Interfaces are often simply protrusions from the edge of the PCB, although they may be wired up to different-shaped connectors on the casing.

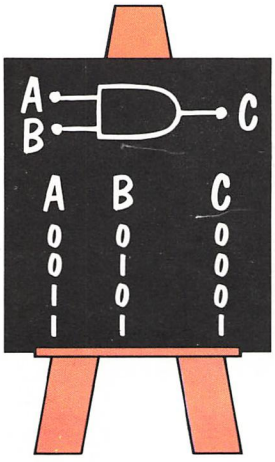
Interface chips
A computer will typically contain several dedicated interface chips. Each one looks after the connection between the computer board and one type of device. There will be a keyboard controller and a video controller for the screen. On some machines there will be an analogue-to-digital converter chip, which is especially useful in robotics.



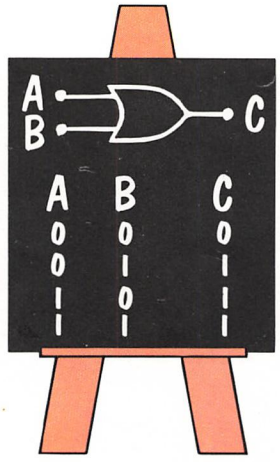
Decimal Value	*Binary Value*
0	0
1	1
2	10
3	11
4	100
5	101
6	110
7	111
8	1000
9	1001
10	1010

Logical thought
Modern computers and robot controllers work in binary – every value is broken down into strings of 1s and 0s. Individual binary digits (called bits) are manipulated using logic gates, which have one or two inputs and one output. Four types of logic gate are shown on the right.

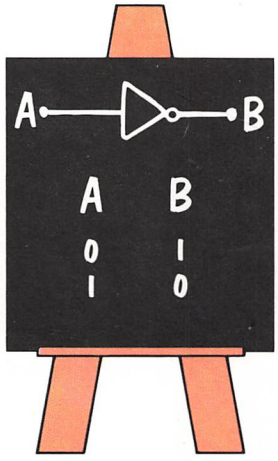
The blackboard above specifies the operation of the gate in a truth table – showing what value the output will take for each possible combination of inputs. Below is the symbol for each gate used by circuit designers. It is possible to build an entire computer using enough of these gates as building blocks.



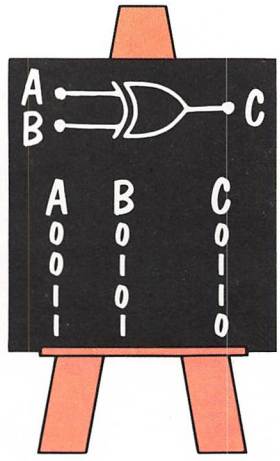
The AND gate
The output line (C) is 1 only when both inputs, A and B are at 1, otherwise C will be 0.



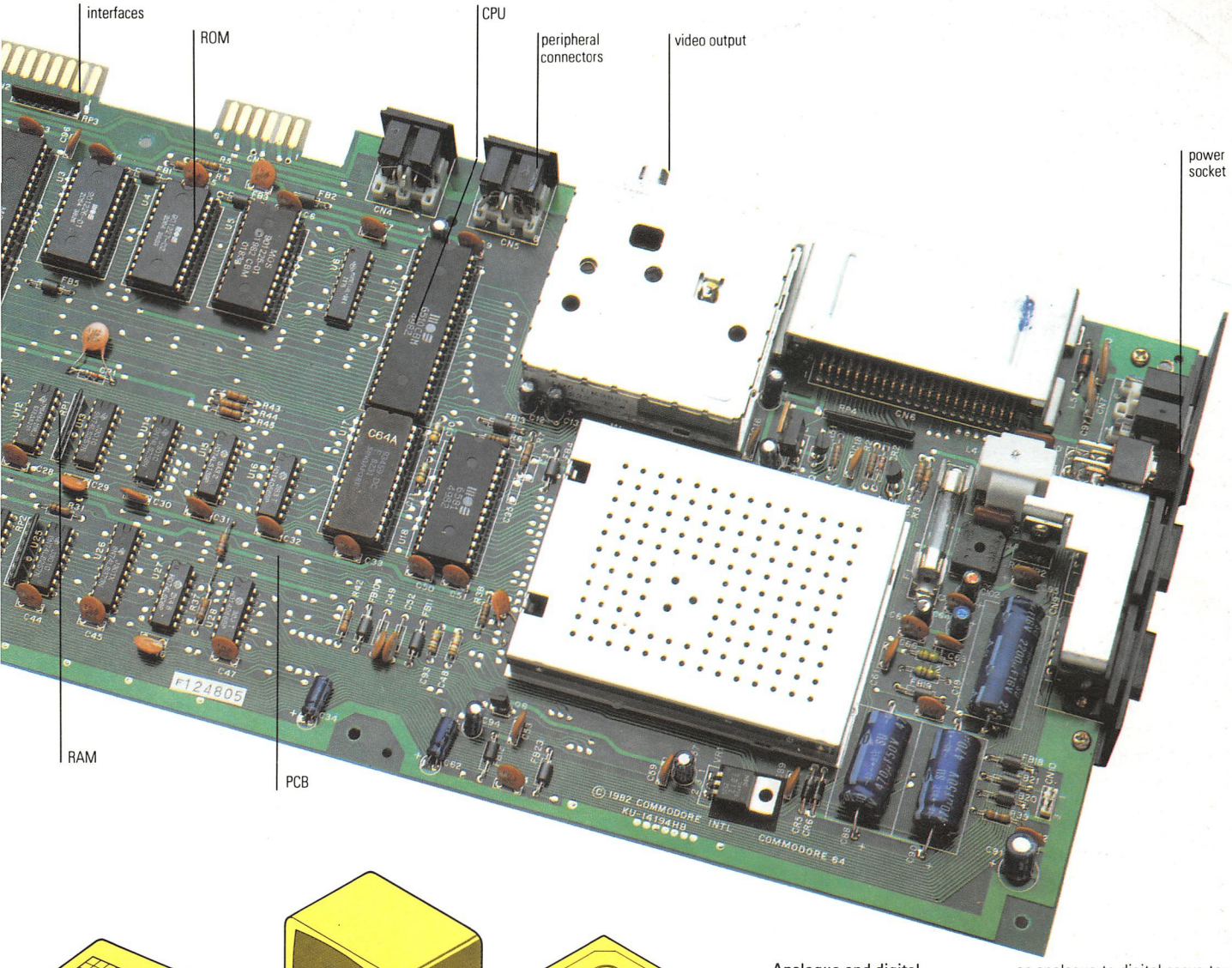
The OR gate
The output (C) is 1 when either input, A or B, is 1. If both inputs are zero, C will be 0.

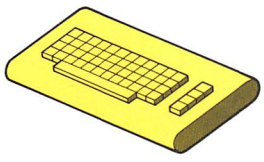


The NOT gate
Also called an invertor, because the output (B) is the inverse, or opposite, of the input (A).



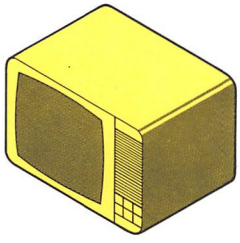
The exclusive-OR gate
C is 1 if either A or B is 1, but not if both A and B are 1. C is 0 if A and B have the same value.





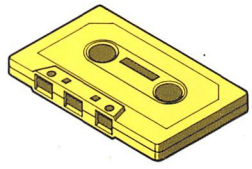
Keyboard

All computer keyboards follow the typewriter QWERTY layout. The programs for controlling the robot will be entered first via the keyboard. Some robots can be moved 'live', using the Q key to rotate the wrist, W to raise the forearm, and so on.



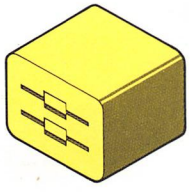
Screen

The screen is used to check the program as it is entered, and for the system to report any errors or messages such as 'JOB FINISHED' to the user. Home computers use a television set for the screen but dedicated robot systems use a purpose-designed monitor.



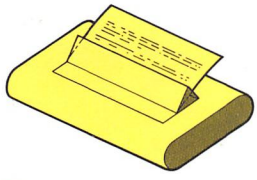
Cassette

Some means is needed to store the control programs even when the computer is switched off. Many home computers use a domestic cassette recorder. Some dedicated robot computers use a microcassette similar to those used in dictation machines.



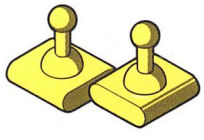
Disk drive

As an alternative to cassette storage, the disk drive is faster, more reliable and can store more programs, but is more expensive. The disk is a circular piece of plastic, covered in magnetic material, which is rotated at speed by the drive.



Printer

A means for printing information from the screen onto paper is useful for checking programs while away from the computer and for providing a permanent record of what the robot has done. The characters are usually made up from tiny dots of ink.



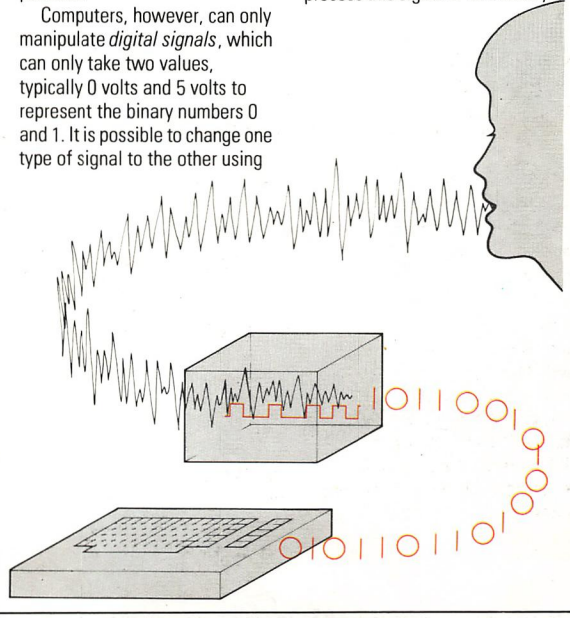
Joysticks

Although mainly used for playing action games on home computers, the joystick provides a convenient way of moving the robot's limbs. Small joysticks are frequently built into the teach pendants of industrial robots for this purpose.

Analogue and digital

Most electrical signals, for example the output from a microphone and from many robot sensors, are *analogue signals*. They can vary continuously between two limits, and may take on very complex shapes and patterns.

Computers, however, can only manipulate *digital signals*, which can only take two values, typically 0 volts and 5 volts to represent the binary numbers 0 and 1. It is possible to change one type of signal to the other using an analogue-to-digital converter (ADC). The process is called 'digitizing the signal', and the pattern is of 1s and 0s coming out of the ADC below represents the way in which the waveform coming into it is changing. The computer can then store or process this signal in its memory.



INTERFACING ROBOT DEVICES

Interfaces enable a computer to communicate with other devices, including computer peripherals such as disks and printers, other computers, through a telephone link-up, and robots and their sensors. All computers, from large mainframes to cheap microcomputers, have interfaces.

Interfaces are also called ports, because in effect they are 'holes' in the computer through which information flows. On a microcomputer, the interfaces actually are holes – in the back or the underside of the plastic casing, with electrical connectors protruding through them.

Three factors specify a type of interface: the size and shape of the plugs and sockets used (including the number of pins on the plug), the electrical voltage or current employed and the format in which the data is to be sent over the wires. There are over a dozen types of interface found on microcomputers alone, each one designed for a different purpose, and having names like IEEE-488, RS 232, S-100, serial, parallel and centronics.

Two devices can exchange data only if they have the same type of interface. There is a great diversity of physical connectors; this is to avoid damage by plugging a device into the wrong port. Microcomputers with a large range of interfaces are better for robotics experimentation.

Connecting cables

There are different kinds of cable for connecting robots to computers, too. Ribbon cable (shown opposite) is flat, wide and flexible; it is a ribbon of up to fifteen wires stuck together, sometimes with each strand a different colour. However, ribbon cable would not stand up to the rigours of an industrial environment, nor could it carry the higher electrical current needed to drive large manipulators. Conventional round-section cable is used, with extra protective sheaths.

For similar reasons, the connectors on a dedicated robot computer will be larger and heavier. The fundamental principles on which the interfaces operate, however, will be the same as in many micro interfaces.

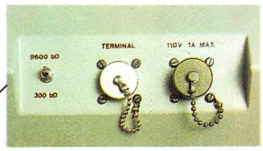
Most interfaces are either parallel or serial. On the former type, several bits of data (commonly, eight) will be sent simultaneously across several wires running in parallel. In serial transmission, the bits must be sent one after the other down a single wire. Parallel transmission is faster, but serial is more suitable for connections over long distances.

Ports

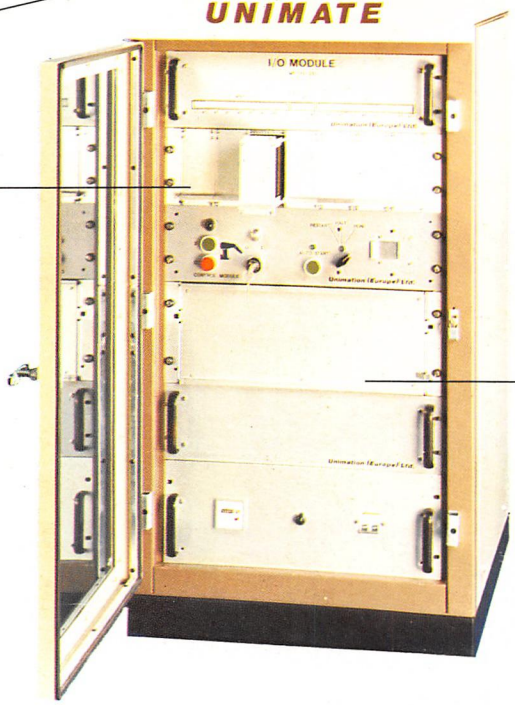
A sophisticated microcomputer may feature up to a dozen interfaces – normally called 'ports' – each having a different application to robotics. Analogue sensors, such as the light sensor on a floor robot (orange), must be connected to an analogue input port. A vision system usually comprises a small camera and a control box (blue), which plug into the memory expansion port. The digitized image appears to the computer as data in an extra section of RAM memory. Most small robot arms (red) plug into the computer's user port, called a parallel port because the data is sent, eight bits at a time, down eight parallel wires. A speech synthesizer connected to an external speaker (yellow) will plug into the micro's printer port and will pronounce words instead of printing them on paper. The simplest way to interface home-built robots (green) is by means of a relay unit plugged into the cartridge port. Motors can then be turned on or off from the keyboard.

The 'operator interface' – the means by which he instructs the computer – is a standard terminal, with keyboard and screen.

Emergency stop button. Cuts the power instantly, and activates the brakes on all joints.

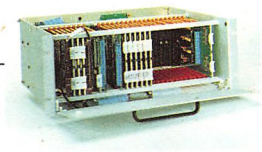


Heavy duty connectors are used on all ports, but the interfaces work on the same principles as home computers.



The Input/Output (I/O) module, interfaces the computer with other robots or automation equipment, using relays. A line of lights on the front, displays the status of each input and output line.

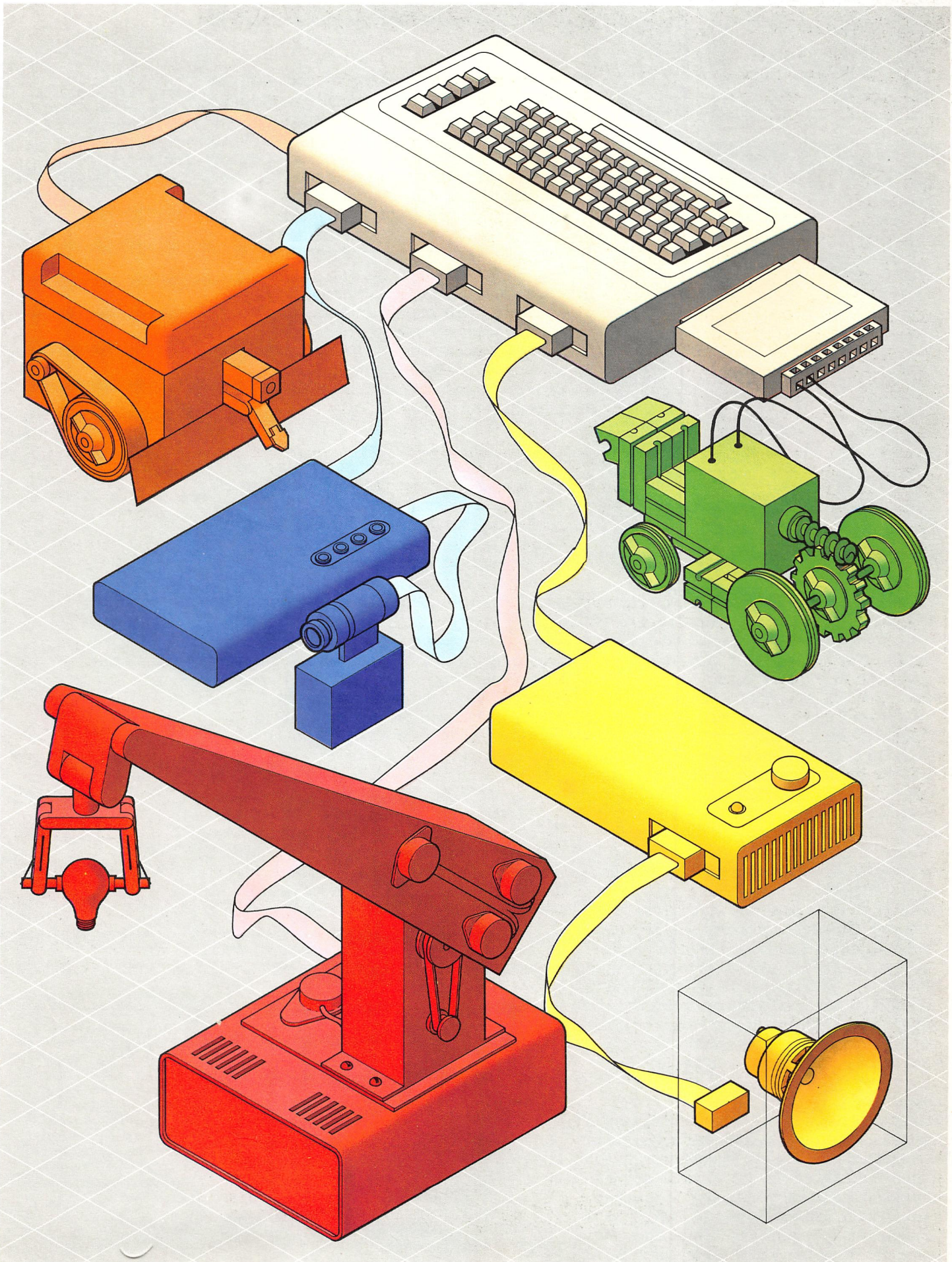
These modules interface with the servo motors – one for every degree of freedom on the arm.



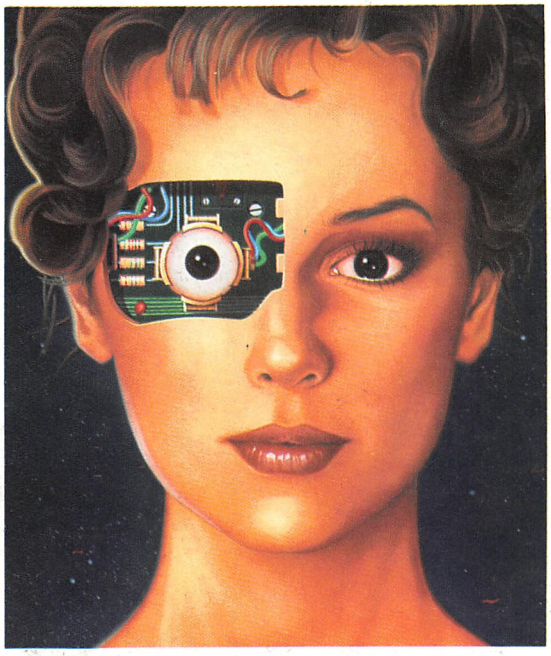
The control module contains the CPU and RAM memory – 16 Kbytes on this machine. An interpreter, stored in ROM, allows the arm to be programmed in a special robot programming language.

Complete control

The control computers of many industrial robots are designed around a racking system, similar to top-quality hi-fi units (left). Modules to control joints, monitor sensors, or interpret the program of instructions, slide in and out of a main casing. This makes maintenance easier, and the manufacturer can tailor the computer to the specific needs of a customer. Because industrial robots are more powerful than educational ones, the computer has to control large electrical currents. The modules employ heavier-duty components than a microcomputer, but the principles of the interfaces are the same as those shown opposite.



ARTIFICIAL INTELLIGENCE



Artificial intelligence (AI) describes an attribute of machines that mimic what we choose to call intelligent behaviour in man and other higher animals. To many people, a thinking machine is a contradiction, and the AI community has always functioned in the face of public scepticism.

AI research may seem rather theoretical, but it is highly relevant to robotics, and the two disciplines are often grouped together. For although there are still many mechanical problems, particularly in locomotion systems and end effectors, the main limitation on robot usage in both industry and home is the robot's lack of intelligence.

AI is a diverse subject, and this is reflected by the spectrum of intelligent effects that researchers are attempting to mimic. There is no unifying theory or strategy, and indeed there are fierce arguments between proponents of AI regarding the best approach or solution to each problem. The results obtained are still crude compared with human intelligence, or robot behaviour described in science fiction for that matter, but they do give a foretaste of what robots might be like in a few decades' time. So we'll now look at some of the chief areas of development.

Language

Because language seems to be fundamental to human intelligence, giving computers the ability to communicate in natural language has a high priority. HAL from *2001*, the best known intelligent computer in fiction, received all its instructions verbally and could engage its masters in companionable conversation. Generating electronic speech doesn't really come under the AI banner, you can buy a speech synthesizer for just a few pounds, and improvements in sound quality are dependent only on the technology available. Speech recognition by computer is more difficult (some of the techniques are described on page 78), but again it is more of a mathematical exercise than true AI. Experiments with natural-language processing, which is a true form of AI, are usually conducted via a keyboard and screen, although speech synthesis and recognition could easily be added.

Language has two facets: syntax, the rules governing the construction of sentences, and semantics, the meaning conveyed by sentences. English syntax is complex, but well understood, thanks particularly to the American linguist Noam Chomsky. Semantics is far more nebulous. Consider these two sentences:

'Time flies like an arrow.'

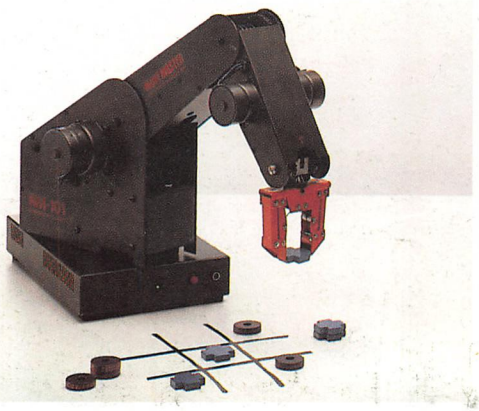
'Fruit flies like a banana.'

In the first, 'flies' is a verb, while in the second it is part of a noun phrase. We can discern this because we understand the subject matter. If computers are to handle natural language, they must be equipped with a similar knowledge base.

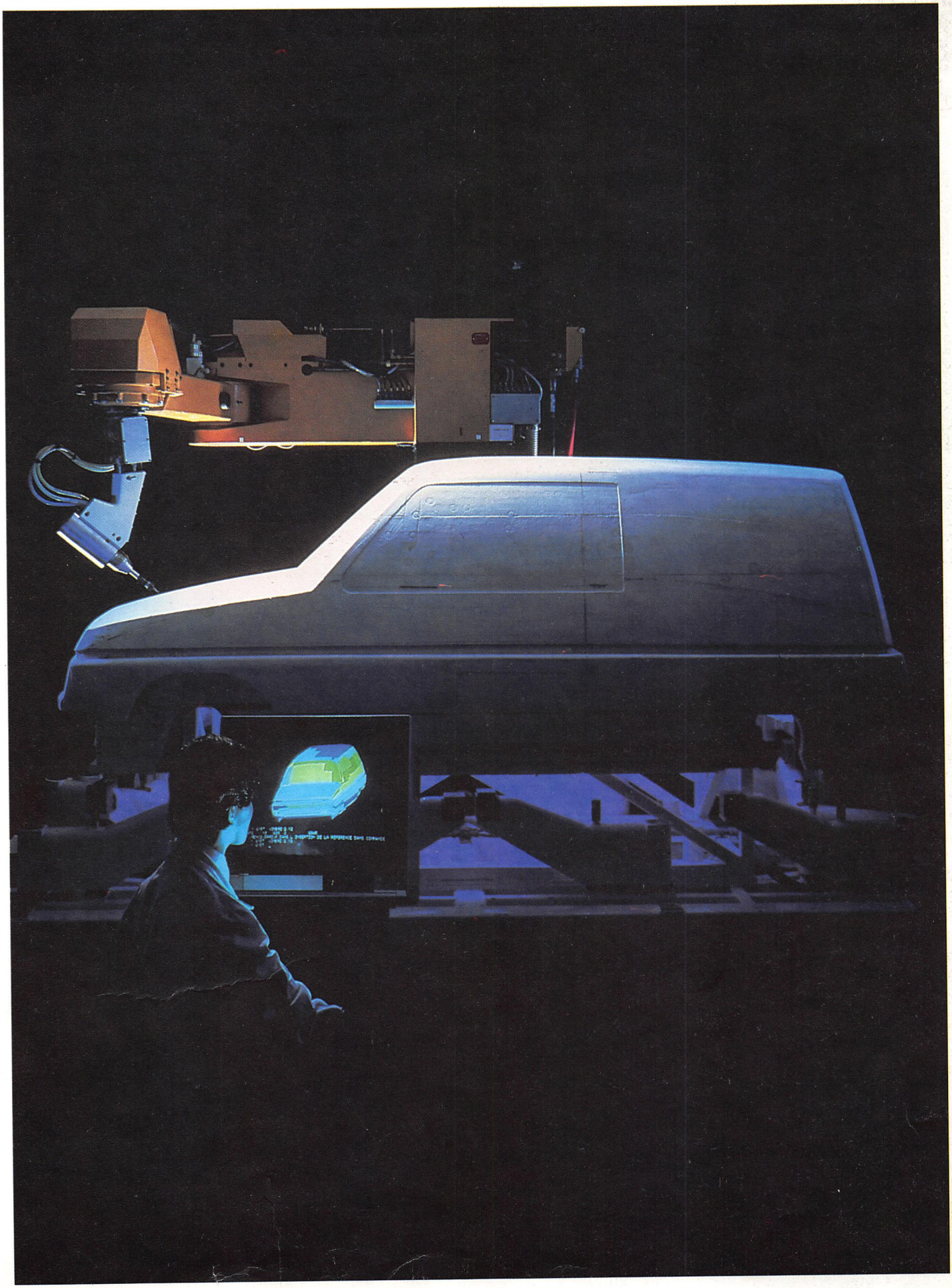
The difficulty of identifying and supplying such a base, and giving rules for its operation, is the main barrier to one potentially very profitable application for computers – language translation. One machine is supposed to have translated 'The spirit is willing but the flesh is weak' from English to Russian and back again, arriving at 'The wine is agreeable but the meat is spoiled'! Real machine-translation systems can currently produce only draft text, which has to be edited by hand. Near-perfect translation, between any two of the world's major languages, is one of the objectives on the Fifth Generation computer project, now receiving massive backing in Japan.

Perhaps the most famous natural language program is Eliza, the computer psychiatrist, developed by Professor Joseph Weizenbaum in the USA. He has since changed his views on AI, partly because of his horror that Eliza was taken seriously, now holding that its 'very contemplation ought to give rise to feelings of disgust in every civilized person'.

The application of artificial intelligence may result in computers that can design a sophisticated product to a required specification, and manufacture the finished item without any human intervention. This robot (right) belongs to Renault. From computer-based plans, it can carve an accurate, full-scale mock-up of a new body design from polystyrene in a few hours. Conventionally, this is the job of skilled model makers working with wood and clay, taking days or weeks for each model.



Game playing is a major facet of artificial intelligence. By learning from past mistakes, computers can quickly develop winning strategies for simple games like noughts and crosses. With more complex games like chess, part of the problem is that we do not really know how humans play the game. The brain cannot calculate as many possible moves as the computer, but seems to be able to evaluate a board position with relative ease.



Eliza was developed as a parody on the Rogerian school of psychotherapy, where the psychiatrist takes on a purely passive role, bringing out the patient's thoughts. Here is a sample conversation with Eliza:

HI! I'M ELIZA. WHAT'S YOUR PROBLEM?
I feel lonely
DID YOU COME TO ME BECAUSE YOU FEEL LONELY?
Yes, I thought you could help
WHY DID YOU THINK I COULD HELP?
I've got to talk to someone
YOU'VE GOT TO TALK TO SOMEONE?
The situation at work is becoming unbearable
TELL ME MORE ABOUT THAT

First impressions of Eliza's intelligence are deceptive. It is simply scanning responses for a few keywords like YOU and MY, then responding with a slight modification to the same sentence. Failing to find such a key, Eliza produces one of a dozen stock phrases such as the last one. Ironically, computers have also been used to simulate psychiatric disorders. A program called Parry, written by Professor Kenneth Colby, mimics chronic paranoia. It is interesting to speculate what might be the result of linking the two!

Less trivial programs have made great strides in the interpretation of English sentences. FRUMP, developed at Yale, can extract the salient points from a news story, and there are several programs that can analyze a simple children's story and then answer questions relating to the characters or plot.

One of the most sophisticated systems with this ability to assimilate knowledge and then answer questions from it is SHRDLU. It is an excellent example of a 'limited world' – one in which blocks of material can be moved around and stacked on each other. By creating these simplistic situations, it is possible to get at the fundamental principles of knowledge assimilation, rather than having to cope first with the superficial complications of the real world. SHRDLU has parallels with the learning process that young children go through with building blocks.

SHRDLU gives the computer a limited understanding of the spatial relationship between physical objects. In theory it should be possible to extend this concept and apply it to the field of CAD/CAM (Computer Aided Design/Computer Aided Manufacturing), although this has not yet happened. Current CAD systems can greatly reduce a designer's workload by performing all the engineering calculations in the background and by allowing a design to be modified many times on the computer screen before being printed out. But CAD can assist little in the actual design process until the computer has a greater understanding of the relationship between the objects it is manipulating.

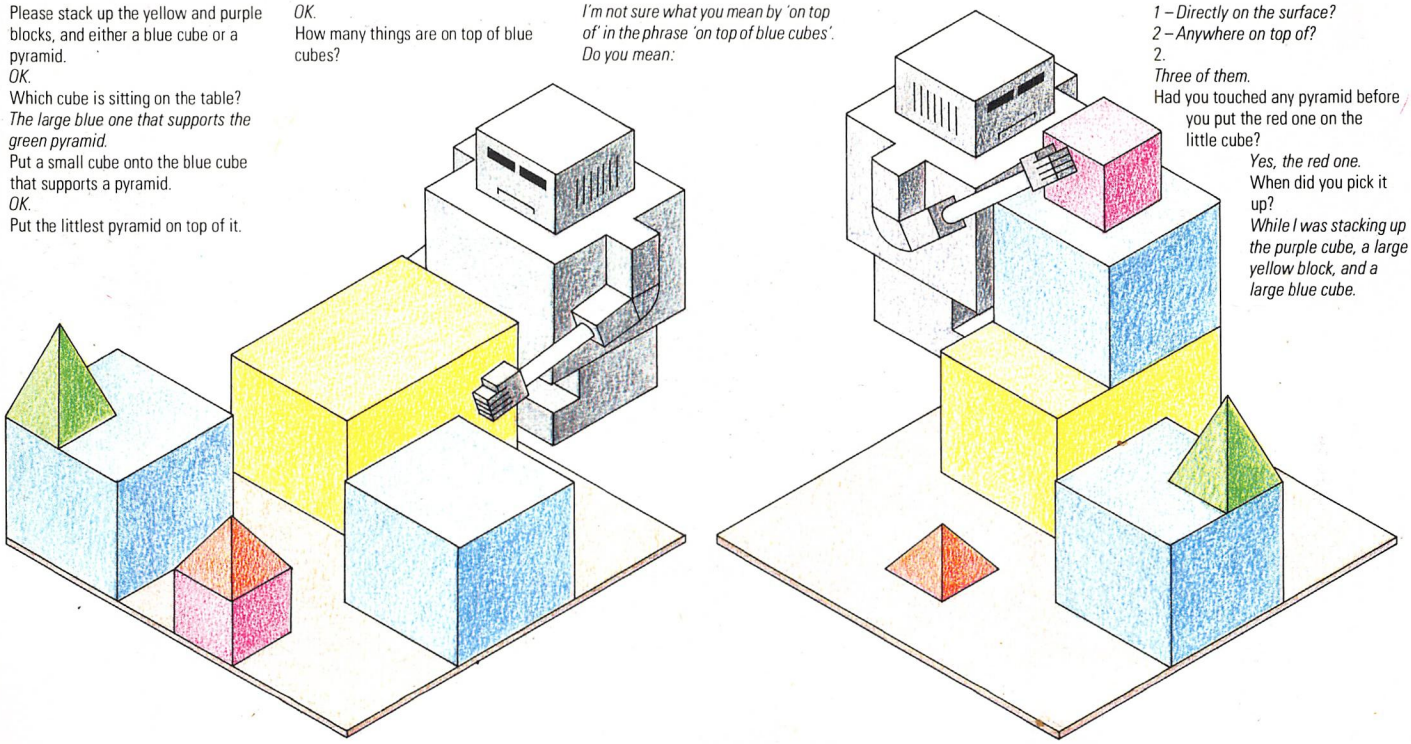
Games

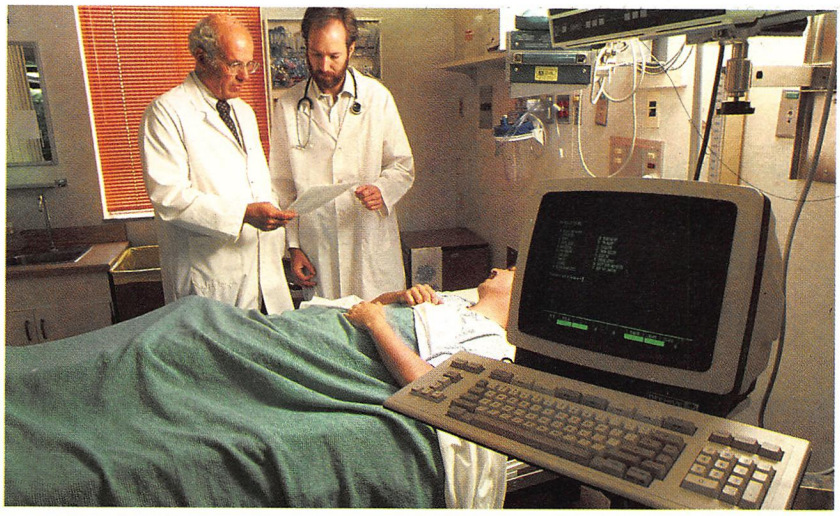
SHRDLU also has much in common with another field of research into AI – game playing. Given the final objective of, say, stacking the three green objects, the program must work out a strategy for getting there, drawing on previous experiences. This is similar to the way that a computer plays chess, evaluating the possible moves up to, say, three goes ahead, and also working backwards from the final objective.

In 1961, A. L. Samuel of IBM made history by

SHRDLU is the most famous example of a 'limited environment' – a simplified version of some facet of the real world, in this case involving shape recognition and manipulation – in which a computer can learn from experience. SHRDLU is just a computer simulation; it features neither graphics nor robots, although both would be simple to add. Communication with the program is conducted not in a computer language but in English. Given a complex instruction, SHRDLU evaluates possible moves both forwards from its existing position and backwards from the goal position until it finds a route. The sort of experience it acquires is that a block cannot be moved until everything has been cleared from on top of it. This may seem trivial, but it is exactly the kind of knowledge that young children acquire through playing with building blocks.
Printed below is a typical conversation (via keyboard and screen) with SHRDLU. The computer's responses are in italics. Note how it queries ambiguities that arise when using a natural language such as English.

Please stack up the yellow and purple blocks, and either a blue cube or a pyramid.
OK.
Which cube is sitting on the table?
The large blue one that supports the green pyramid.
Put a small cube onto the blue cube that supports a pyramid.
OK.
Put the littlest pyramid on top of it.
OK.
How many things are on top of blue cubes?
I'm not sure what you mean by 'on top of' in the phrase 'on top of blue cubes'. Do you mean:
1 – Directly on the surface?
2 – Anywhere on top of?
2.
Three of them.
Had you touched any pyramid before you put the red one on the little cube?
Yes, the red one.
When did you pick it up?
While I was stacking up the purple cube, a large yellow block, and a large blue cube.





Expert systems are the most practical product to have come out of research into AI. Within a limited sphere of knowledge (for example the diagnosis of coronary disease) they apply hundreds of rules, learnt from a human expert, and can explain the reasoning behind any conclusion. Simply by applying human-generated rules more consistently than humans, they can produce more accurate diagnoses. One day, even the surgeon's knife may be wielded by a robot arm.

writing a draughts program that could consistently beat him. In chess, The Grand Masters can still narrowly beat the best computers, but the world backgammon champion fell to a machine in 1979. Poker is now receiving a lot of attention, because good play draws on a number of human subtleties. One program concentrates on 'selling' and 'buying' – deliberately losing a series of games to give misleading information to other players (selling) concerning its true strategy and to gain information (buying) concerning theirs. Another program models a human trait known as the adaptive aspiration level – taking bigger risks when play has gone well in the past.

Expert systems

The joker in the AI pack, so to speak, is the field of expert systems. This is a comparatively recent development, but one which has already had tremendous commercial application. An expert system is a computer program tied to a specific application, incorporating the knowledge of a human expert. Applications already developed include diagnosis of medical disorders and crop diseases, prospecting for oil and precious minerals and repairing diesel locomotives. The most difficult part of designing an expert system is extracting the knowledge from the human expert and expressing it in the form of rules that the computer can apply – rules typically numbering hundreds or thousands. Some rules are hard and fast, others merely express probabilities, for example that high blood pressure may be indicative of heart disease.

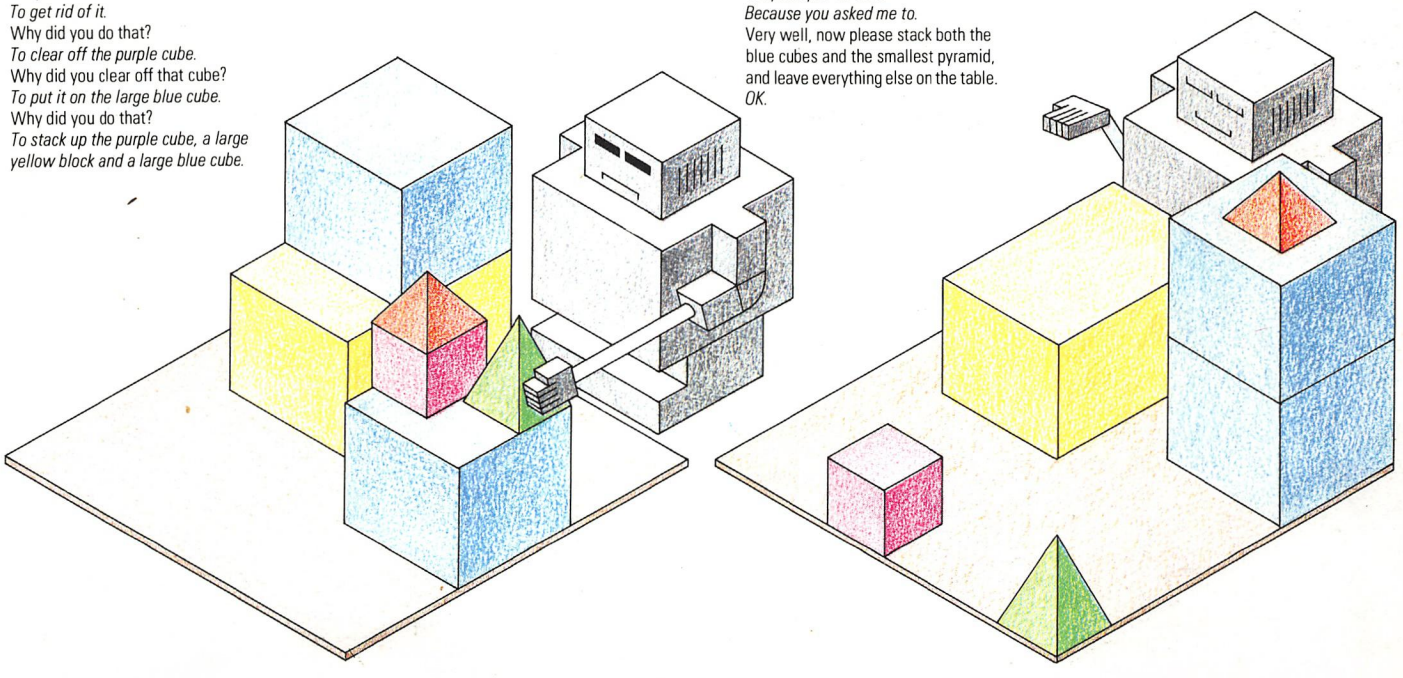
Expert systems have been found to diagnose more accurately than humans, because they can consider more factors at once and apply the human expert's own rules with greater consistency. Ironically, some experts have found that developing an expert system has actually improved their own performance, because the computer has inferred rules and pointed out errors that they haven't seen before.

The most useful facility of an expert system is that it can justify its own conclusions, displaying the rules that it applied. This inspires confidence in the system, and means that any erroneous judgements can be corrected with new rules, and the system can learn as it goes along.

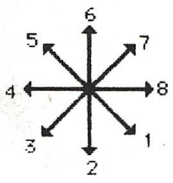
Expert systems are now being developed specifically for robot applications. Remote-controlled vehicles in space or on the seabed could be replaced by autonomous robots that have an expert system governing both the navigation and the work that it is doing. Even the static industrial manipulator, if it is to progress beyond welding and paint spraying, will need this kind of artificial intelligence. The idea of a product being designed on a computer and manufactured at least to prototype level without human intervention has already been mentioned. But a combination of robot plus expert system could mean an end to grubby fingerprints on the bonnet when you take your car in to the garage....

Why?
To get rid of it.
Why did you do that?
To clear off the purple cube.
Why did you clear off that cube?
To put it on the large blue cube.
Why did you do that?
To stack up the purple cube, a large yellow block and a large blue cube.

Why did you do that?
Because you asked me to.
Very well, now please stack both the blue cubes and the smallest pyramid, and leave everything else on the table.
OK.



INTERPRETING IMAGES



Vectoring
If an image is reduced to a series of outlines separating black and white areas, it can be stored as a vector list. Starting with the top left-hand pixel, the computer traces the outline, pixel by pixel, recording its movements by the eight points of the compass. The small section of an image on the right produces the vector list printed below it. On the images opposite the vector list is printed in the middle of the screen.

Giving sight to robots involves two separate processes. First, the visual image must be converted into a form that can be read by the robot's control computer – this was dealt with on pages 84–85. Then the computer must interpret that image, in order to decide what action to take. This process, in turn, has two stages: image processing and pattern recognition.

Image processing

This comprises a number of techniques that can be applied to an image stored in computer memory. These can improve the visual quality of the image and can extract the salient features so that the computer doesn't waste time examining irrelevant detail.

One such technique is noise elimination – so called because it is the visual equivalent of removing crackle and hiss from a music recording. If there is a single white pixel on a large black background, it can usually be assumed to be a spurious signal and removed. By making each pixel the average of all its neighbours (the eight pixels that surround it) an image can be made smoother and clearer. This technique was used to improve the live pictures of space missions.

Outlining is another image-processing technique – the image is reduced to a series of lines that indicate boundaries between black and white areas. This is achieved by scanning the entire image and comparing each pixel with its immediate neighbours. Where there is a difference, that pixel is noted as being on a boundary. Further processing reduces these outlines to a width of just one pixel, and eliminates small irregularities from otherwise straight lines or smooth curves.

Outlining has the advantage that vectoring can be used instead of bit-mapping. A conventional television picture or computer screen is generated by an electronic beam scanning the entire image. One bit of memory is required for every pixel on the screen (typically 64,000) whether it is black or white. This is bit-mapping, and is inefficient both in terms of storage space and processing time. Vectoring is a much more efficient system, but only works with outlined images. The outline is traced one pixel at a time, specifying each jump by the eight points of the compass.

Pattern recognition

Once the image has been reduced to its salient features, the next stage is pattern recognition. Here the computer has to match the objects in view with those it has been programmed to recognize, or indicate that there is no match. In the simplest system the computer lays a series of templates over the image (inside its memory), one for a nut, one for a bolt and so on. It counts the number of pixels that fall inside and outside the mask, and the one with the greatest correspondence is declared to be the match.

In most real applications, however, the objects may arrive at any angle. If a bolt appears at an angle significantly different from that in the template, there will be little overlap. Consequently, the template system is used only when the angle at which objects come into view never varies.

Practical vision systems use either adaptive or algorithmic pattern recognition. One of the best examples of the adaptive approach is the neural network (see pages 100–101), which can cope with subtle variations, such as those of the human face. The algorithmic technique is more suited to industrial applications, such as the recognition of machine parts coming down a conveyor belt. From the outlined image, the computer measures a number of quantities, such as the silhouette area of the object and the length of its perimeter. Unlike, say, height and depth, these measurements do not change significantly as the object rotates. Even more elaborate quantities can be measured. For example, the square of the perimeter divided by the area gives an indication of the 'wiggleness' of the shape – a circle has a value of around 13, a star might be 20, and a spider 90!

For each type of object it has to memorize, the computer has a list of these characteristic quantities stored in memory. As the photographs show, a key can be distinguished from a nut by comparing just area and perimeter. If an object contains any holes, these are also indicated in the outline drawings. When it analyzes an image, the computer will calculate the same list of factors for each of the 'objects' (they may be holes) contained within the main outline – for example the hole in the key.

For flat objects, the position of the centroid (centre of mass) is also calculated, as this makes a useful reference point, irrespective of where the object is located on the screen. You can write a program that recognizes outline pictures of animals, for example, by drawing a series of concentric rings around the centroid of the image, and counting the number of times each ring is crossed by the outline, to calculate the number of limbs and appendages.

These techniques will work with a multiple grey-level system (see page 84) but the processing is far more complex. Shading is vitally important in the analysis of three-dimensional images, in order to get some idea of the depth of each part of the picture. The alternative is using two

Processing the image

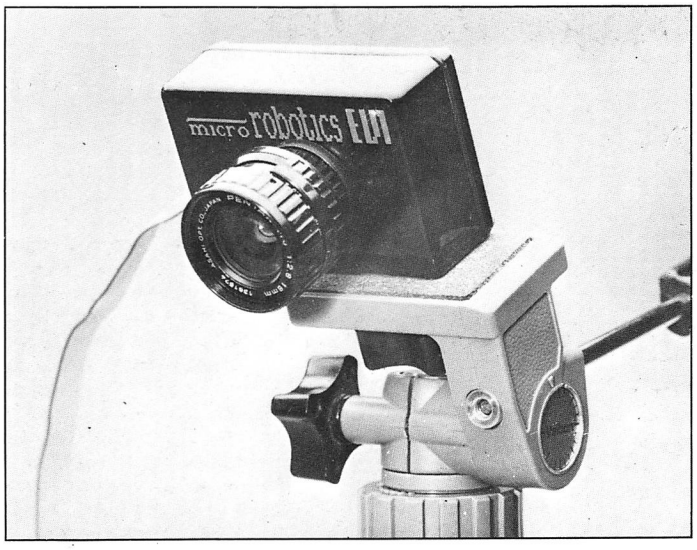
(1) The first stage in image processing is to set the exposure of the electronic camera. The wrong value for the threshold between dark and light areas will result in some spurious data being read from the background.

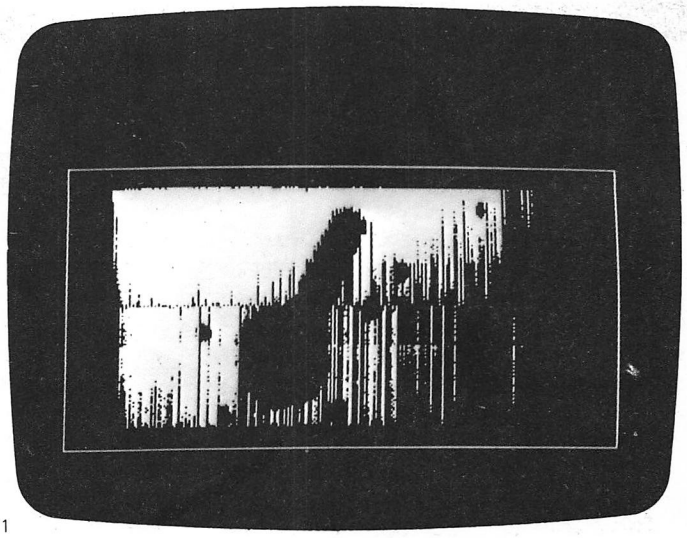
(2) When the exposure is correct, the image will be crisp and clear. There may still be some visual noise, such as the blobs around the key here. The next stage in image processing is therefore to eliminate any small objects that aren't connected to something larger.

(3) The image is now turned into a series of outlines representing boundaries between light and dark areas. This outline is stored in the form of a vector list displayed in the middle of the screen – see diagram above left for explanation. A series of parameters, such as area and perimeter, are measured and this list is stored in memory, together with the object name.

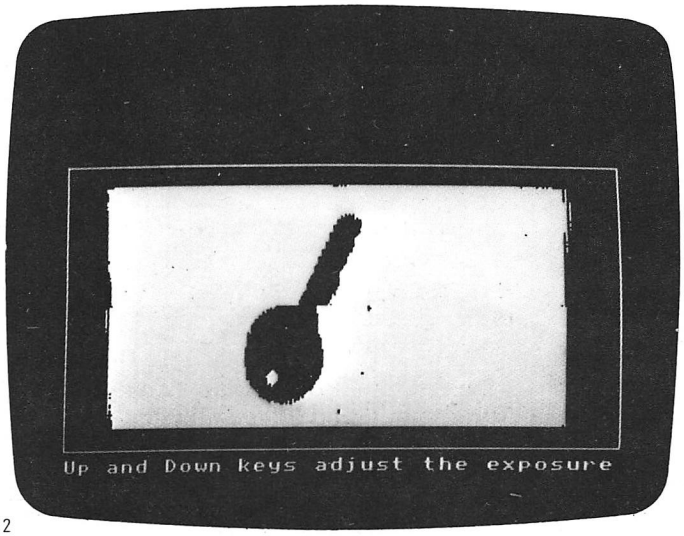
(4) When a new object is presented, the computer compares the list of extracted features with its list in memory and finds the closest match. Because parameters like area and perimeter don't change significantly as the object rotates, the computer correctly recognizes it as a key. The slight change in values is because a pixel representation of an image is necessarily an approximation.

(5) A different object, like this nut, produces a quite different set of values. The list specifies that the outline contains one other object (actually the hole), and the computer will measure the same set of parameters for this contained object also. The shape value is the perimeter squared divided by the area – a measure of how irregular the outline is.





1



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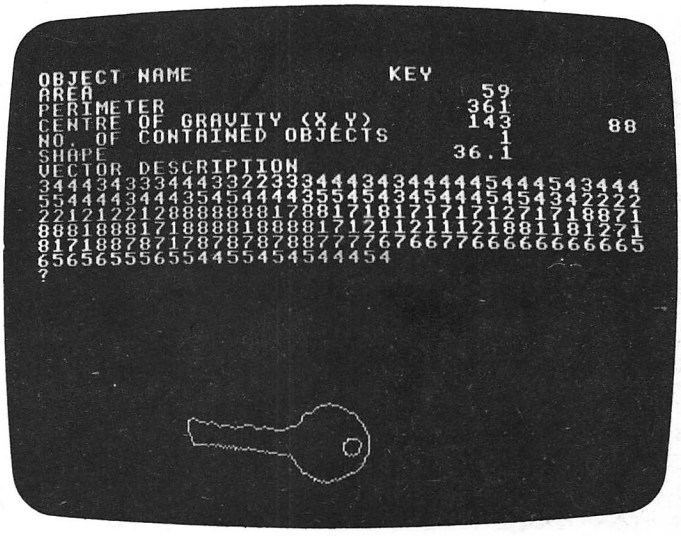

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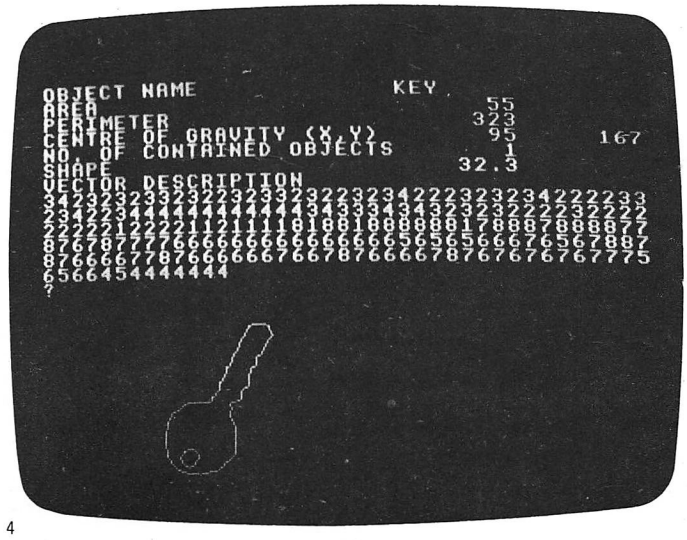

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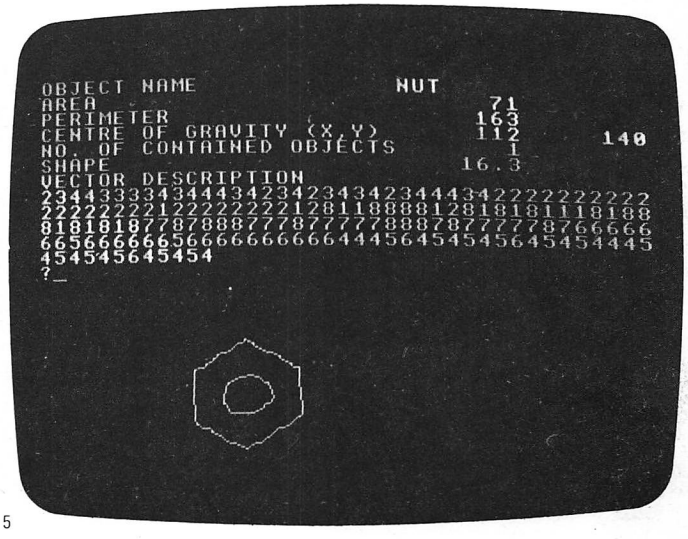


5

The images and data shown above were produced by a £130 robot camera linked to an inexpensive micro, but they are typical of what would be seen by an industrial parts recognition system – costing several thousand pounds.

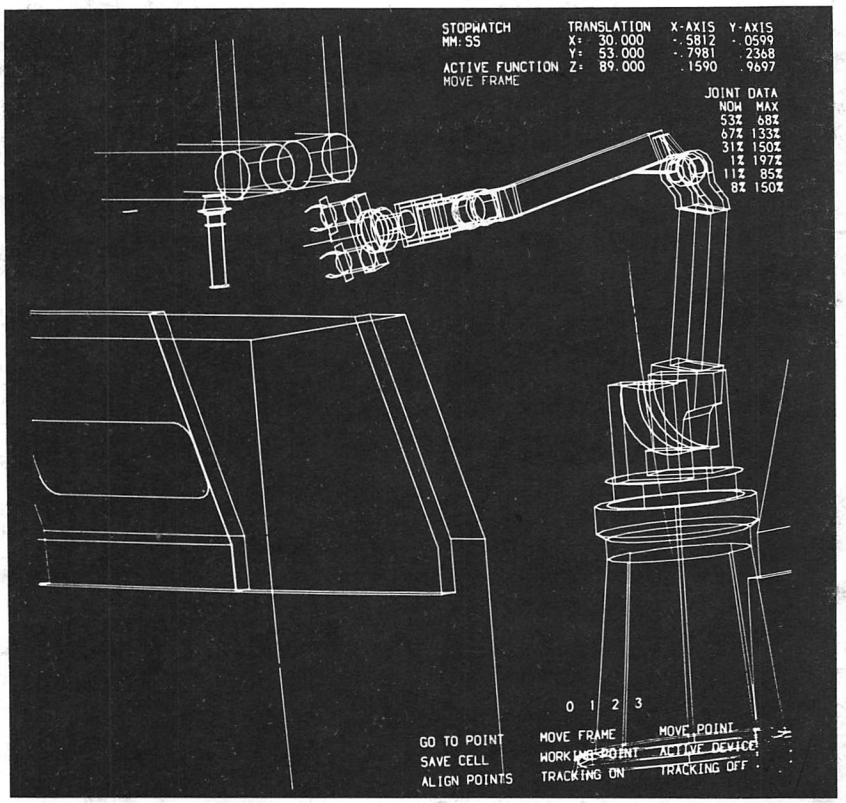
cameras to give stereoscopic robot vision; this is still only at the experimental stage. The image viewed from one camera will be slightly different from the other, placed a few centimetres away, and by comparing the two it should be possible to calculate the depth of each part of the picture. The problem is deciding which parts of the left image correspond with which parts of the right. As with many facets of robotics, it is unlikely that much progress will be made until we have a better understanding of how this function operates in humans.

PROGRAMMING

One of the inherent advantages of the robot over other forms of automation is its programmability. A robot can be taught to follow a prescribed sequence of operations and, if it is subsequently required to perform a different task, it can simply be reprogrammed.

The first industrial manipulators were programmed using a peg-board – an array of jack-plugs and sockets, similar to the old-fashioned telephone exchanges. Reprogramming effectively meant rewiring the robot. There were alternative systems based around timing mechanisms similar to the cylinder in the musical box, or using a loop of punched paper tape.

The most significant breakthrough was the arrival of the solid-state digital computer. The effect of electronic, as distinct from electro-mechanical, control was to separate the hardware from the software. Altering the robot's sequence of movements now meant changing only the stored electronic patterns, not the physical configuration of the controller. Programs could be typed in via a conventional keyboard.



Large automated assemblies, such as car production lines, can be simulated entirely on computer before they are built. In this way, the cost of the installation can be measured against the improved productivity in advance, and it is possible to identify potential bottlenecks. Simulation packages can also prevent costly mistakes, such as an end effector colliding with another moving unit.

Programming by example

In fact, most robots are not programmed via the keyboard, but taught by example. This is a particularly appropriate method for jobs such as paint spraying, where the robots are designed to replace human workers on a one-for-one basis. Here, the end effector is a conventional spray gun, complete with handle and trigger. To teach the robot, the operator merely sprays one item. The arm offers virtually no resistance, but its internal position sensors (see page 74) are conveying the movements of each joint back to the controller. The stored sequence of movements is then reproduced by the arm's actuators.

Other robot arms would be too large and heavy to guide by hand, so they are equipped with teach pendants. Using joysticks or buttons, the operator can adjust any of the joints in either direction, although the speed of movement will be restricted for safety. When he is satisfied that the end effector is in the correct position and orientation for a particular point in the proposed duty cycle, he presses the POINT button. The controller records the angle or extension of each axis, and the operator can proceed to the next point.

When the cycle is finished, the controller will usually display on its screen a list of the specified points in the cycle, giving a value for each joint. This list can be edited from the keyboard, and the operator can, additionally, specify the speed at which the arm should move between each point, if that is important.

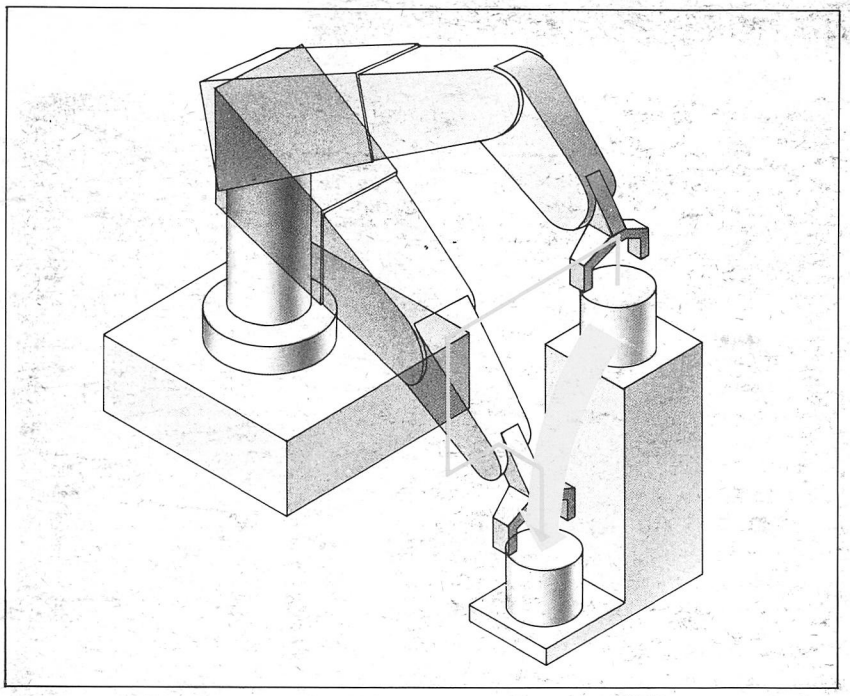
Next, the controller calculates the optimum route between each point, so as to complete the cycle in the minimum time. It follows that if the robot must wait at any point, this must be programmed in specifically. The optimum route will usually be different from the one taken by the operator, who will probably have made trial-and-error adjustments to position the end effector precisely. Hence the computer stores only the specified points and not the individual joystick movements or key presses.

Care must be taken to ensure that when the computer optimizes each leg of the sequence, the new route won't result in a collision. Where there are obstacles to get round, the operator must specify intermediate points.

The teach-pendant method of programming (sometimes called 'follow-me') is only applicable where the robot's cycle is purely a function of time and position – that is, where it merely has to start and finish a particular task, rather than interacting with a range of more complex inputs. However, in many applications the robot must wait for a specific signal before it can proceed to the next part of the cycle. The signal might be from one of its own sensors or from an external device, for example to indicate that a machine tool has finished with the next component.

Writing programs

In this case the robot program must be written out formally, just like a computer program, typed into the controller and then stored on magnetic tape or disk. In addition to the straightforward instructions specifying the movements of each joint,



When a robot arm is being taught a sequence of movements, the operator need not be worried about the exact route he takes between each point (black line), because the computer will automatically calculate the optimum path (red line). If there is a danger that the arm will hit a stationary object, the operator must specify intermediate points through which it must pass.

```
 1 --* CARTON WORKPOINT DECLARATIONS
 2 LL: NEW PT( 250.00,550.00,-250.00,90);  --LOWER LEFT  CARTON POSITION
 3 LR: NEW PT( 000.00,550.00,-250.00,90);  --LOWER RIGHT CARTON POSITION
 4 UR: NEW PT( 000.00,450.00,-250.00,90);  --UPPER RIGHT CARTON POSITION
 5 PP: NEW 3;                              --PARTS PER ROW IN CARTON
 6 NN: NEW 12;                             --NO. OF PARTS IN CARTON
 7 CARTON : STATIC PALLET(LL,LR,UR,PP,NN); --CARTON DEFINITION
 8 HOPPER :NEW PT(-200.00,450.00,00.0,90); --POSITION ABOVE HOPPER MOUTH
 9 --* DI/DO ALLOCATIONS AS USED IN PROGRAM
10 -- DI POINT #4 = HOPPER CONDITION SENSOR      0=EMPTY,1=FULL
11 -- DI POINT #5 = CARTON POSITION  SENSOR      0=NOT IN PLACE,1=IN PLACE
12 -- DO POINT #3 = CONVEYOR CONTROL SWITCH     0=STOP,1=START
13 -- DO POINT #6 = HOPPER EMPTY WARN LIGHT     0=OFF,1=ON
14 --*
15 --* MAIN PROGRAM ROUTINE
16 --* THE PROGRAM LOADS ITEMS INTO A 3 X 4 CARTON FROM A HOPPER
17 --* THE CARTONS ARE ON A CONVEYOR WHICH IS CONTROLLED BY THE PROGRAM
18 --*
19   CARTONLOAD:SUBR;
20               --* SUBROUTINE TO PICK UP BLOCKS
21               LOAD:SUBR;
22                    PMOVE (HOPPER);        --MOVE ARM TO HOPPER
23                    WAITI (4,1,0);         --IF HOPPER NOT EMPTY
24                    ZMOVE (-100);GRASP;    --DOWN AND GRASP ITEM
25                    DELAY (0.5);           --
26                    ZMOVE (0);             --RAISE Z-AXIS
27                    END;                   --
28               --* SUBROUTINE TO DROP BLOCKS
29               DROP:SUBR;
30                    ZMOVE (-250);          --MOVE Z-AXIS DOWN
31                    DELAY(0.5);RELEASE;    --AND RELEASE GRIPPER
32                    DELAY (0.5);           --
33                    ZMOVE (0);             --RAISE Z-AXIS
34                    END;                   --
35 --* MAIN PROGRAM EXECUTION STARTS HERE
36         SETPART (CARTON,1);               --INIT CARTON START POSITION
37   NEXT : WRITEO (3,1);                    --START CARTON CONVEYOR MOVING
38         DELAY  (3.0);                     --WAIT 3 SECONDS
39         TESTI  (5,0,STOP);                --TEST IF CARTON POSITIONED
40         WRITEO (3,0);                     --IF YES,TURN OFF CONVEYOR
41         BRANCH (GO);                      --BRANCH TO LOAD ITEM
42   STOP : WRITEO (6,1);                    --TURN WARNING LIGHT ON
43         WAITI  (5,1,10);                  --WAIT MAX 10 SECS TO POSITION
44         WRITEO (3,0);                     --TURN CONVEYOR OFF
45   GO :  LOAD;                             --PICK UP ITEM
46         NEXTPART (CARTON);                --INCREMENT CARTON NEXT POSITION
47         GETPART  (CARTON);                --MOVE ARM TO OVER NEXT POSN.
48         DROP;                             --AND PUT ITEM DOWM
49         TESTP (CARTON,12,NEXT);           --CHECK IF CARTON IS FULL YET
50         BREAKPOINT;                       --OPERATOR INTERVENTION POINT
51         BRANCH (GO);                      --BRANCH TO GET NEXT ITEM
52     END;
```

Programs to control industrial robots are often written in dedicated robot language. This routine controls an IBM 7535 assembly robot, and is written in IBM's own language AML. Using the language, the programmer can define his own high-level functions such as NEXTPART and DROPOFF. The comments shown here explain the function of each line.

there will be control statements such as: 'Wait until next item ready on conveyor', 'If pallet full send signal to transport' and 'Repeat this subsequence until rack is empty'.

Programs have to be written in a programming language. The higher the level of the language, the closer it is to English and therefore the easier it is to read a program listing and understand the routine it is performing. Some robots are programmed in conventional computer programming languages, like BASIC, FORTRAN, LISP and Pascal. Others have programming languages specially designed for robot control, such as Unimation's VAL. Here the actual phrases used in the program listing will be related directly to the robot world: GRASP, MOVE, WAIT, TURN, SPEED and so on. Programs written in a robot language will use fewer lines of code to perform the same function, but the computer will then have to spend more time interpreting these high-level commands into the movements required.

Some programming languages such as FORTH and LOGO (see page 179) allow the programmer to define his own high-level command words and then use these in the program, or even to define higher-level commands. He might start with a command PICKUP, build this into a routine MOVEPACKAGE, and use this as a component in the complex sequence STACKPALLET. Thereafter, the entire routine can be executed using just that one last word.

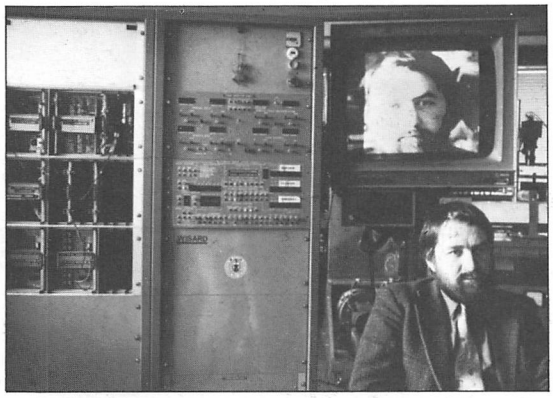
Computer simulation

All programmers know that no program ever works correctly the first time; they all have to have operational errors filtered out during several trial runs – the phrase for this is de-bugging. But when you are dealing with robots and automation equipment worth tens of thousands of pounds, errors could be very expensive.

One solution is to test out the entire installation, including the robots, the workpieces and all the ancillary equipment, by simulation on a large computer. The proposed program can be typed in and the results observed as an animated graphical display. Not only can bugs be identified and removed, but it is possible to test the efficiency and economic viability of the project in terms of the resulting throughput.

These simulation programs are extremely complex, and have much in common with Computer-aided design (CAD) packages. Most feature some form of graphical output, on a high-resolution screen or digital plotter, so that the operator can see the layout of the components. An automation assembly, such as a car production line, is built up with the aid of a light pen, which is connected to the computer by a single cable and which can be used to point at items on the screen. The building blocks of the robot system are therefore displayed on one side of the screen, and the user simply selects from this menu, and positions the component in the desired place. In the background, the program puts together the equations that govern the operation of each feature.

NEURAL NETWORKS



Neural net vision systems such as Wisard (above) use digitized television pictures of the subject to be recognized.

The human brain (right) contains around 10,000 million neurons, interconnected into a giant network.

When the modern computer was invented, science fiction writers and technologists alike assumed that to build an electronic equivalent of the human brain was only a matter of making the computer large enough and fast enough.

Yet despite massive advances in computer size and speed, the 'intelligent machine' is little closer to being a reality. Some researchers have questioned the whole rationale of AI. Instead of attempting to simulate intelligent behaviour using conventional computers, they argue, why not mimic the construction of the brain, and see how the resulting device behaves? This kind of hardware is called an electronic neural network.

Actually, the concept is not new. In 1947 Norbert Wiener proposed that artificial intelligence should be approached in this way when he published *Cybernetics*. Sadly, his ideas were drowned out by the demonstrable success of John Von Neumann's stored-program computer – on which design all computers have since been based.

The brain comprises some ten thousand million neurons, connected, apparently at random, into a network. Though we know little about their internal functioning, the operation of a neuron in terms of the electrical pulses entering and leaving it was determined back in 1943 by McCulloch and Pitts. It transpired that a very crude model of a neuron could be built, not from a microprocessor, but from a humble RAM chip.

A neural network, or net, then, is constructed entirely from RAM chips; there is no central processor. The intelligent properties of the net are a natural property of its structure, not the product of a program written by a human.

The falling price of RAM chips has now made neural networks a possibility. Wisard is an experimental system, developed at Brunel University, England, which has since gone into commercial production. The first application has been visual recognition, partly because that is one of the highest forms of human perception and partly because of the demand from industry for robot vision.

There are two principal advantages of the neural network over conventional image analysis by computer. The first is that the system is taught to recognize an object simply by moving it around in front of the camera and pressing a 'teach' button, instead of by having lists of specifications entered. The second is the unparalleled ability of the system to cope with variations in the image. This has been the main problem with industrial parts recognition: objects can arrive at any angle and in different lighting conditions. Wisard's flexibility is epitomized by its ability to recognize human faces, and even determine whether they are smiling or frowning.

Next in line for the neural net is speech recognition – and the integration of speech and vision is being investigated, too. It has already been proved that a more advanced version of the network, in which part of the output is fed back to the input, will – of its own accord – learn to associate sounds with pictures, in much the same way that a child learns to speak and read.

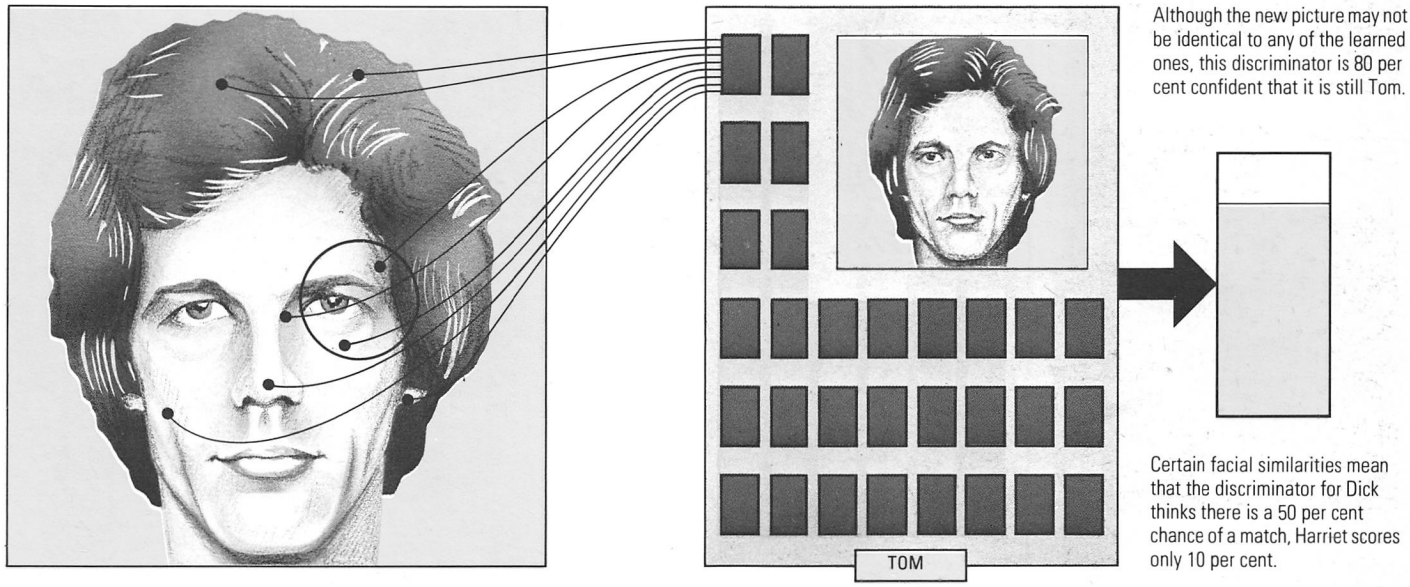
HAL, the infamous computer from *2001*, was taught by a personal tutor rather than programmed. Ultimately it acquired abilities unforeseen even by its makers – including lip-reading. Although the film's directors wouldn't have recognized it as such, HAL behaved in many respects like a neural network. At first encounter, Wisard appears very intelligent; in reality it is still a crude system. Nevertheless, it opens up an interesting discussion, foreshadowed by science fiction writers, concerning the wisdom of developing machines whose behaviour we cannot fully predict.

Wisard

Wisard is a vision system for robots that isn't based on conventional computers, but on an electronic model of the neurons inside the human brain. Though still crude compared with human perception, Wisard displays some remarkably 'intelligent' properties.

Although designed initially for industrial applications, the ability of electronic neural networks like Wisard to recognize human faces demonstrates their extraordinary capabilities. The system is not programmed, because it has no processor like a computer. Instead, 'learn' mode is selected, and the object or face is put in front of the camera and shown to the system in as many different lighting conditions, orientations or expressions as possible. Each change in the seen image causes one or more of the RAMs simulating neurons to change its function.

The system is not using formal techniques of pattern recognition, but is learning the characteristics of the object or face.



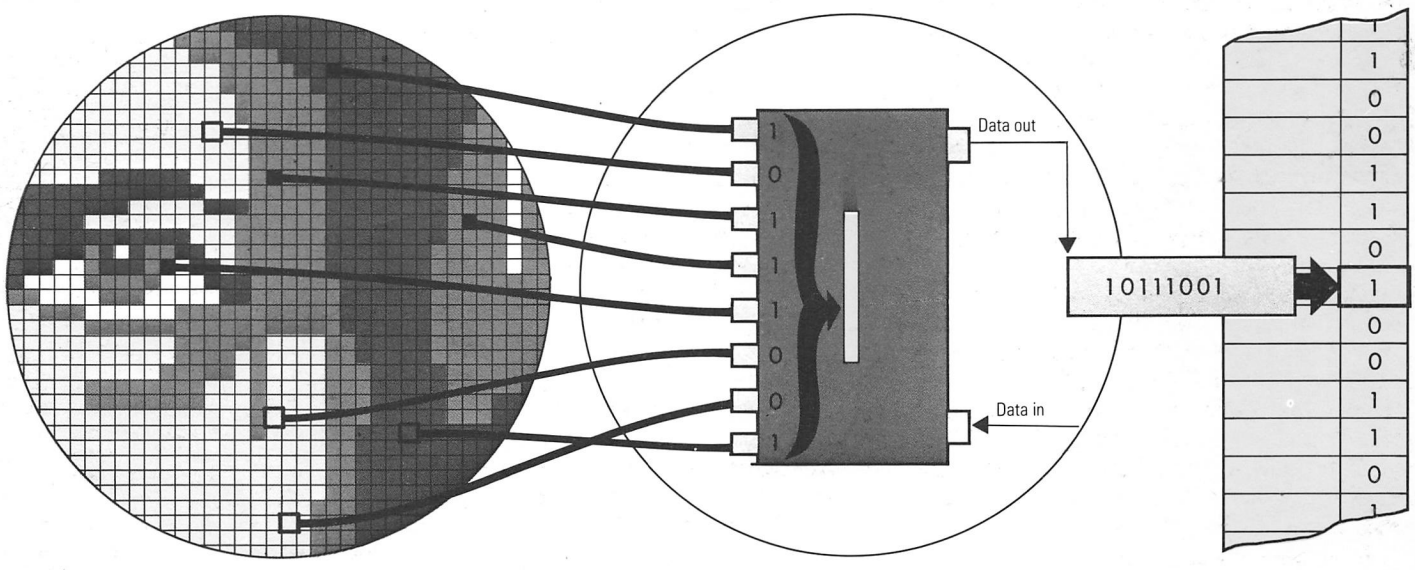
Although the new picture may not be identical to any of the learned ones, this discriminator is 80 per cent confident that it is still Tom.

Certain facial similarities mean that the discriminator for Dick thinks there is a 50 per cent chance of a match, Harriet scores only 10 per cent.

Wisard requires one discriminator for every class of object it has to recognize. The system shown here has three discriminators, taught to recognize Tom, Dick and Harriet respectively. Equally, there could be one to recognize a face smiling and one frowning, or one for nuts and one for bolts.

In 'recognize' mode, the image, which has been digitized by a conventional robot camera, is shown to all discriminators simultaneously. Each then produces a score between 0 and 100 per cent of the likelihood that the image corresponds to the one it has been taught.

A discriminator comprises dozens of RAM chips, each connected at random to eight points on the picture. The discriminator score represents the proportion of its RAMs (the ones shown tinted here) that have seen their particular part of the image during learn mode.



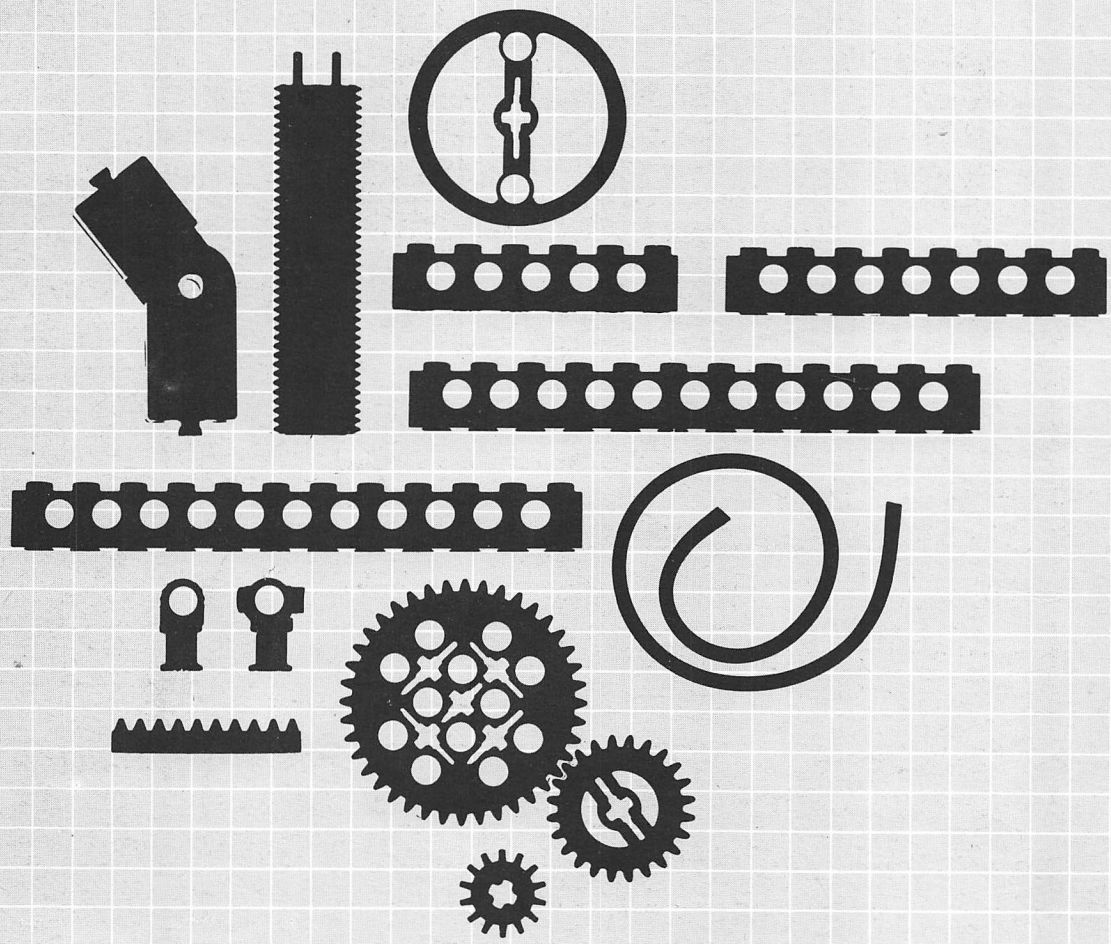
Each RAM chip in a discriminator crudely mimics the function of a neuron. It has eight address lines, and the pattern of 1s and 0s on them specify one of 256 single-bit memory locations inside the chip. The eight address lines are wired at random to eight picture points on the digitized image and correspond to the nerve inputs. A dark point produces a 1 and a light one a 0.

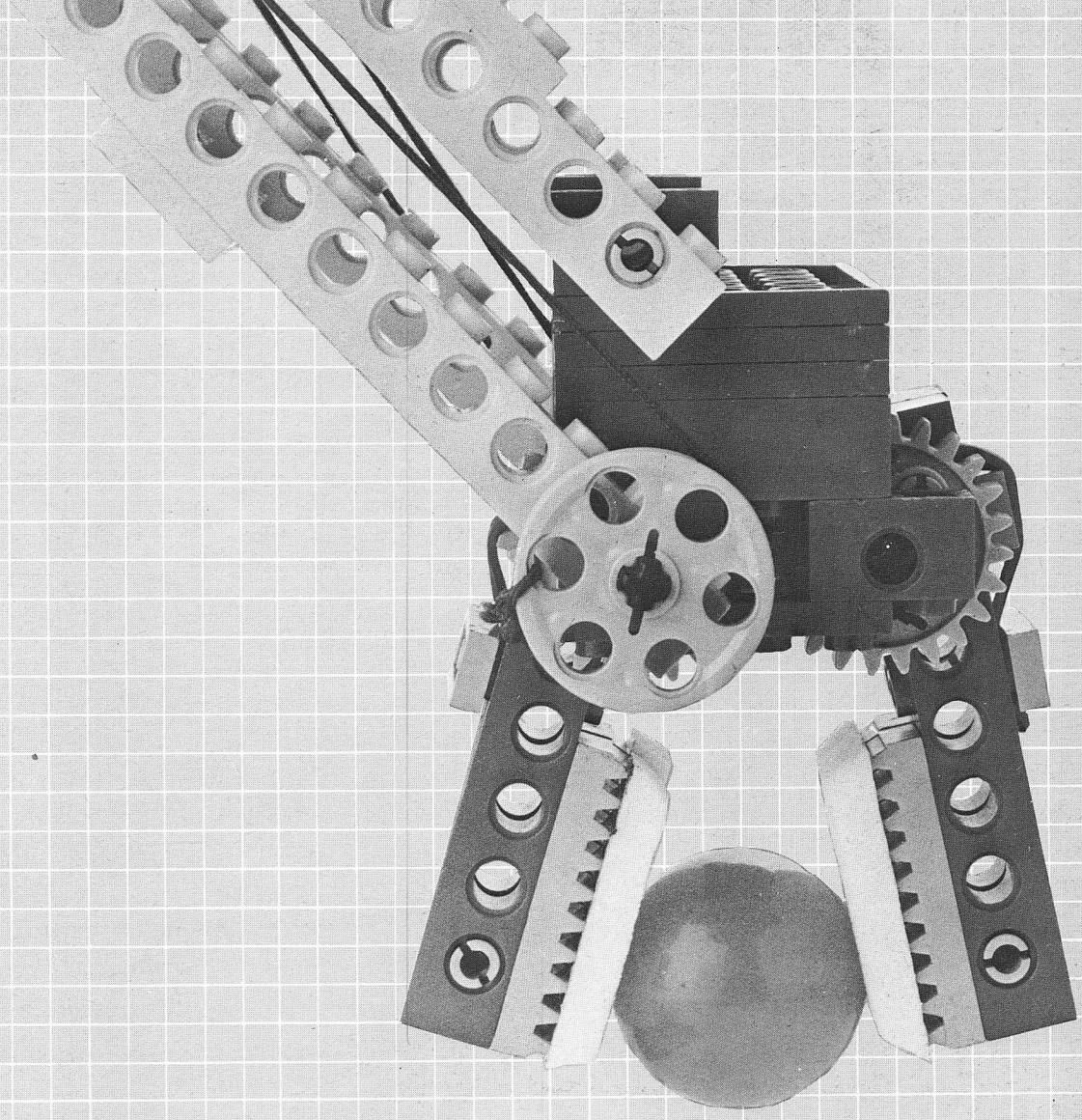
Initially, all 256 locations contain 0. In learn mode, the pattern of light and dark points specifies one of those locations, and a 1 is stored there by means of the *Data In* line. The same thing happens each time the image changes, even if the change is very subtle.

In recognize mode, each RAM looks at the same eight points as before. If it has been taught that particular pattern of light and dark there will be a 1 in the corresponding location, which will be put on the *Data Out* line, corresponding to the output fibre of a neuron. The RAM will therefore add to the discriminator's vote. If it hasn't seen that pattern on its eight lines before, the output will be 0, and therefore won't contribute to the vote.

PART 4

PRACTICAL PROJECTS





INTRODUCTION	102
CONSTRUCTION KIT GUIDE	104
BASIC ELECTRICAL SKILLS	106
KEY TO WIRING DIAGRAMS	108
INTERFACING TO A COMPUTER	110
BUGGIES IN FISCHERTECHIK AND LEGO	112
HARMONIC DRIVE SIMULATION	117
MOTOR CONTROL	118
TOY ANDROID	120
THREE-AXIS ARM	126
DRAUGHTS-PLAYING ROBOT	130
LEGO ROBOT ARM	134
CARD-DEALING ROBOT	140
FREE-ROVING ROBOT	146
WALKING MAN	154
X-Y PLOTTER	158
POLAR ARM	164
INTERFACING BIG TRAK TO A COMPUTER	170
MODIFYING THE MOVITS	174
LOGO PROGRAMMING	179

INTRODUCTION

The best way to learn how a motor car works is to take one to pieces and put it back together again. The best way to learn about robotics is to build and experiment with your own robot devices. What follows in this section is a series of practical projects you can try out for yourself, at home or at school.

Some of the robot designs can perform nominally useful tasks such as dealing a hand of cards or playing draughts. The purpose of the projects, however, is not to create supposedly labour-saving devices but to demonstrate the principles from which real robots are constructed. After following a few of our designs, you should be able to combine the features into a robot of your own specification.

Construction materials

Most of the following projects have been designed with standard educational construction kits, either Fischertechnik or LEGO®. This eliminates the need for any specialist tools or techniques such as machining or gluing. It also makes it easier for you to reproduce each model exactly as we originally designed it – before going on to experiment with your own modifications and embellishments if you wish.

Building robots from these standard materials has advantages and disadvantages. Both the chosen manufacturers can now supply a good range of sophisticated components such as motors and gears, and these will run with little friction or loose play, the latter being very undesirable where motion is to be accurately controlled. Construction kits are also re-usable, which apart from letting you build a variety of models, makes it possible to experiment with different structures and mechanisms to find the best solution.

The main drawback is that every part of the model must conform to standard lengths and fittings – not always convenient. Furthermore, on some occasions they can work out more expensive than, say, balsa wood, plastic or sheet metal. If you are familiar with working these materials then you should certainly apply them to your robotics experiments.

We have attempted to keep the cost of the projects as low as possible, though most will still require two or four electric motors. The more Fischertechnik or Lego that you have available, the greater the range of projects you can attempt, so it is a good idea to club together with other enthusiasts or to use your school's or college's facilities. On pages 104–105 some advice is given as to which Fischertechnik and Lego components are the most useful for robotics projects and how to buy them most economically. (For suppliers' addresses see page 183.)

Control systems

When building robots, construction is just one half of the problem – the other is control. To qualify for true robot status, mechanisms should be programmable, which used to mean expensive, purpose-designed electronic circuits for each application. Fortunately, many people now have access to a general-purpose programmable device: the home computer. Most of our robot projects can therefore be linked to a home computer, and either operated live from the computer's keyboard or left to execute a program that has been previously typed in and stored in the computer's memory.

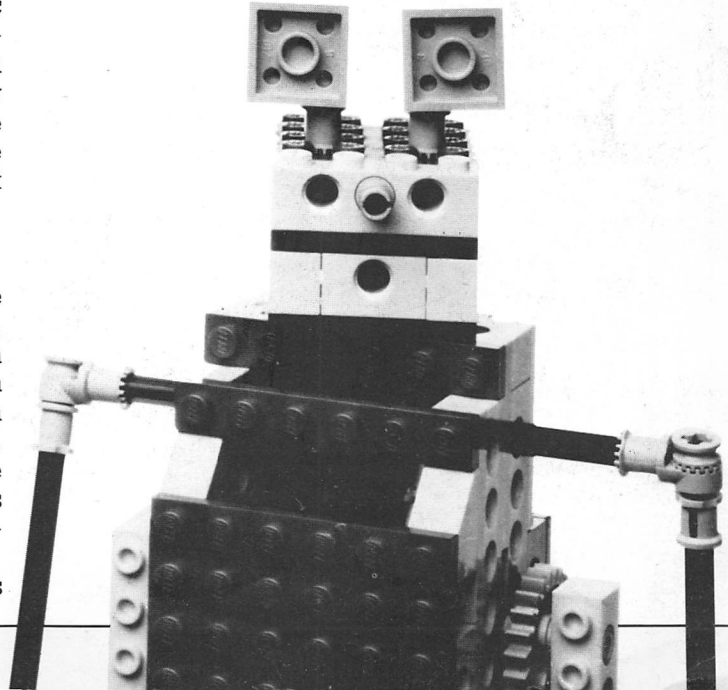
Linking an electromechanical device to a computer is called interfacing, and traditionally calls upon skilled electronic engineering. Our approach is somewhat different. All the interfacing is done through a general purpose interfacing unit called a relay block, which can be purchased for most home computers for between £20 and £50. By using one of these blocks (the functioning of the devices we used is explained on page 110) you will not need to buy any electronic components, nor in most cases will you even need a soldering iron, since the circuits simply plug together. If you do have a knowledge of hobby electronics then you may well find that you can come up with cheaper and more efficient interfaces, but this book is written for those with no such knowledge.

The main difficulty with computer control is that no two models of home computer or interfacing units operate identically. It is assumed that you already know how to program your own computer (if not, there are many books now available to teach you) and that you are fully conversant with the commands required to operate your relay block should it differ from the one that we use.

Each of the projects includes a schematic wiring diagram showing how the motors and other components are connected to the relay block. There is also a sample program to demonstrate the operation of the model. The program has been carefully written and documented so that it will be easy to modify it for your own system, provided that you have some previous experience of programming.

If you don't have access to a home computer, or haven't yet grasped the essentials of programming, then it is possible to operate most of our projects using the conventional battery boxes and switches supplied by Fischertechnik and Lego. The models, however, are less exciting with the programmable element removed, and you will not learn as much about robotics.

These projects are intended to give you the flavour of robotics experimenting. Having completed several of them, you may find that you want to learn more sophisticated techniques of construction and circuit design, and perhaps even go on to design much larger-scale domestic or educational robots with a full range of sensors and an onboard computer. Robot building can be a fascinating hobby, combining the skills of the programmer with those of the model engineer, and it has considerable educational value, too.



CONSTRUCTION KIT GUIDE

Here we compare Lego and Fischertechnik, highlighting their relative merits as robot construction kits. We also give advice on buying the components you will need for our projects.

Lego

Lego started out as a more sophisticated replacement for conventional building block sets, which could be used by young children for constructing model houses. The patented system of knobs and holes for holding components together was actually based on a feature from ancient Greek architecture. Over the years, the original components have been supplemented by wheels, lights, motors and gears to increase the range of models that can be built. Lego now accounts for around 80 per cent of the construction set market.

Technical Lego – now called Lego Technic by the manufacturers – took this a stage further. Intended for use by older children, it was designed with mechanisms rather than just static objects in mind. It has to a large extent filled the niche vacated by Meccano, who fell into difficulties in the 1970s but who had previously dominated that market.

Lego (for which read Lego Technic) is thus highly suitable for constructing your own robots. At the time of writing, Lego have yet to introduce their first robot-related set, but that cannot be far away. Hopefully, the range of technical components will be expanded in the future to incorporate sensors and other electrical devices.

Buying Lego

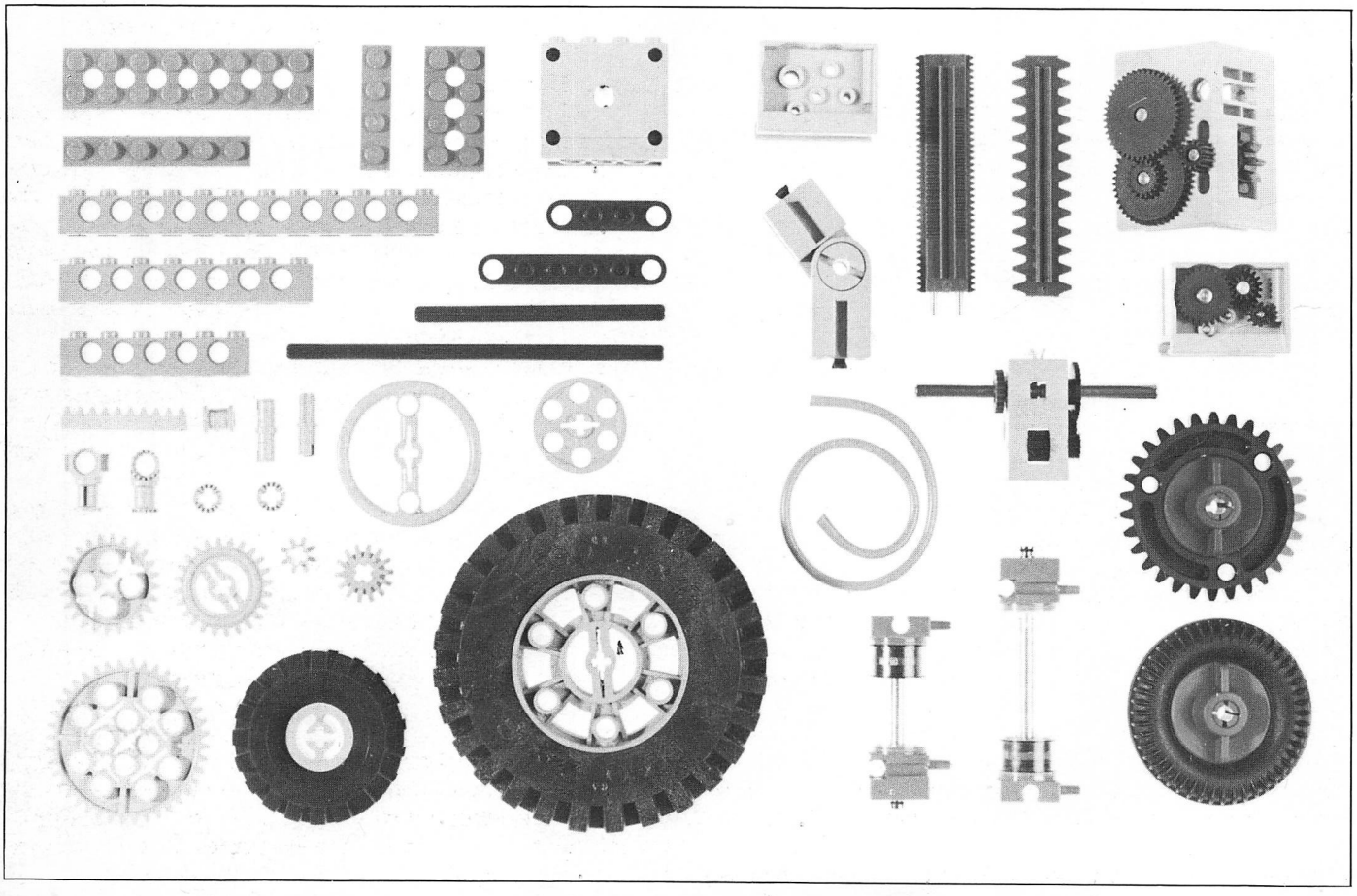
Lego Technic is sold primarily through toyshops and department stores, and most people start out with one of the larger sets, based on a specific model such as a tractor or motor car chassis. These provide a good stock of components with which to start experimenting but are not an economical way of expanding your set.

The 8710 Supplementary Set offers very good value for money – the servo-driven robot arm on pages 126–131 could be made from two such sets alone. Lego also run a spares service, through which you can purchase individual packs of axles, beams, joints, etc. If you don't have the tractor set, or similar, then this is the best way to acquire the large wheels and tyres. Several projects make use of the 40-tooth gear wheels which do not feature in many sets but are available in a spares pack.

Many schools are unaware that they can purchase special educational packs of spares at a substantially reduced price, so it's worth suggesting these robot projects to your teachers!

There's no avoiding the fact that robot projects need plenty of motors – some can be built from one or two, but several require four. Lego motors come in two varieties: 4.5 volt and 12 volt. All the Lego projects in this book feature the former type, but should work perfectly well using the latter. It is best to start with a couple of the 8700 motor sets, which include the battery boxes and switches, but thereafter individual motor units can be purchased for half the price of a motor set through the spares service.

The 8720 gearbox set is also very useful, supplying two types of gearbox and a chain drive as well. The robot arm on pages 134–139 uses one such set – the rover on pages 146–153 uses two. They are quieter in operation and more compact than a whole train of individual gears.



Lego v. Fischertechnik

A comparison of strengths and weaknesses

Lego	Fischertechnik
All measurements must be multiples of the standard unit spacings.	Sliding fittings allow fine adjustments.
Easy and fast to assemble.	Order in which components must be put together not always obvious.
Fixing system relatively weak.	Fixing system very strong.
Fixing system based on original building blocks and therefore very 'directional'. It is possible to align any component any way, but only with difficulty.	No directionality to the fixing system and therefore very good for building three-dimensional objects, particularly the supporting structures around mechanisms.
Easy to pivot one beam or structure on another with connecting pins.	Difficult to make a pivot joint, except with the bulky elbow bricks.
Beams long and slender.	Building blocks rather fat and cumbersome for some applications.
Useful range of gear wheels with fine teeth.	Limited number of gears, each rather bulky.
Gears and wheels fit positively on splined axles. However, wheels can't be made to spin freely.	Gears and wheels rely on friction to grip axles and therefore can't transmit very high torque. Can be made to freewheel, though.
Complete lack of electrical sensors for feedback or control purposes.	Wide range of electrical sensors and other components suitable for robotics.

Fischertechnik

Fischertechnik is manufactured in West Germany, and though it is a rival system to Lego Technic, it has different origins. In the first place, Fischertechnik was designed originally for technical applications (both statics and and mechanics), where Lego grew out of an educational toy. Secondly, it is aimed firmly at the educational and even industrial marketplace. As a family product, in this country at least, it has a low profile, largely due to its higher relative cost and low availability in toyshops, though this may change with the growing interest in home robotics.

In schools and universities, Fischertechnik is used for teaching maths, physics and engineering, while in industry it has formed the basis for engineering prototypes of new products and even to simulate the operation of large plants such as car production lines.

Though in some ways more difficult to assemble than Lego, robots constructed from Fischertechnik more closely resemble their real life counterparts, both visually and functionally. The wide range of sophisticated components, particularly electrical, reduces the need to incorporate non-Fischertechnik parts, which would be difficult to mount.

Buying Fischertechnik

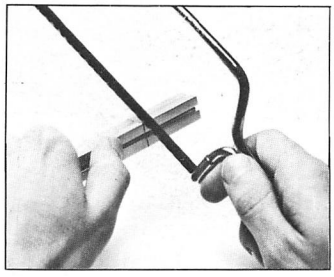
All Fischertechnik sets are general purpose rather than geared towards specific models, and this works to the advantage of the robot experimenter. The UT1 is the best startpoint, preferably supplemented with a UT2 motor set. The minimotors are more useful for robot building than the main motors, though you will need at least one of the latter. Minimotors can be purchased in special sets, complete with a useful range of gears, racking and electrical circuit components, or individually through the spares service.

It is in fact possible to order any component through the spares service, and this is one of Fischertechnik's great assets. The range of electrical components is the best of any construction system, with microswitches, electromagnets and light sensors to name but a few.

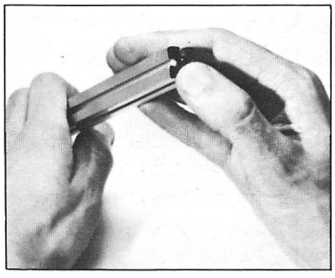
The aluminium extrusion is also invaluable for our purposes, and was interestingly developed specifically for the BBC Buggy. Sawn to the desired length and fitted with end pieces, it provides a neater and stronger structure than individual blocks and is a first-class engineering material.

Two more recently introduced sets of value in robotics are the pneumatics and computing kits. We have used these in two projects only (pages 140–145 and 164–169 respectively), though if you have them they could be built into more. Again, the individual components are available as spares. The statics set looks as though it could be useful because the beams are much thinner than the conventional blocks. They are, however, much more pliable, and therefore not to be recommended for robots.

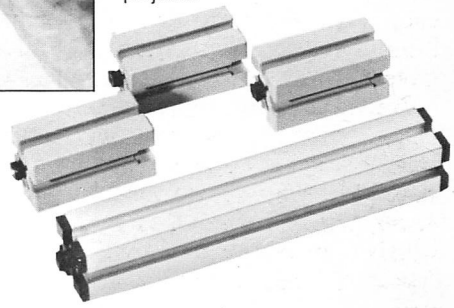
FISCHERTECHNIK ALUMINIUM EXTRUSION



For long beams, aluminium extrusion is neater and stronger than lengths of standard bricks. It is purchased in lengths of 3m (10ft) and can be cut with a junior hacksaw. Mark around the extrusion with a pencil to make sure that the end is sawn off straight.



Black plastic endpieces are purchased separately and inserted. You are advised to cut the extrusion only to standard block lengths (allowing for the endpieces), so that your long beams can be used in a wide variety of projects.



BASIC ELECTRICAL SKILLS

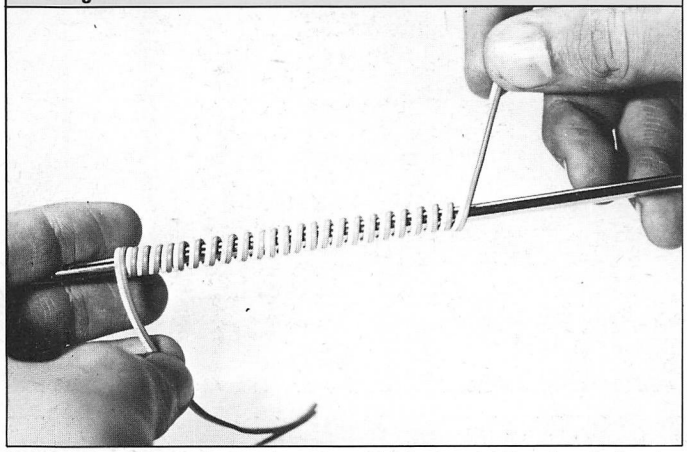
The projects described in the following pages, and other robots that you may build, can be run 'live' from a series of battery boxes fitted with on/off or reversing switches. Interfacing a working model to a computer, however, is far more satisfying. It not only opens up the possibility of programming a sequence of movements into the computer's memory, but it is a very good way to learn about electrical circuits and electronics in general.

Accordingly, the electrics contained in this book are designed to be followed by someone with no previous experience of electronics. Those who have such experience can certainly improve on the performance of the models, using specially designed circuits. But the projects as shown do not require the purchase of any electronic components, and with the exception of the one or two that entail soldering, can be wired together with a small screwdriver.

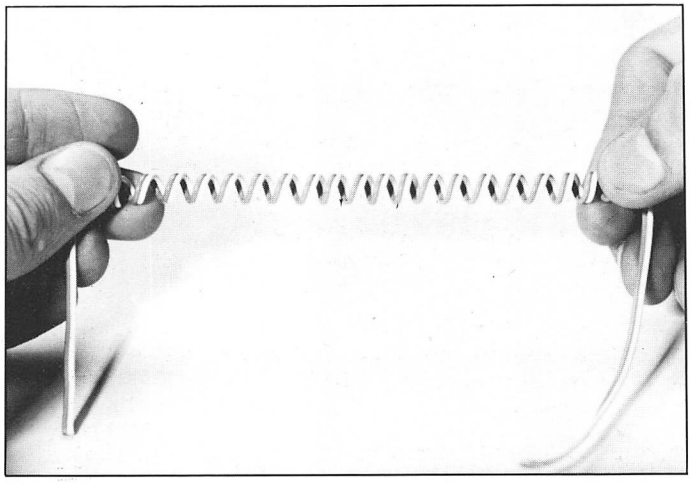
We need to start off with three necessary cautionings. First, none of these projects involve mains electricity. Controlling household appliances from a computer is becoming a popular application, and would be particularly appealing to the robotics experimenter. There are standard and quite safe interfaces available from electronics shops for this sort of thing, but unless you are very experienced in electronics, you are advised not to try interfacing mains devices to a computer yourself.

The second hint is for your equipment's safety, as well as your own: before wiring up a circuit or making modifications, make sure that all equipment is switched off, batteries removed and the computer unplugged from the mains. Third, while most of the projects are built from scratch, the last few are modifications to electronic toys or off-the-shelf robots. The modifications are all reversible – with a little soldering, the toys could be made to function in their original manner. They would nevertheless invalidate the original warranty, and there is alway the risk that the product could be accidentally damaged. These projecta are intended to add excitement and educational value to the toys.

Coiling cable

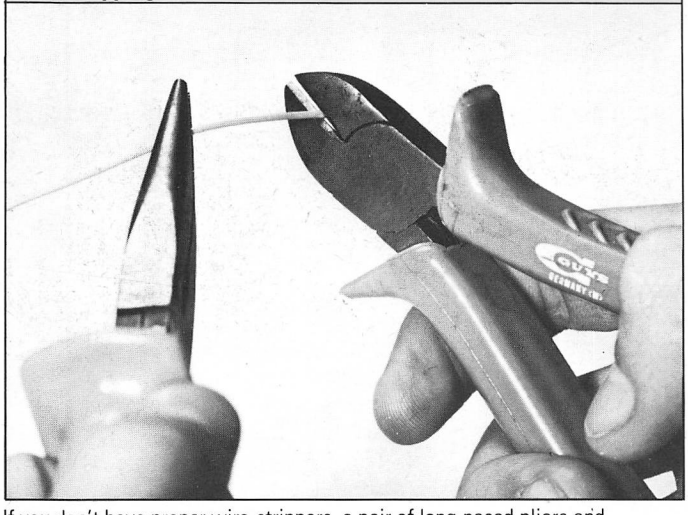


Coiled cables add a professional touch to a finished model. Start by winding the wire around a thin rod or axle, ensuring that it lies flat as shown.



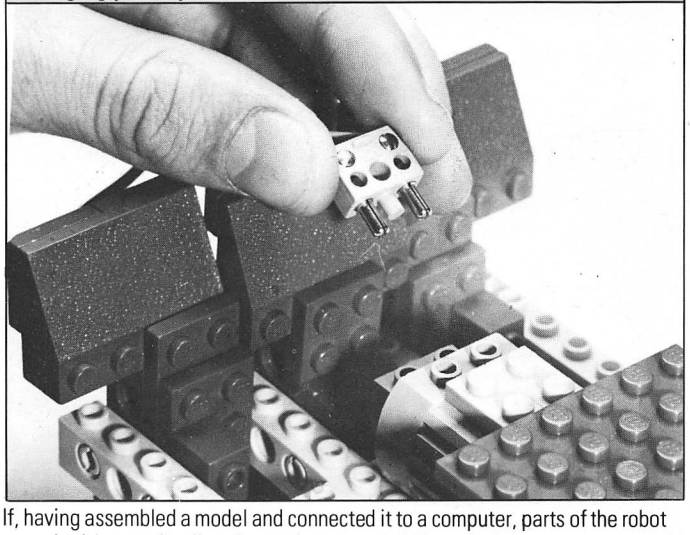
Slide the axle out and stretch the coil slightly. Coiled cable is slightly elastic, which keeps the wiring neat, even when there is movement between the ends.

Wire stripping



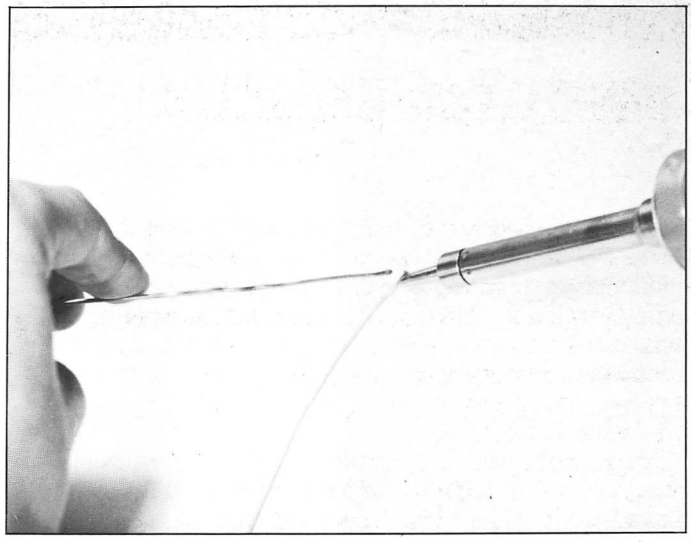
If you don't have proper wire-strippers, a pair of long-nosed pliers and sidecutters can come in very useful for stripping the ends of short lengths of wire.

Changing polarity



If, having assembled a model and connected it to a computer, parts of the robot move in the opposite direction to that expected, the polarity on one or more of the motors simply needs to be reversed. That entails swopping over the two wires leading to the motor, or in the case of Lego, turning around the motor plug.

Soldering

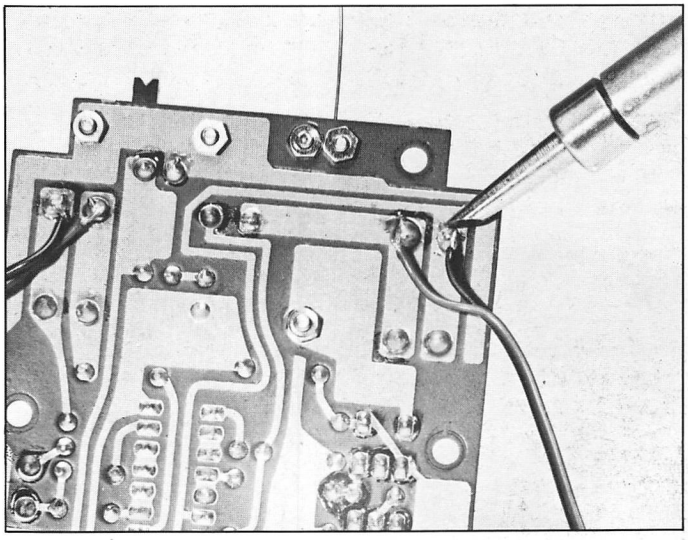


Very few of our projects require any soldering, but for those that do, the technique is shown here. Soldering requires care, but it is not difficult. You will need a soldering iron with a fine tip – preferably a fairly modern design that is intended for electronics work – and some multicore solder. If you don't have access to a vice, Blu-tack is useful for holding the workpiece at the right angle.

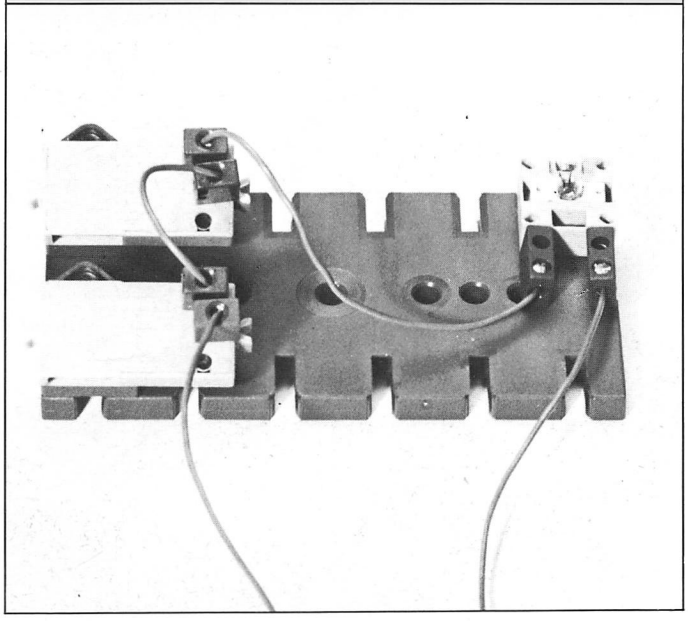
The Golden Rules of Soldering: (1) Disconnect all batteries and power supplies from whatever you are soldering. (2) 'Tin' (coat with solder) all components before attempting to join them. (3) Never apply solder to the soldering iron and then try to transfer it to the joint. (4) When soldering an electronic component or a printed circuit board (PCB), don't leave the soldering iron on the joint for more than a few seconds or the electronics could be damaged.

Tinning the ends of all wires helps considerably. Hold the tip of the iron against the bare wire for a few seconds, then add the solder until a little runs onto the wire. Remove iron and solder and wait to cool.

A tinned piece of wire should affix to a joint on a PCB without additional solder. Place the wire on the joint, then apply the soldering iron for a few seconds. A little solder can be added if the joint is weak.

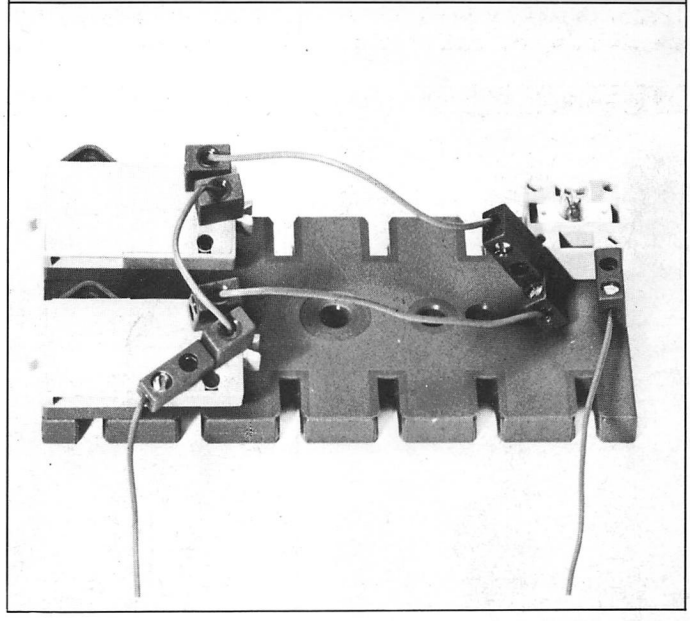


A series circuit



These two microswitches are connected in series and they behave like an AND function in a computer. The circuit is completed (in this case to light the bulb) only when both switches are pressed.

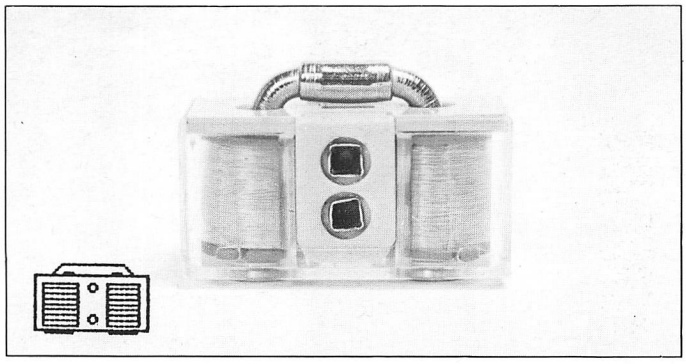
A parallel circuit



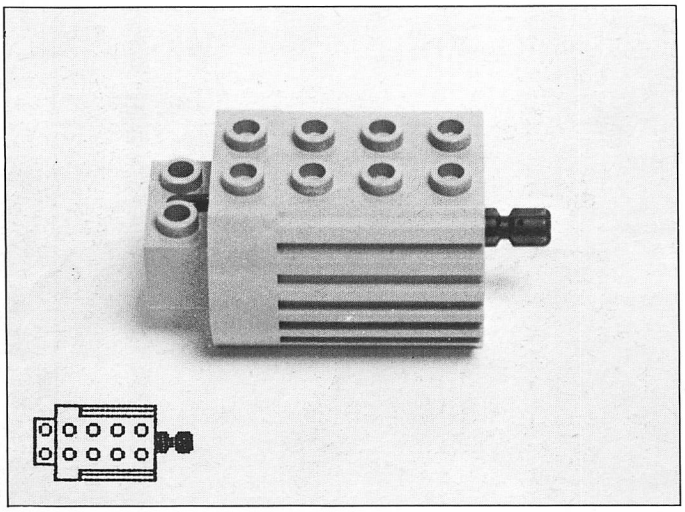
These two microswitches are connected in parallel and they behave like an OR function in a computer. The circuit will be completed by pressing either (or both) of the switches.

KEY TO WIRING DIAGRAMS

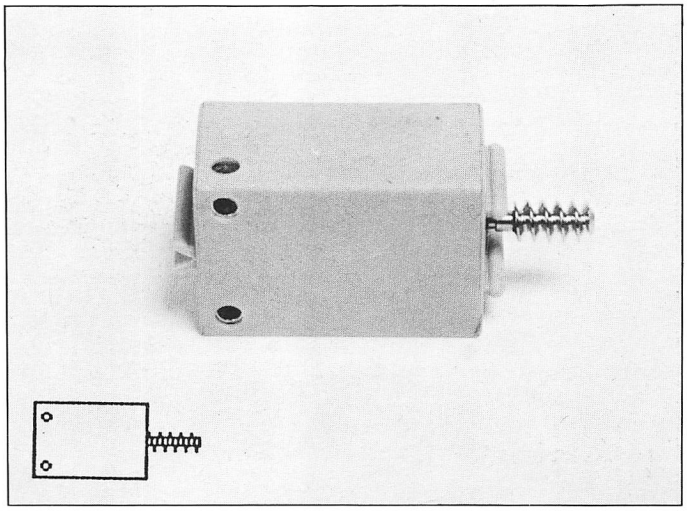
Each of our projects that can be connected to a home computer features a schematic wiring diagram, which shows the interconnection of components but not the actual lengths of wire to be used. Shown here is an explanation of each of the symbols used in these diagrams, together with some of the common circuit arrangements.



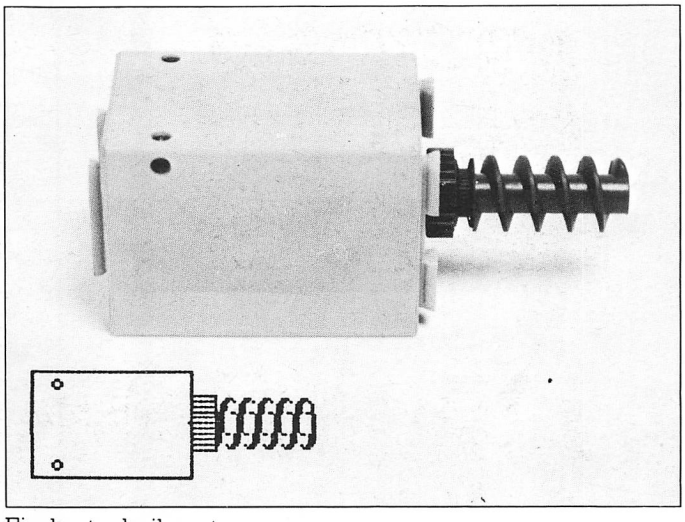
Fischertechnik electromagnet



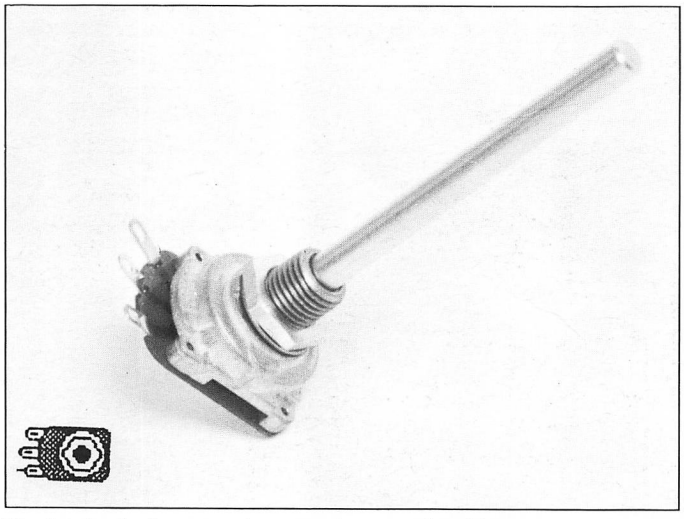
Lego 4.5v motor



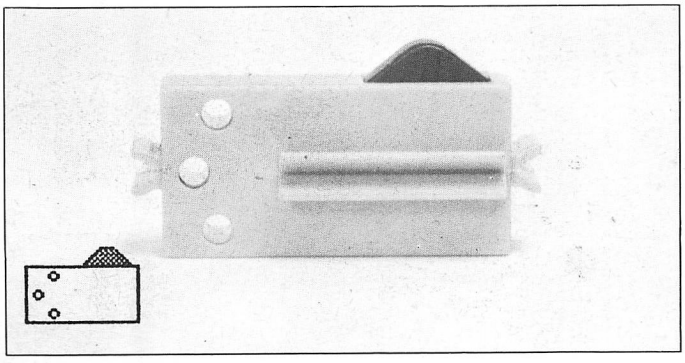
Fischertechnik minimotor



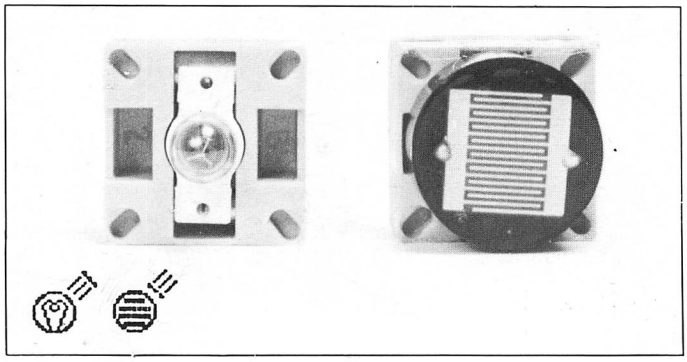
Fischertechnik motor



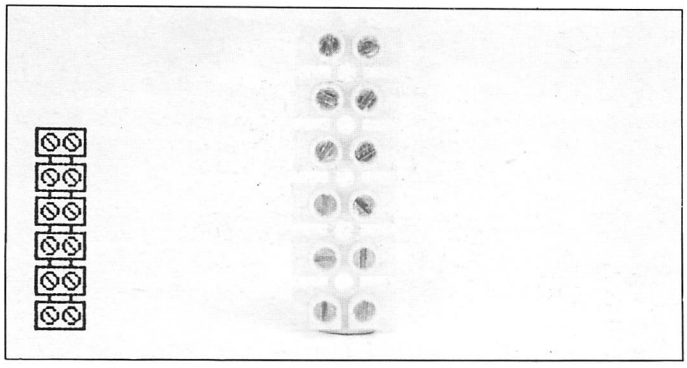
Fischertechnik potentiometer (computing kit)



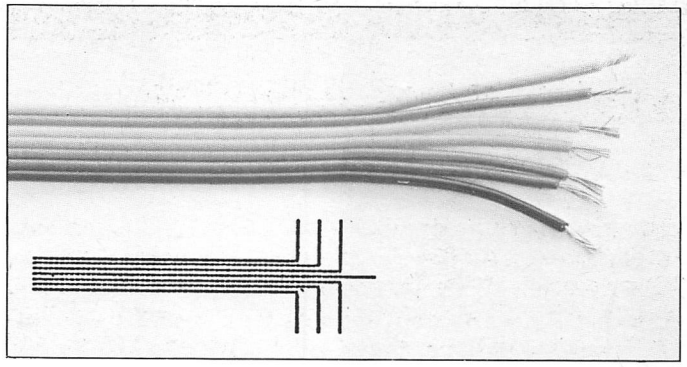
Fischertechnik microswitch



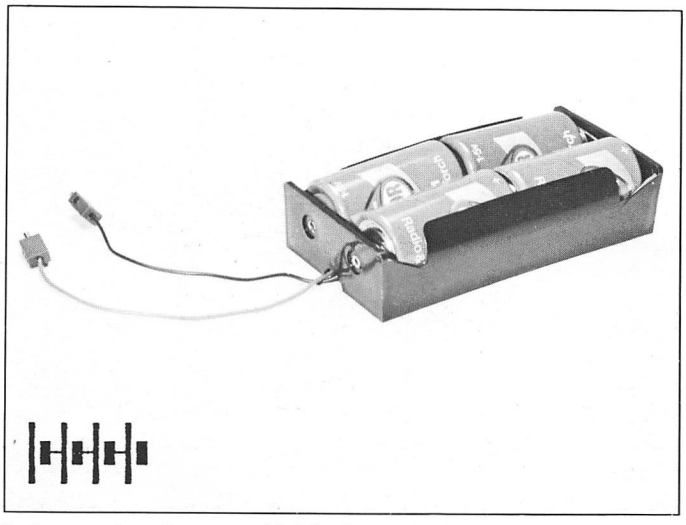
Fischertechnik light bulb and light-sensitive cell



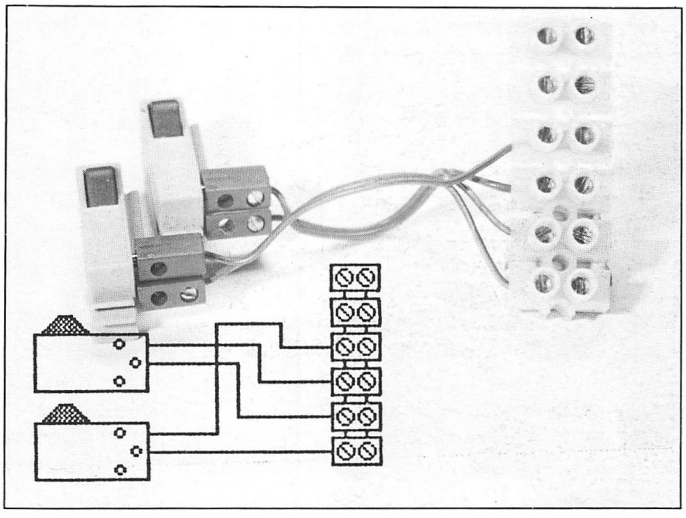
Connector block



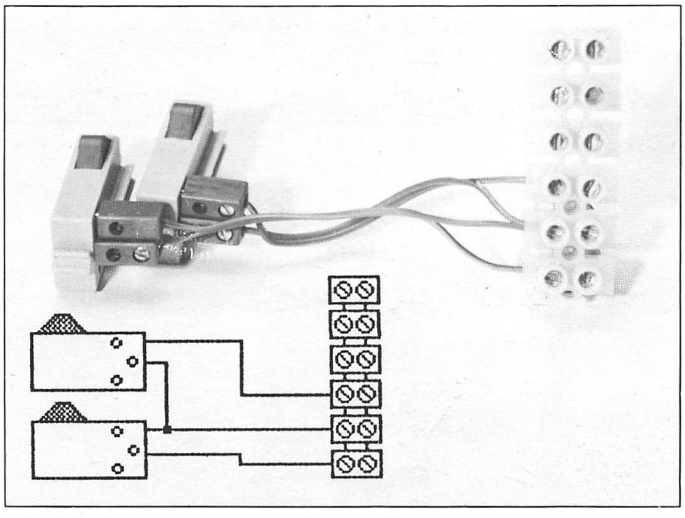
Ribbon cable



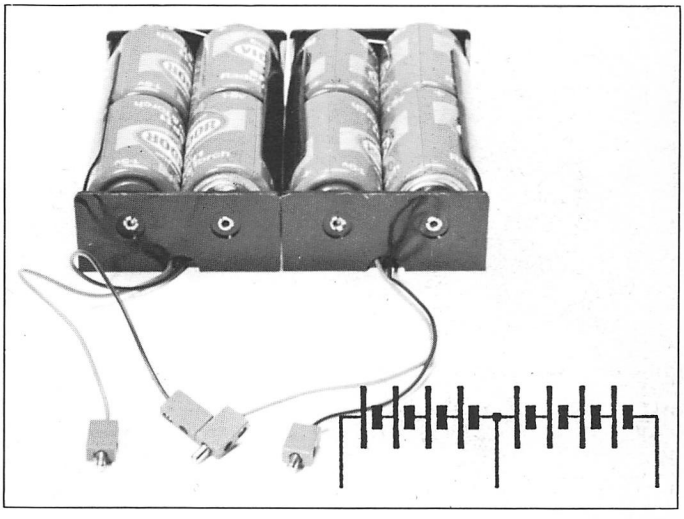
6v battery box for use with Fischertechnik



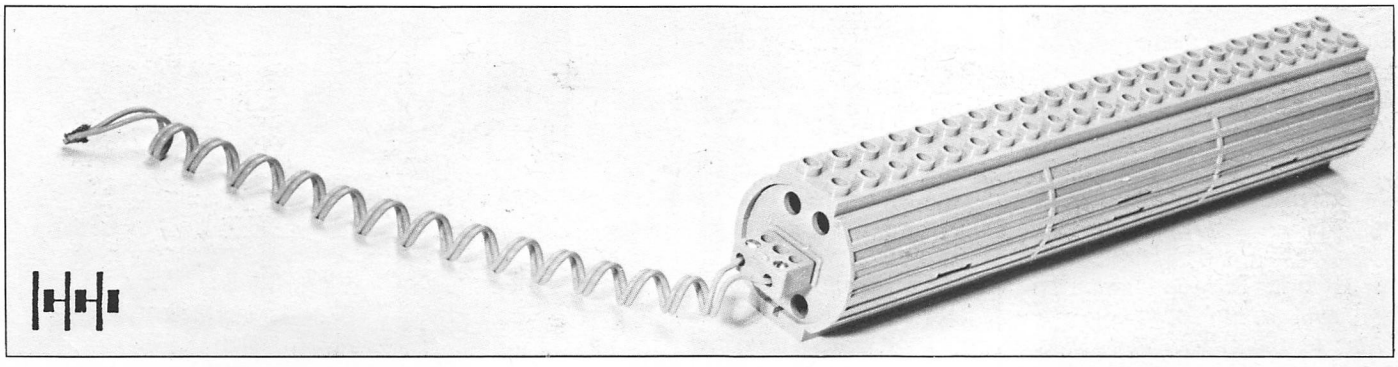
Two wires crossing, without joining



Two wires joining (join usually made at nearest junction)



Double battery box



Lego 4.5v battery box

INTERFACING

Despite their apparent speed and power, computers operate on tiny electronic signals – neither the current nor the voltages inside a computer are large. Devices like motors and electromagnets, however, require much larger currents to operate. A Lego motor, for example, consumes about ½ amp when running freely, and upwards of 2 amps when turning a heavy load. The output ports on a home computer are primarily intended to drive other computer devices, and their maximum current is measured in milliamps (thousandths of an amp). Were you to connect a motor to the output port of most computers, not only would it not turn but it might 'cook' the computer's chips.

The solution is to drive the motors from their normal sources (batteries) and use the computer to make and break the circuit, but without letting the large currents leak back into the computer. The easiest technique for achieving this is to use a relay. A relay has two separate circuits: an input circuit that works on low current, and an output circuit that can handle larger currents. Current in the input activates an electromagnet, which closes the output circuit. Most motor cars employ a relay (though it is called the solenoid) to operate the starter motor, because it would be dangerous to have the 100 amps or so needed by the motor running through the ignition key switch.

A relay is not the only solution to the problem. There are purely electronic devices that employ no mechanics at all, but the relay is an inexpensive device and more difficult to overload and burn out. A relay interface unit, or relay block, is available for most home computers, and with some you will get the choice of several different types. They all work on the same principles, but the method of programming them from the computer varies, as does the nature of their output connections. Here we have insufficient space to print instructions for all possible computers working with all possible relay blocks, and in practice we have restricted ourselves to working with the three widely available systems illustrated: the Commodore Vic-20 with the VicRel (the latter will also work with the Commodore 64), the Sinclair Spectrum with the InterSpec, and the BBC Model B with the InterBeeb. The suppliers of the relay units are listed at the back of the book.

We have tried, however, to make the wiring diagrams sufficiently clear and the programs sufficiently well structured and documented to make it easy to convert them to work with another system, assuming that you have read the instruction manuals of your computer and interface units.

Which relay?

The VicRel has been used in the majority of projects because its six independent relays offer the most flexibility. The InterSpec and InterBeeb (the units are effectively the same) feature only four relays, and one terminal from each of the four is wired together. Most of the projects will transfer easily across – the example on this page shows an equivalent circuit wired up for the two different systems. For the sophisticated projects that do require more than four relays, the only alternative is to implement some of the functions manually – such as the reversing switch as seen in the polar arm project (pages 164–169).

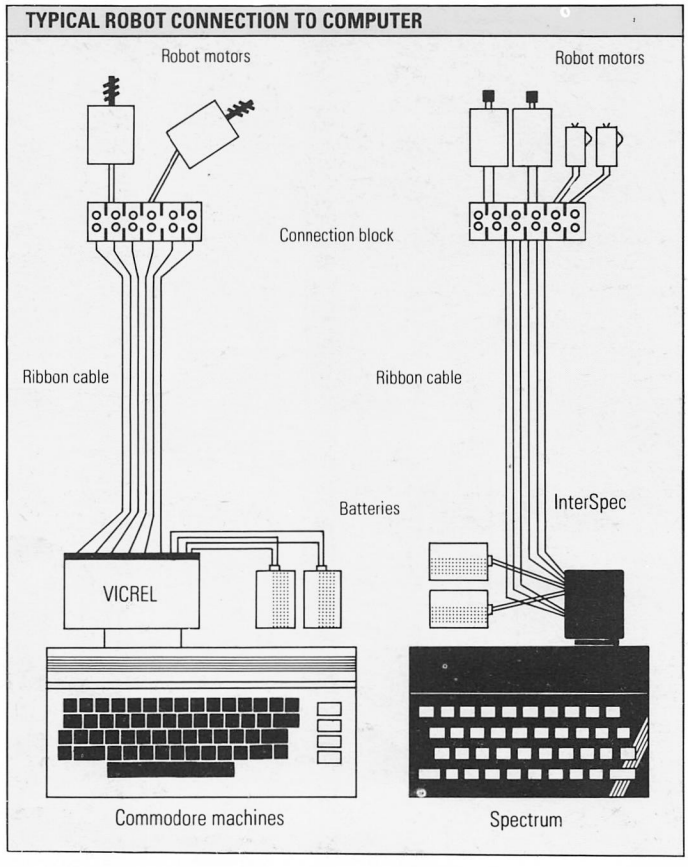
Having all the relays combined together also means that it is only possible to control motors in both directions by using two battery boxes. Accordingly, this approach has been used even with the VicRel, to make conversion easier. The technique of controlling a motor in both directions from one set of batteries is shown in the Lego Toy Android project (see pages 120–123).

Both the interface blocks used have facility for inputs as well as outputs so that the robot can be fitted with sensors such as microswitches or light-sensitive cells. The VicRel has two switch inputs, and the InterSpec and InterBeeb units four. Though constructed from solid state electronics, they act a little like relays in reverse – they protect you from accidentally damaging your computer by inputting too large a current.

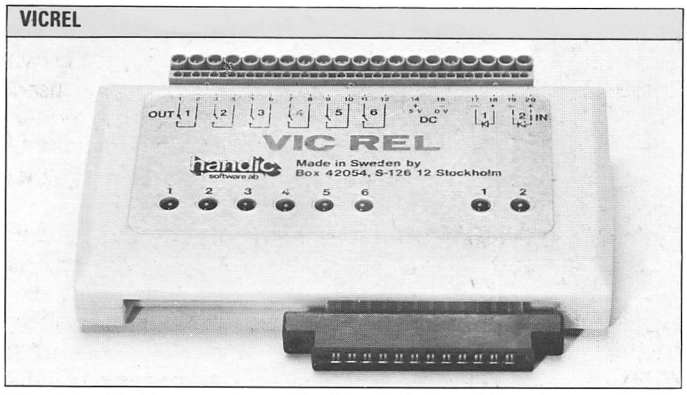
Where the InterSpec and InterBeeb really score over VicRel is with their eight analogue inputs, which can be used with analogue sensors such as microphones and potentiometers. The only project that uses these here is the polar arm, but you can add analogue sensors to many of the others if desired. Some computers have their own analogue input ports specifically for experimentation, and others have inputs for analogue joysticks that could be adapted with appropriate referral to the manual.

Computer control

Programming the relays to open or close and to read the switch or analogue inputs is explained in each system's manual. Programs written on the computer in BASIC will generally access the interface unit through PEEK and POKE statements or their equivalent. We have printed here a very brief summary of the operation of our three choice units, again to assist conversion between them. Lines of BASIC in our printed programs that refer to the interface are few in number – the bulk of each program is concerned with deciding what to control rather than how.



VICREL



Works with Commodore Vic-20 or 64. Provides six independent relays (with two terminals each), two opto-couplers (for linking to switch inputs), 5v and Ground terminals.

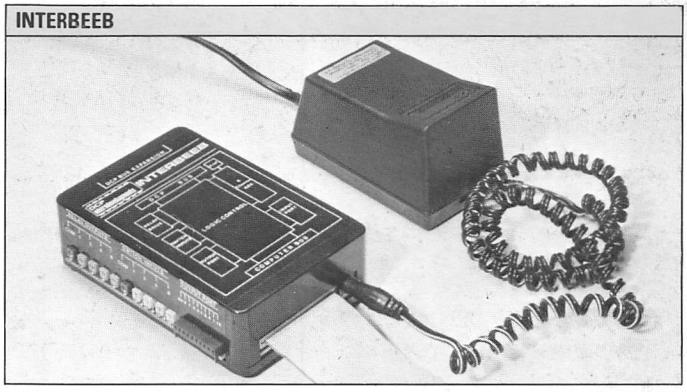
VicRel plugs into the user port and is initialized by POKE 37138,63 (Vic) and POKE 56579,63 (Commodore 64). Relays are controlled and switch inputs read through location 37136 (56577 on the '64) – the lowest six bits controlling the relays, the highest two bits reading the switches. Thus:

POKE 37136,53 will close four of the six relays, because 53 is 110101 in binary.

PRINT PEEK(37136)AND64 will print 0 if the first switch is closed and 64 if it is open.

PRINT PEEK(37136)AND128 will print 0 if the second switch is closed and 128 if it is open.

INTERBEEB



Works with BBC Micro and comes with an external transformer. Provides four commoned relays (a total of five terminals), four commoned switch inputs, 8-bit input port, 8-bit output port (these function like a user port), eight analogue inputs which can measure any voltage between 0 and 2.45 volts, plus 5v and Ground terminals.

To close relays: ?&FCC1=n, where n is in the range 0 to 15; e.g. 0 opens all relays, 11 closes relays 1, 2 and 8.

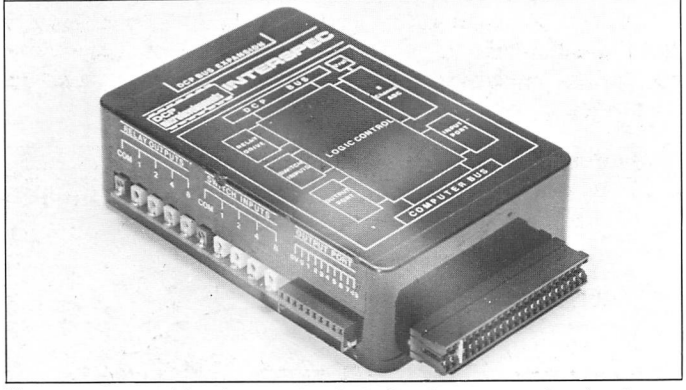
To read switch inputs: PRINT ?&FCC1 returns a number in the range 0 to 15, corresponding to the closed switches. 0 means all are open.

Output port: ?&FCC2=n (n is in range 0 to 255).

Input port: PRINT ?&FCC2 returns a value in range 0 to 255.

To read an analogue input, ?&FCC0=n, where n is in the range 0 to 7 corresponding to the input required. PRINT ?&FCC0 will then return a value in the range 0 to 255 proportional to the voltage being read.

INTERSPEC



Has same specification as the InterBeeb, except that it takes its power from the Spectrum computer.

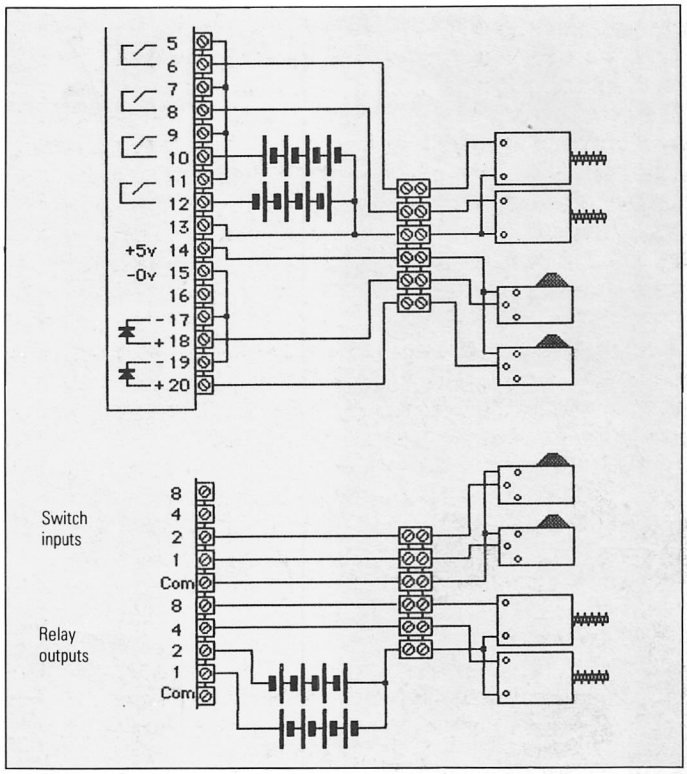
To close relays: OUT 63,n where n is in the range 0 to 15. Set the appropriate bit to 0 to open the relay again.

To read switch inputs: PRINT (IN 63)–240 will return a value in the range 0 to 15.

Output port: OUT 95,n where n is in the range 0 to 255.

Input port: PRINT IN 95 returns a value in the range 0 to 255.

To read an analogue input: OUT 31,n where n is in the range 0 to 7 corresponding to the channel required. Then PRINT IN 31 returns a value in the range 0 to 255.



Wiring. The diagrams show an identical circuit (the one for the buggy built from Fischertechnik) wired to the two types of interface block. On the VicRel, the four relays are connected together with an external common wire. On the InterSpec/InterBeeb the relays are commoned internally. The same is true for the switch inputs. Note also that the switch inputs on the VicRel must be driven from the 5v supply, whereas the other units merely require a connection between the input line and the common line.

IMPORTANT NOTE:

After switching on, all relays must be set to open before any batteries are connected. When the relay block is first switched on any of the relays may be closed – in some circuits this could short-circuit the batteries and cause possible damage. The program listings in this book contain an initialization routine, so the safest policy is to load and run the program first.

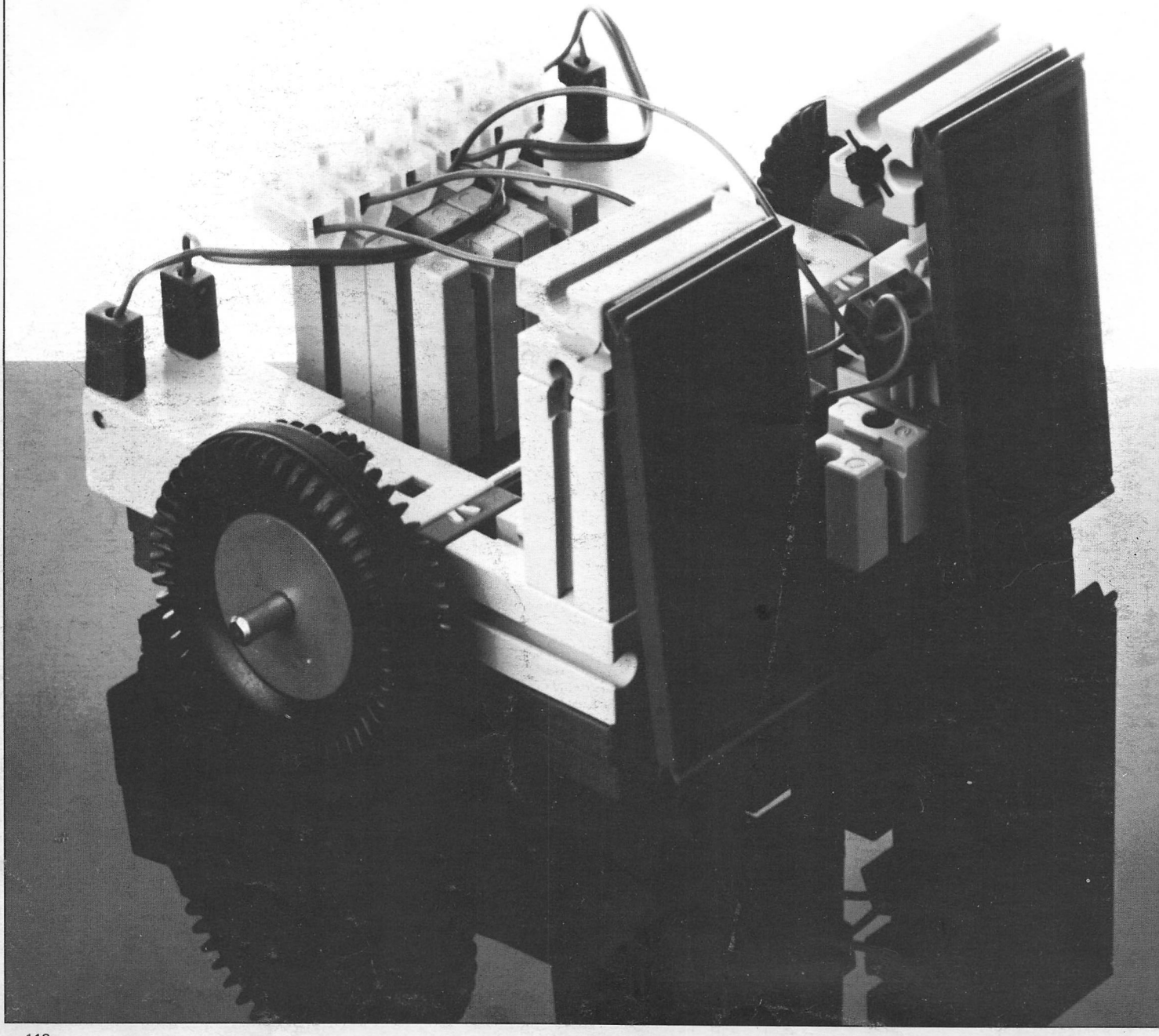
BUGGIES IN FISCHER-TECHNIK AND LEGO

Floor buggies are the simplest type of robot device to design, build and interface to a home computer. A floor buggy is a small mobile unit linked to a computer by means of an umbilical cord through which the motors receive their instructions and their electrical power – unless batteries are carried onboard.

Most buggies feature two main wheels, independently driven by motors, and the chassis is balanced with either a third, castor, wheel or a simple peg that drags along the ground. Buggies are designed to move around on smooth surfaces, and few will function correctly on a carpet.

The buggies can move in a straight line forwards or backwards, or they can be made to turn on their axis by driving the two wheels in opposite directions. The movement can be controlled in live mode, by pressing keys on the keyboard, or a movement routine can be built up in the computer's memory and then executed at the touch of a button.

Collision detectors mounted on the front or on all four corners of the buggy can send signals back to the computer whenever the vehicle bumps into an obstacle. In this way, the buggy can be programmed to explore a room and build up an

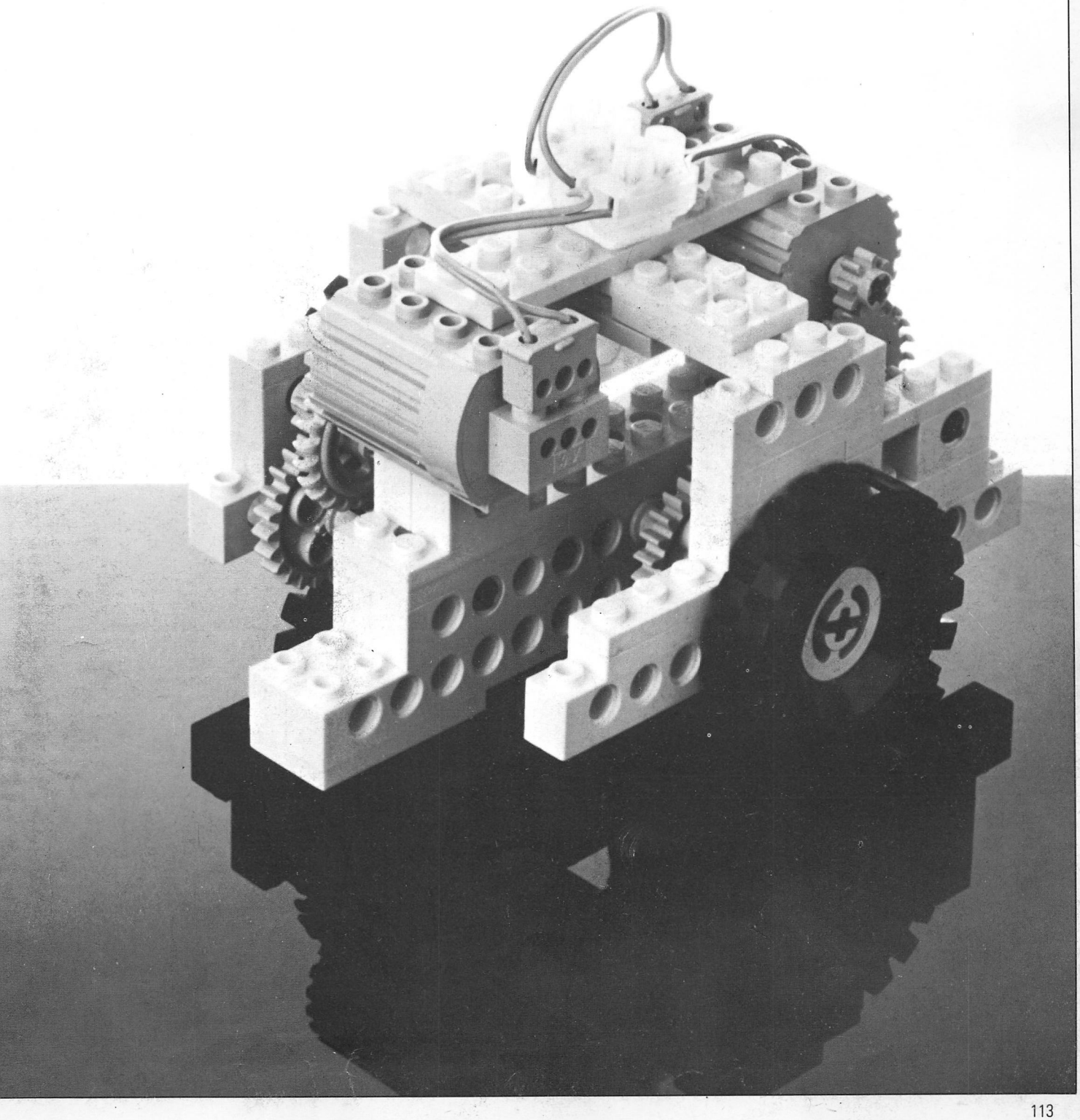


appropriate map in the computer's memory. Other types of sensor that can be fitted to the chassis include ultrasonic rangefinding units for detecting obstacles before the vehicle hits them, and light detectors that enable the buggy to follow lines drawn on the floor.

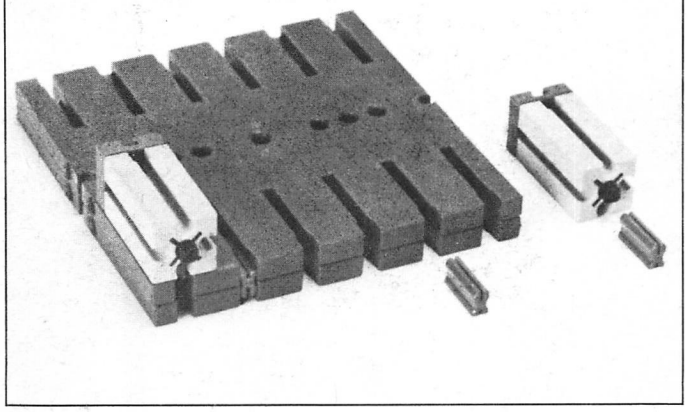
This project shows how to construct a very simple floor buggy from either Fischertechnik or Lego. The two designs can be driven using the same interface and program, though the Fischertechnik buggy is also equipped with two collision detectors made from microswitches. Using our simple program as a starting point, you can write your own applications for the buggies.

Be warned, however, that these buggies do not move as accurately as commercially available floor robots. Unless you are lucky, the two motors will not run at identical speed, so the buggy won't move in a true straight line. Furthermore, the only way to control the distance these buggies move is by activating the motors for a known time. Floor robots costing £100 or more employ electronic feedback to obtain precise movements – it is possible for these buggies to draw fine patterns on the floor by fitting a pen between their wheels.

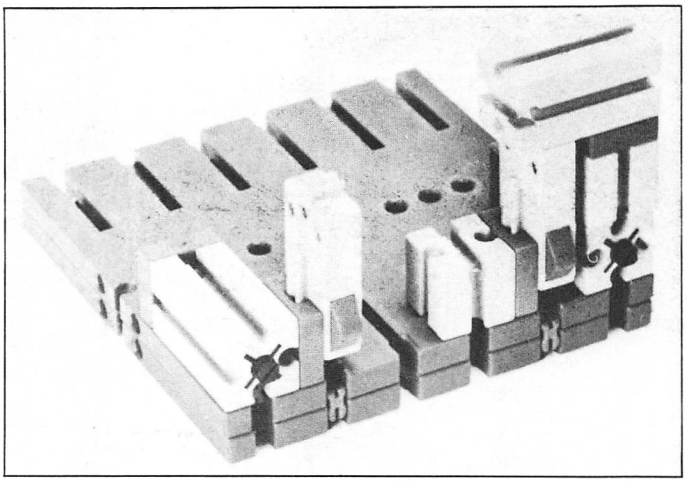
The Motor Control project on pages 118-119 shows how you can incorporate simple feedback into Fischertechnik models and also control the speed at which the motors run. You could therefore go on to design a more sophisticated buggy incorporating both these principles. But for the moment, the two models shown here can be built very cheaply and provide a lot of fun.



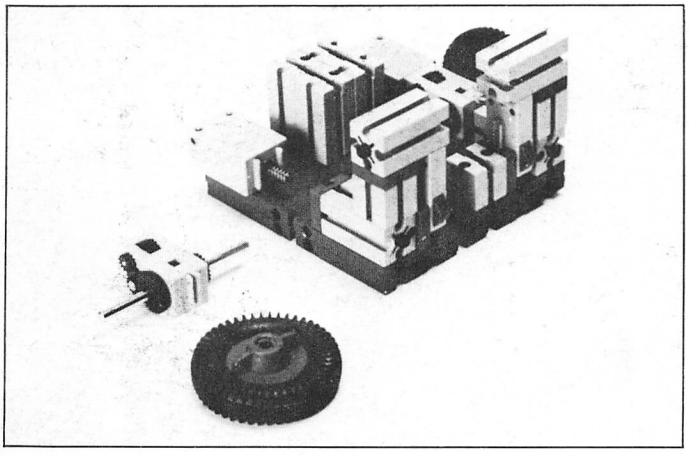
FISCHERTECHNIK BUGGY CONSTRUCTION



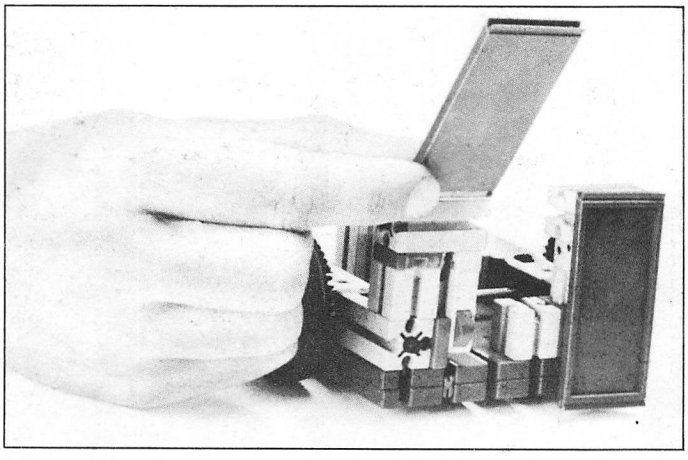
1 Two of the square, red baseboards, one atop the other, form the chassis of this buggy; they are pinned together at the front and back. This gives the vehicle more weight and minimizes the ground clearance so that the buggy doesn't wobble when it changes direction.



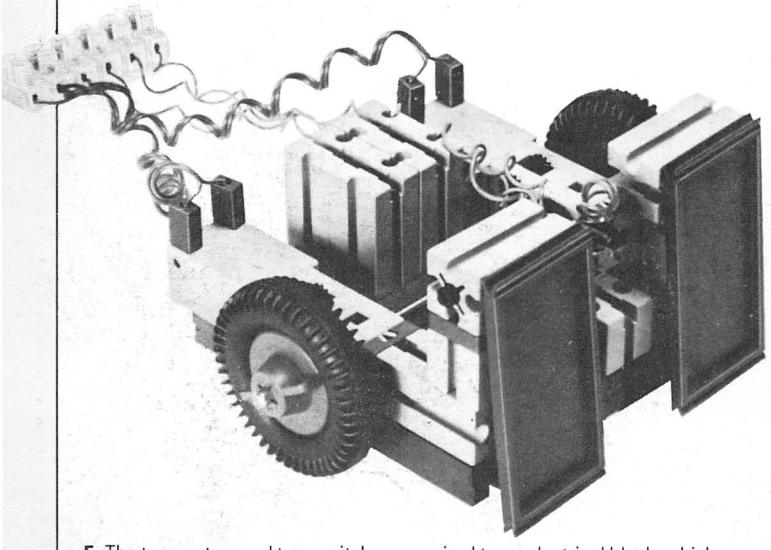
2 Microswitches are used as collision detectors since they require very little force to close the contacts. Because the microswitches feature the Fischertechnik fitting on one side only, the left and right detectors are mounted in different ways.



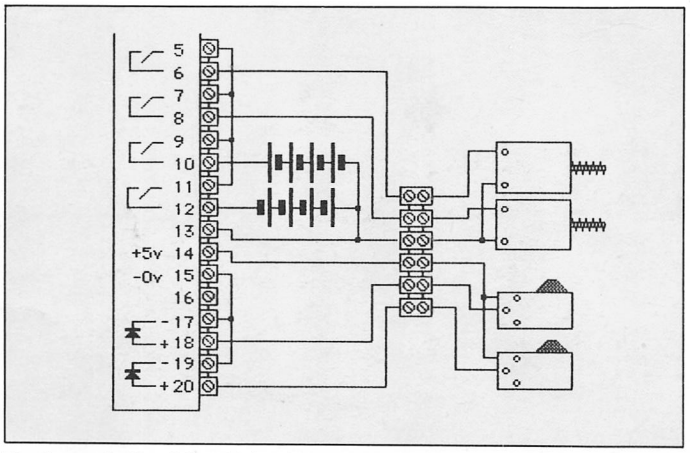
3 Four standard blocks are fitted to weight down the rear. The minimotors slide into the baseboard from the rear, and then each gearbox can be mounted on the motor shaft from the top. The driving wheels need the rubber rings fitted to them for extra grip.



4 Two red plates hang in front of the microswitches to act as bumpers. The most convenient way to mount them is with a piece of sticky tape, acting as a hinge. Check that the switches close when the bumpers are pressed.

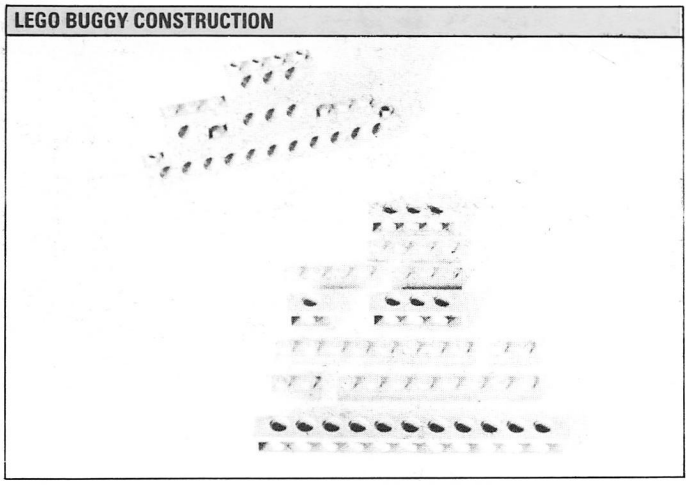


5 The two motors and two switches are wired to an electrical block, which can then be stuck onto the chassis. Ribbon cable or multicore wire, preferably at least 3m (10ft) in length, can be used for the umbilical link to the computer.

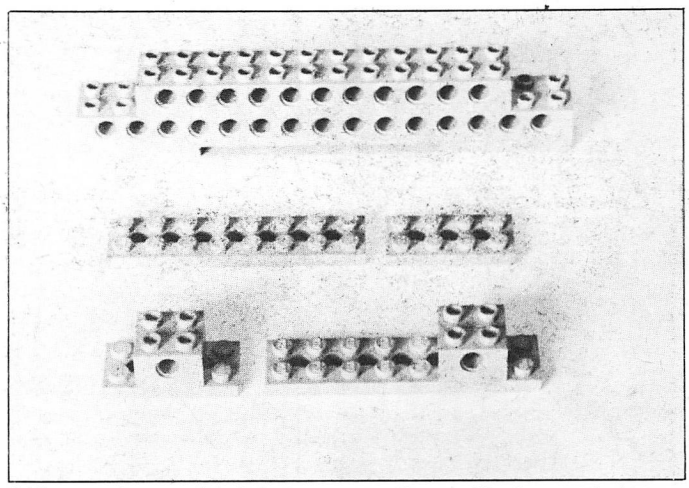


Fischertechnik wiring. Using the VicRel's six relays, it is possible to run the two motors in both directions using just a single set of batteries. Two sets have been used in this circuit so that the buggy can be driven using other interface blocks that feature just four relays. If when connected up the buggy moves forwards or backwards when it should turn, or vice versa, swop over the two wires on one or both of the motors to make them spin in the correct direction.

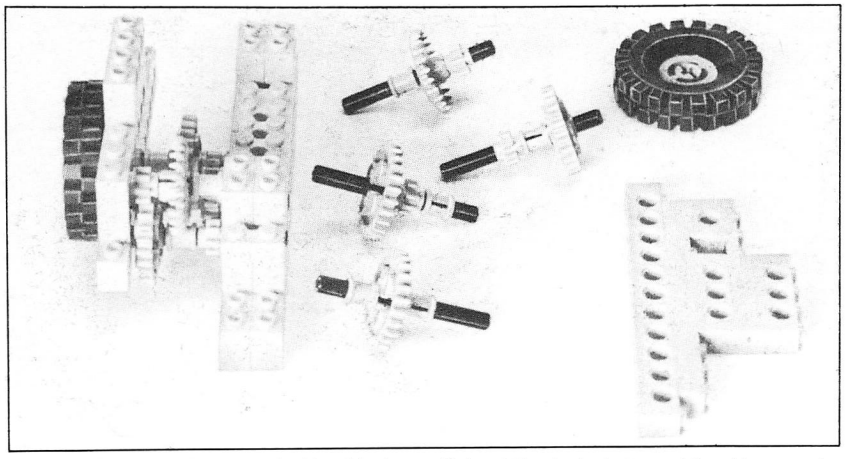
LEGO BUGGY CONSTRUCTION



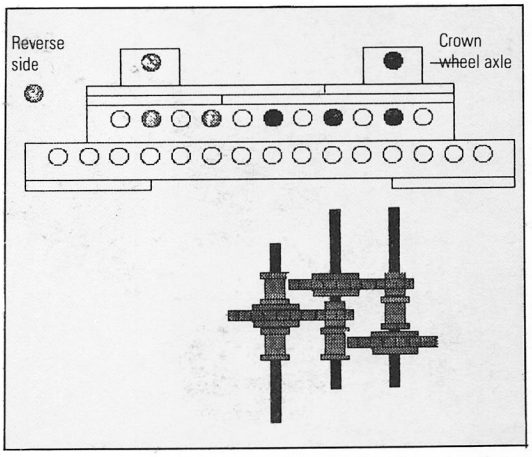
1 This buggy is symmetrical in design. Two identical side supports are constructed first, using single-thickness beams and plates.



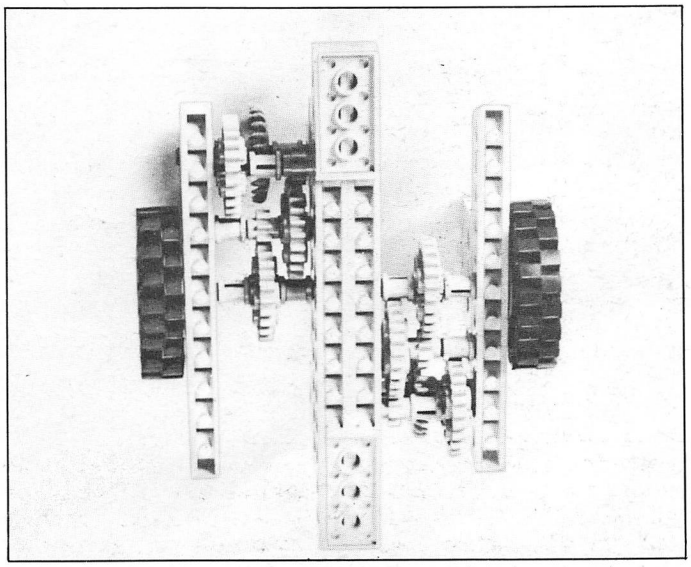
2 The central support is built in three stages. The two thin plates on the bottom of the support are to reduce ground clearance.



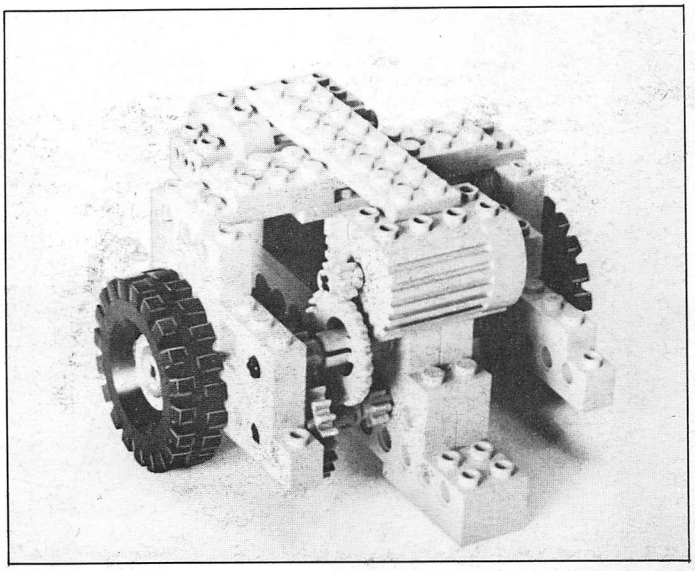
3 Three of the four axles on each side of the buggy fit into holes in the bottom of the side supports and in the middle row of the centre support. The axle with the crown wheel is located in the next rows up.



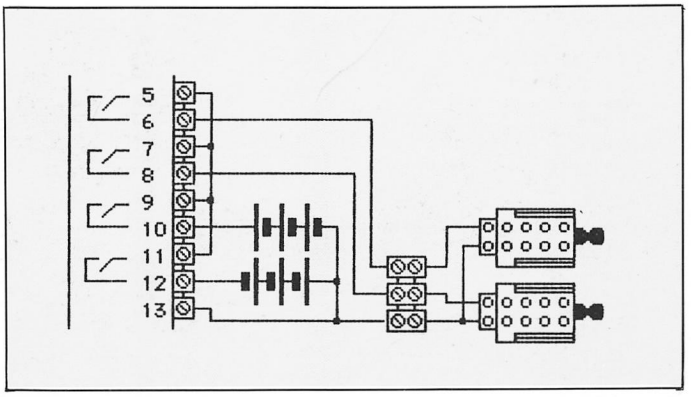
4 This diagram shows the location of three of the axles on each side of the centre support, in the 11-hole beam. The fourth axle sits on the row above and contains a crown wheel to mesh with the motor.



5 The chassis complete and wheels fitted to the central axles, from below. The crown wheels are therefore partially hidden.



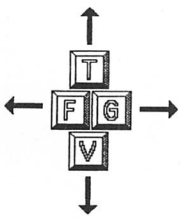
6 The motors, mounted fore and aft, engage on the crown wheels, and two cross-members then hold the structure together.



Lego wiring. Lego motors require three batteries per set instead of four, and there are no microswitches in the circuit. You could construct your own collision detectors using simple push-button switches, or even two pieces of wire that when bumped make contact with one another.

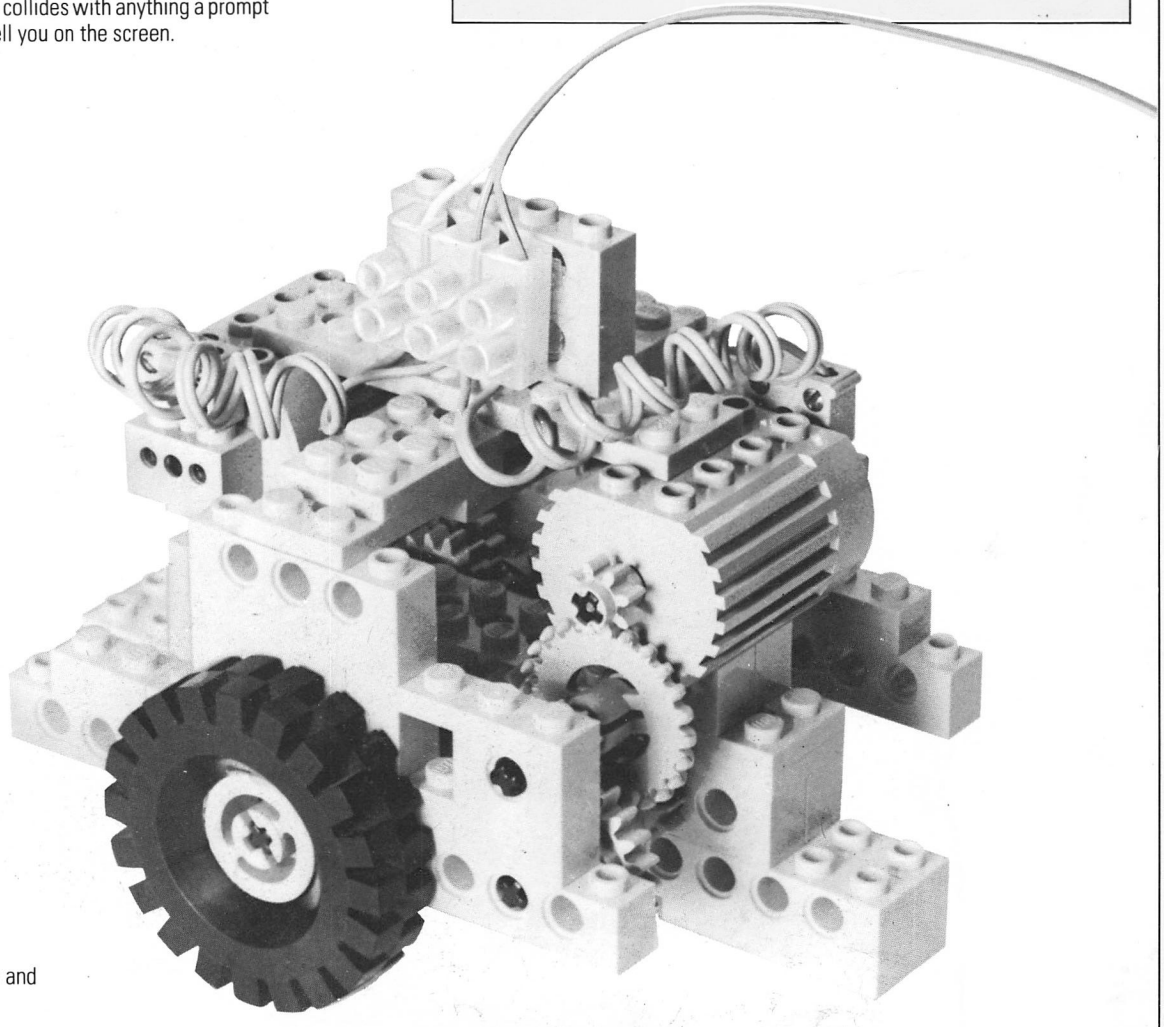
Program. This was written for the Commodore Vic-20 with the VicRel interface unit. It will run on the Commodore 64, too, using the modifications shown. For other computers, re-write each of the subroutines with reference to the instruction manual for computer and interface block.

WARNING: LOAD AND RUN THE COMPUTER PROGRAM BEFORE INSERTING THE BATTERIES IN THE BATTERY HOLDER.



Press T, F, G and V to drive the buggy. Releasing a key stops the buggy. If the buggy collides with anything a prompt will tell you on the screen.

```
10 REM**BUGGY CONTROLLER**
20 REM**INITIALIZE**
30 CN=37136:POKECN+2,63
40 PRINT"INSERT BATTERIES"
50 REM**KEYBOARD VALUES**
60 KA=197:FK=50:BK=27:LK=42:RK=19
70 REM**CONTROL VALUES**
80 FW=28:RV=44:LF=20:LR=36:RF=24:RR=40
90 LB=64:RB=128
92 LH$="LEFT HAND COLLISION"
93 RH$="RIGHT HAND COLLISION"
100 REM**KEYBOARD CONTROL**
110 A=PEEK(KA)
120 IFA=FKTHENGOSUB200
130 IFA=BKTHENGOSUB300
140 IFA=RKTHENGOSUB400
150 IFA=LKTHENGOSUB500
160 IFA=255THENPOKECN,0
170 GOTO110
200 REM**DRIVE FORWARDS**
210 POKECN,FW:GOSUB600
220 RETURN
300 REM**DRIVE BACKWARDS**
310 POKECN,BW:GOSUB600
320 RETURN
400 REM**TURN RIGHT**
410 POKECN,RR:GOSUB600
420 POKECN,LF:GOSUB600:POKECN,0:RETURN
500 REM**TURN LEFT**
510 POKECN,LR:GOSUB600
520 POKECN,RF:GOSUB600:POKECN,0:RETURN
600 REM**TEST BUMPERS**
610 IF(PEEK(CN)ANDLB)=0THENPRINTLH$:GOSUB700
620 IF(PEEK(CN)ANDRB)=0THENPRINTRH$:GOSUB700
630 RETURN
700 REM**STOP+SLIGHT DELAY**
710 POKECN,0:FORI=0TO50:NEXTI:RETURN
```



The complete buggy, wired up and ready to go.

HARMONIC DRIVE SIMULATION

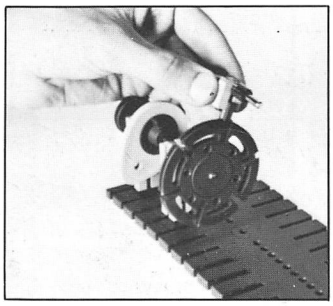
Electric motors used in industrial robots are geared down by a ratio of several hundred to one, to both reduce the speed of rotation and increase the torque (turning force) available to do useful work. The gearing mechanism can be achieved using several stages of conventional gears, but each stage introduces an element of free play, called backlash, which is very undesirable for precise control.

Conceivably the gearing down could be done in just one stage, using one very large cog and one very small one. However, the drive then becomes asymmetrical: the output shaft is not in line with the input shaft. This is awkward for many robot structures. Also, at the join between the two cogs only a few teeth mesh, which reduces the maximum force that can be transmitted.

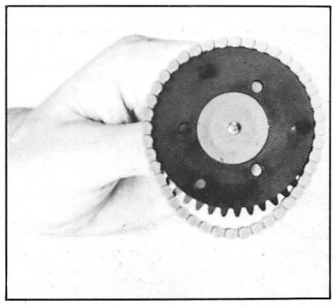
The harmonic drive is an elegant piece of design that employs just three components – two moving, one static – to gear down by as much as 300 to 1. It introduces very little backlash and, because many teeth are meshed together, it can bear very high loading. Four harmonic drives were used on the independently powered wheels of the Apollo lunar rover, and currently they form an integral part of most electrically powered robots.

The drive is precision engineered, and cannot be emulated by the home constructor. The project shown here, therefore, only demonstrates the broad principles on which the harmonic drive works. It uses Fischertechnik.

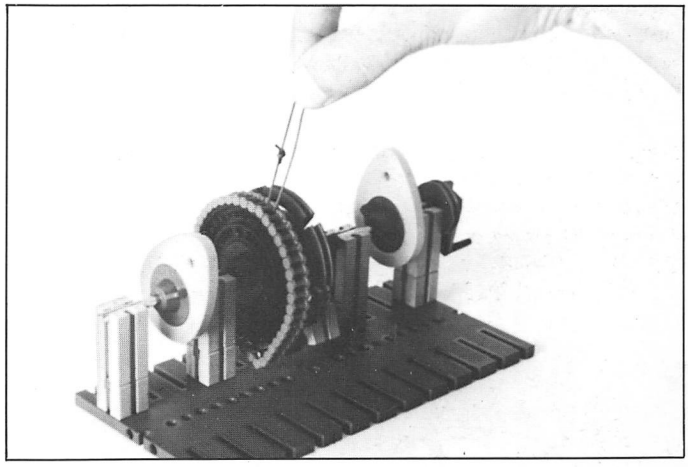
The three components of a harmonic drive are a circular spline, a flexible spline and a wave generator. In our model, the flexible spline (the chain) has 42 links, and is prevented from rotating by the loop of string. The circular spline has 40 teeth and is affixed to the output shaft. As the input shaft is turned, the wave generator moves round between the circular and flexible splines. Now as the flexible spline can't rotate, the circular spline is forced to turn slowly backwards – to keep up with the number of teeth. When the input shaft has turned through one revolution clockwise, the output shaft will have turned anticlockwise by two teeth (42–40).



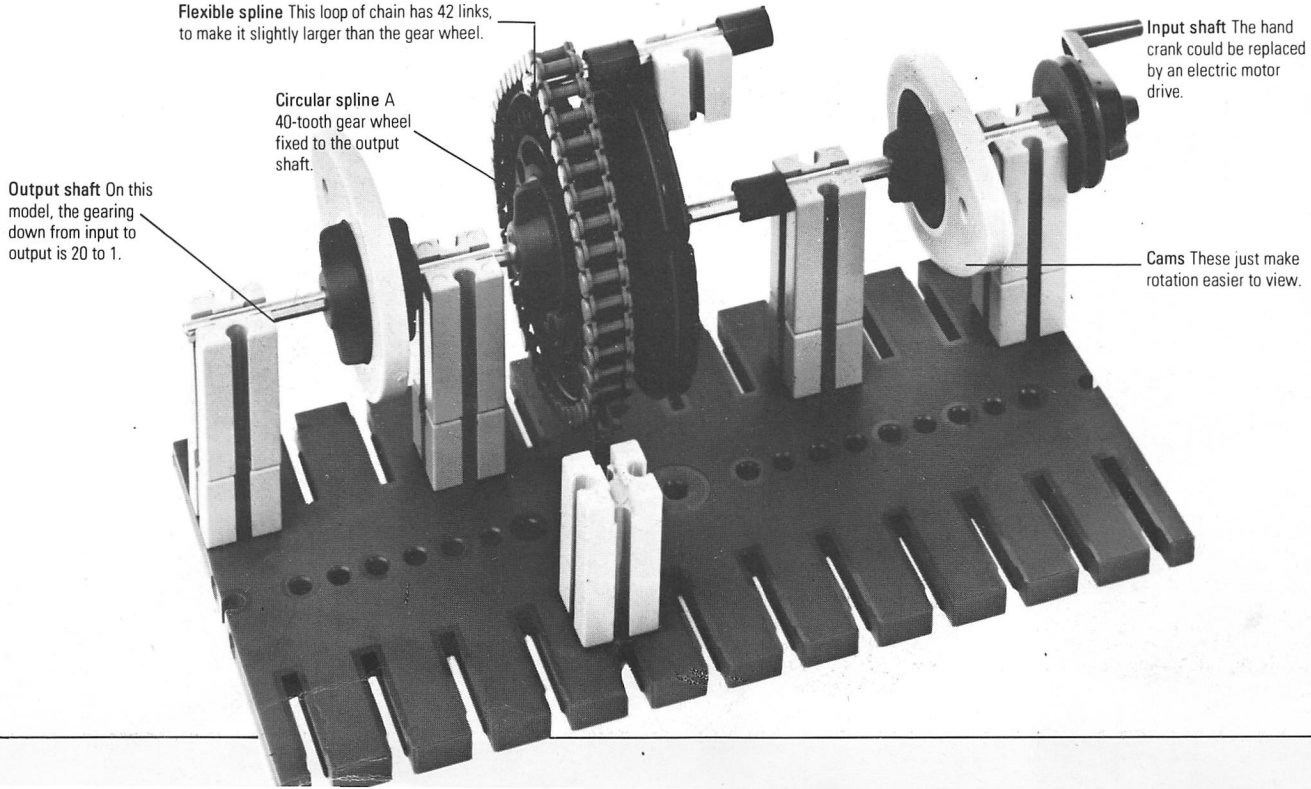
1 The stub axle is mounted on the large red wheel in such a way that it can be adjusted to take up the slack in the chain.



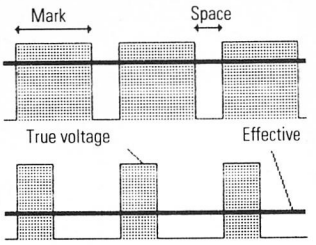
2 Mounted on the gear wheel, the chain should hang away from the lower teeth, forming an egg shape.



3 A loop of string is tied through one link of the chain, then secured to a block on the baseboard. Adjust the tension by sliding the block so that the chain is not pulled away from the gear wheel.



MOTOR CONTROL



Pulse width modulation. The diagram shows how the effective voltage supplied to the motor can be increased or decreased by modifying the length of time the power is left on and off. Long pulses of power at short intervals (above) produce the highest effective voltage.

Though a small electric motor can be linked to a home computer using a relay, and switched on and off by a single BASIC command, building useful robot devices requires far more sophisticated control. The robot engineer must be able to control both the speed at which the motor turns and the position where it stops. This can be achieved using dedicated electronic circuitry, but this project demonstrates that both types of control are possible with a standard interface block and some clever programming.

The photographs show how to build a simple winch mechanism. The objective is to control the rate at which string is wound in and to stop the drum at any desired position – verified by the movement of a weight hanging on the end of the string. The winch itself could be built directly into a model crane, but the principles demonstrated can be incorporated into any small robot device, and indeed form the basis of the more sophisticated projects in this book.

Fischertechnik has been chosen for the design because the kit has its own microswitches. The speed control part of this project will work equally well with a Lego or any other small electric motor. Then the only change needed in the wiring diagram is to fit the correct number of batteries for the motor. To achieve position control with Lego, you will need to incorporate a non-Lego microswitch, several types of which are readily available from radio spares suppliers.

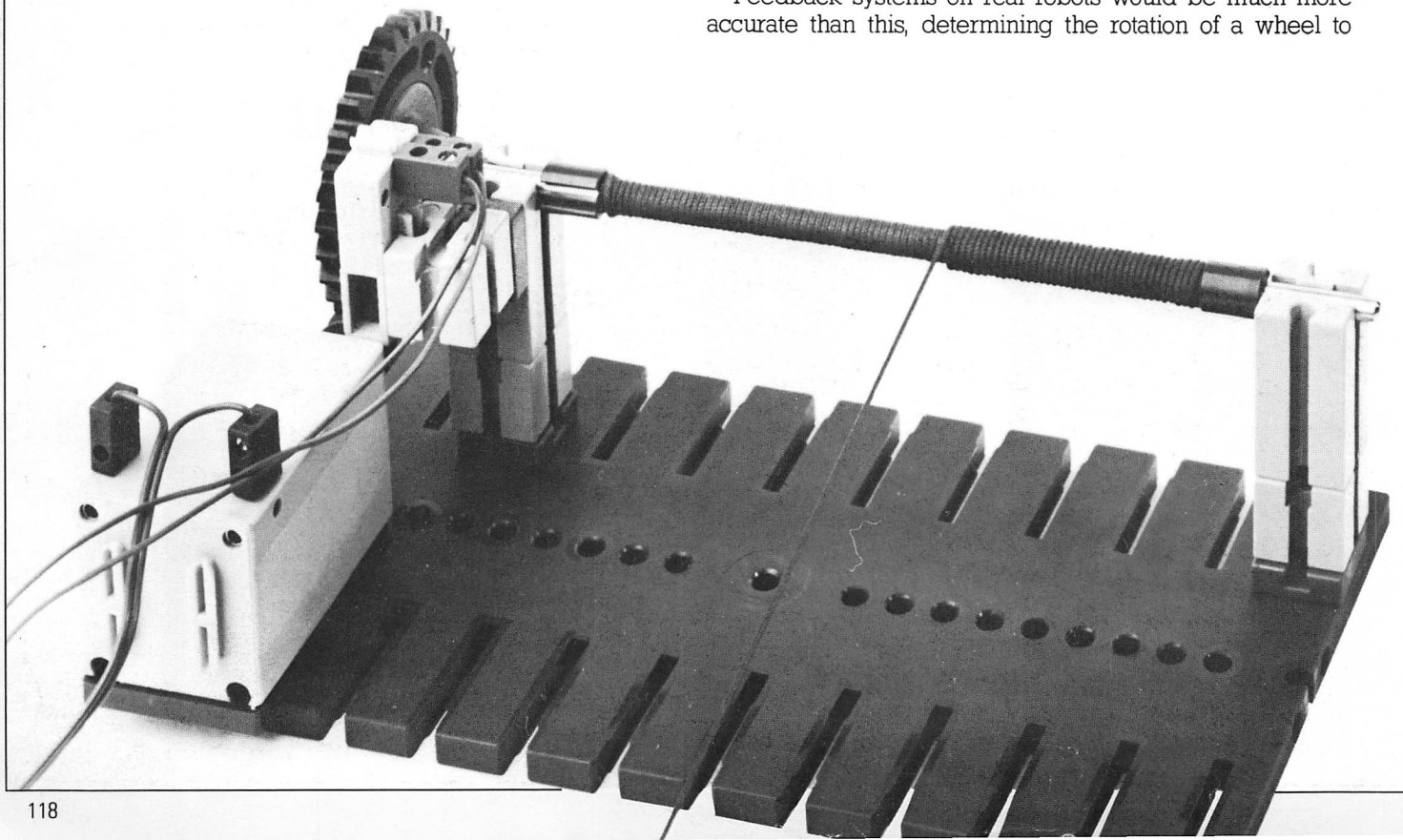
The chosen method of speed control is called pulse width modulation, or voltage chopping. This means that the voltage supplied to the motor is switched on and off many times a second so that the power arrives as a rapid chain of pulses. The speed of the motor will be determined by the ratio of the time for which the power is switched on to the time it is switched off in each pulse. In technical terms this is called the mark/space ratio, but it is best understood by looking at the diagram.

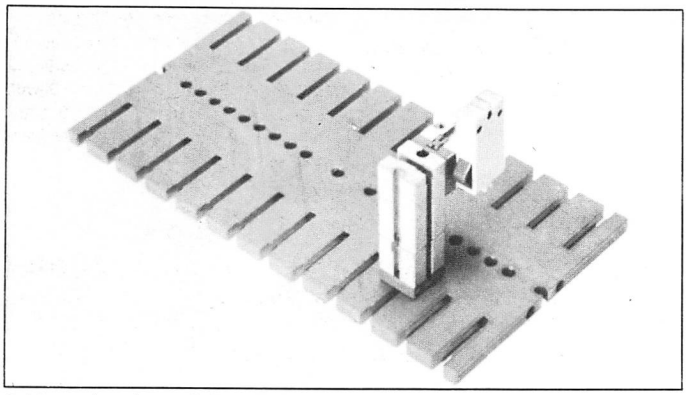
Voltage chopping has its limits – if you try to run the motor very slowly it will simply stall. Performance can be improved by placing a large capacitor in parallel with the motor (assuming you are familiar with elementary electronics). Most relay blocks are quite capable of switching on and off as fast as this experiment requires, but it is a good idea to consult the instructions first.

Programming on a home computer to achieve voltage chopping is a simple matter, as our sample program shows. The pulsing is controlled by a main loop containing two delay loops that determine the duration for which the relay is kept closed and then held open. Try running the speed control program and see what range of speeds you can achieve for winding the string in and out again.

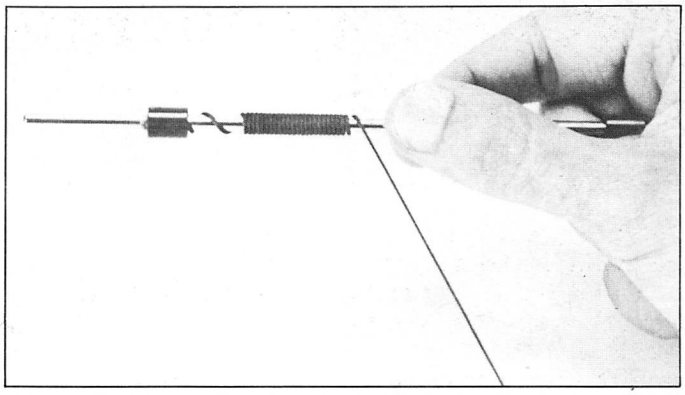
The position at which an electric motor halts can be accurately determined only by using feedback, which means sending signals back from the winch to the computer. This requires some form of electronic sensor mounted on the winch, and our design uses a microswitch. As the winch rotates, the wing-nut on the driving cog depresses the microswitch every half revolution. Each closure of the switch corresponds to the string advancing about 7.5mm (3/10 in). The computer simply counts the pulses and compares the distance moved with the distance required.

Feedback systems on real robots would be much more accurate than this, determining the rotation of a wheel to

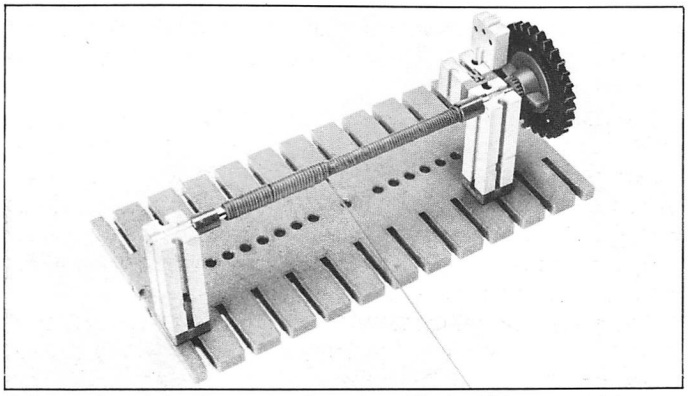




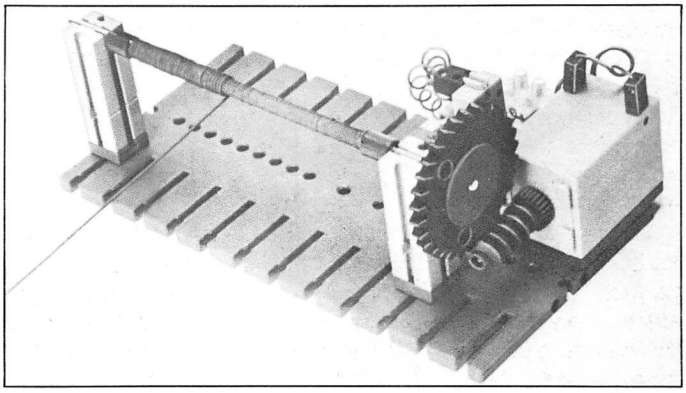
1 Mount the microswitch on the baseboard atop a support made from one and a half standard blocks plus two thin red fillers. When the model is complete the position of the microswitch can be finely adjusted.



2 Secure the string onto the axle with a single red collar, then neatly wind on a further 1m (3ft) of string. Note that if a second layer of string is formed, the effective diameter of the drum changes.



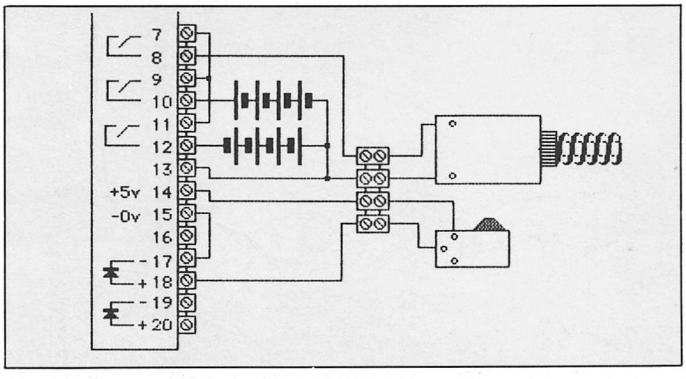
3 Fasten the axle into its two bearings, then affix the driving gear. Make sure that the gear grips the axle very firmly and that when the gear wheel rotates the microswitch is depressed each half-turn.



4 Wire up the model as in the wiring diagram, using coiled cable and a connection block for neatness. Attach a weight (such as an apple) to the free end of the string with a secure knot.

within a single degree or less. In place of our mechanical switch would be a light beam and light detector that counts the passing of holes or teeth on the wheel, a mechanism that eliminates wear and tear.

Run the feedback program and see how accurately it can stop the winch. If you try writing a simple program that activates the motor for a specified time, but that doesn't employ the feedback switch, you will find that this is a lot less accurate. As a final exercise, combine the two themes of this project and write a program that gradually accelerates the motor from rest and then slows it down automatically as the weight approaches the desired position.



Wiring diagram. Two sets of batteries are used to allow the motor to be run in both directions. With the six-relay VicRel it would be possible to achieve the same effect using just one set, but the circuit shown here will work with most relay units. For a Lego motor use only three battery cells per set.
WARNING: LOAD AND RUN THE COMPUTER PROGRAM BEFORE INSERTING THE BATTERIES INTO THE BATTERY HOLDER.

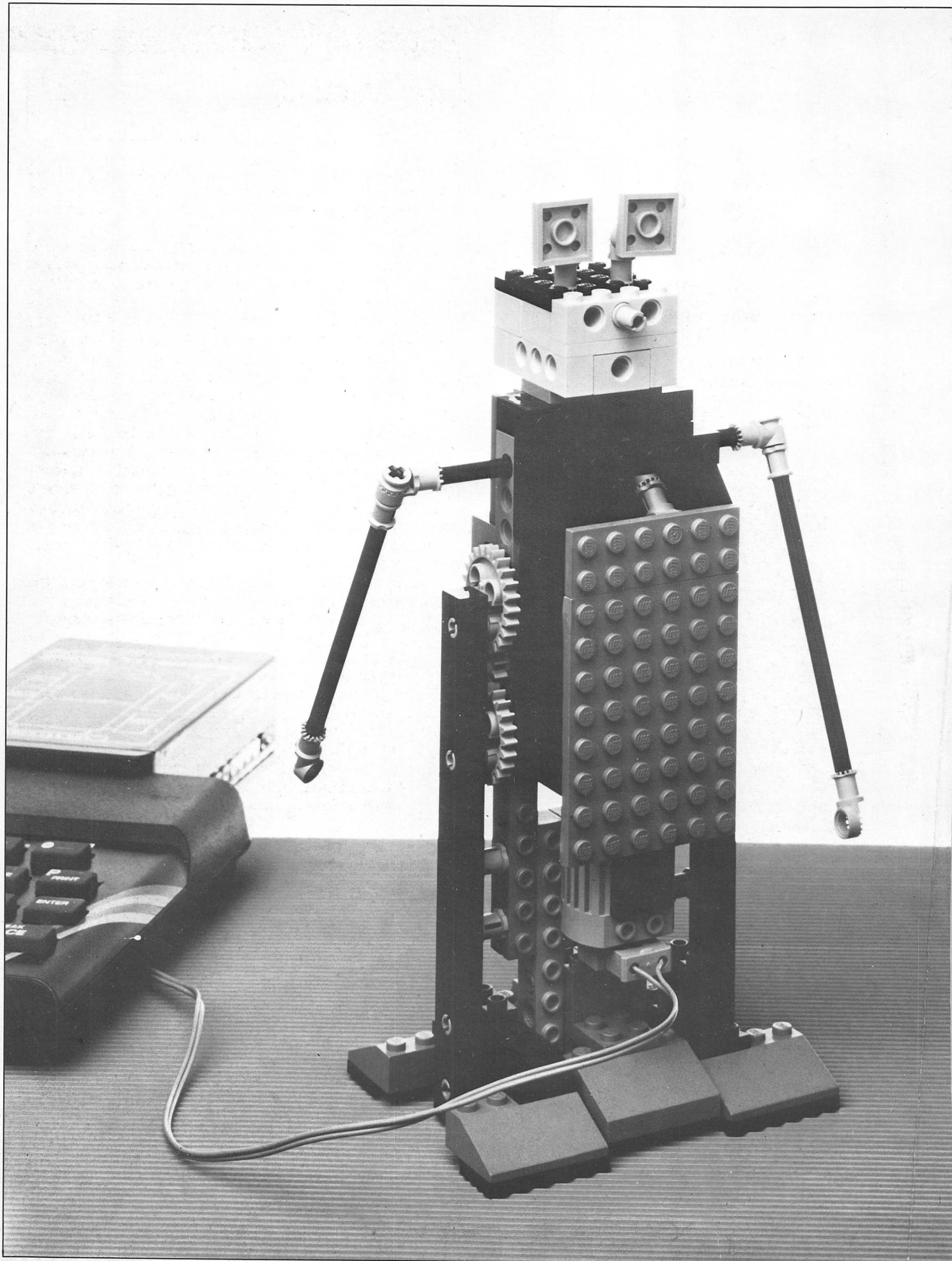
Program 1

```
10 REM**SPEED CONTROL**
20 REM**INITIALIZATION**
30 CN=37136:POKECN+2,63:F=1
40 PRINT"INSERT BATTERIES"
50 PRINT"PRESS 0-9 FOR SPEED CONTROL"
60 PRINT"AND SPACE TO REVERSE"
70 REM**CONTROL**
80 GETA$:IFA$=""THEN120
90 IFA$=" "THENF=-F:GOTO110
100 T1=VAL(A$):T2=9-T1
110 DR=32+F*8
120 REM**PULSE WIDTH CONTROL**
130 IFT1=0THEN80
140 POKECN,DR:FORDL=1TOT1:NEXT
150 POKECN,0:FORDL=1TOT2:NEXT:GOTO80
```

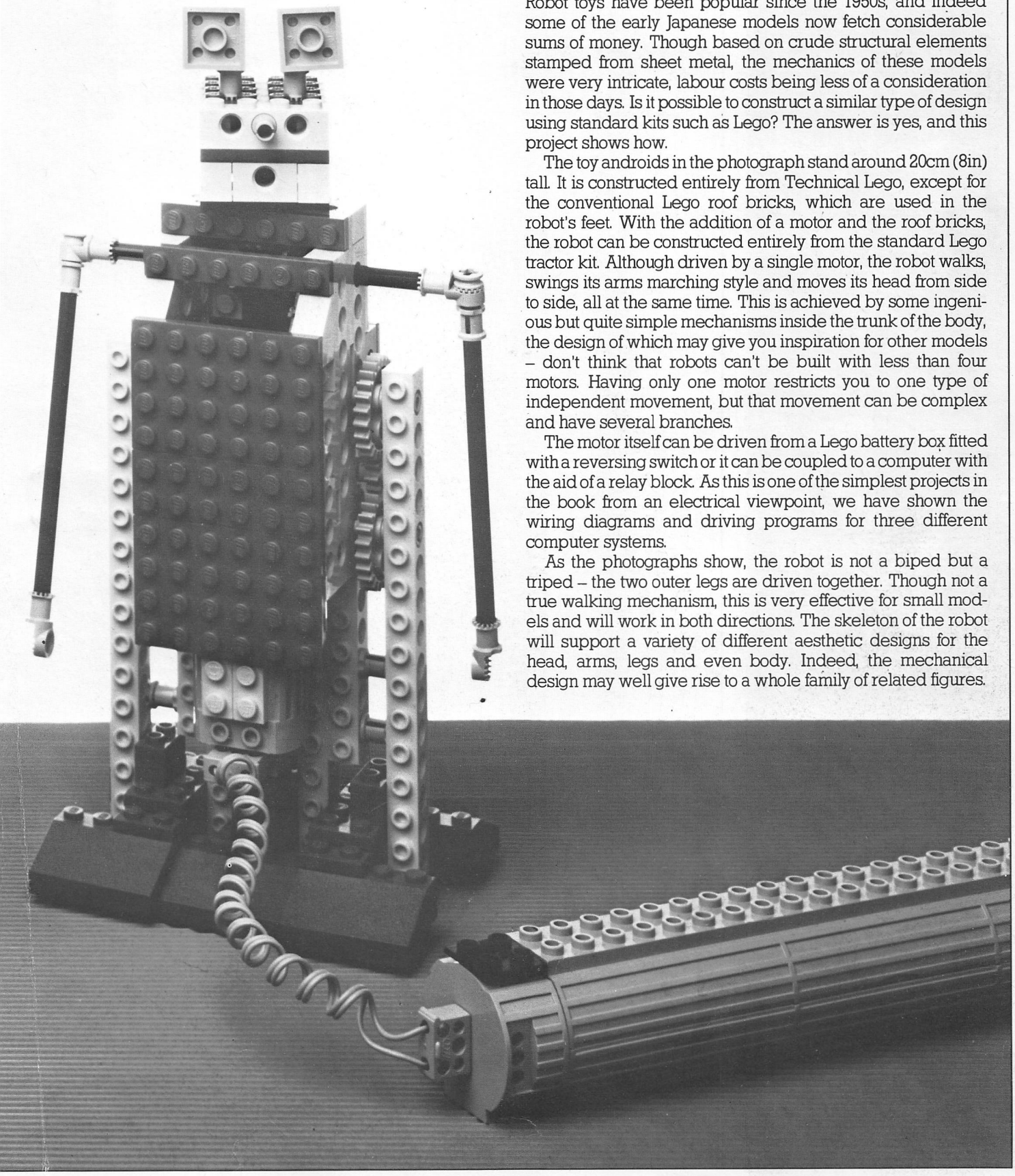
Program 2

```
10 REM**FEEDBACK CONTROLLER**
20 REM**INITIALIZE**
30 CN=37136:POKECN+2,63
40 PRINT"INSERT BATTERIES"
50 DW=40:UP=24
60 INPUT"HOW MANY STEPS";SP
70 IFSP=0THENEND
80 REM**SET DIRECTION OF MOTION**
90 IFSGN(SP)=-1THENPOKECN,DW:GOTO110
100 POKECN,UP
110 REM**COUNT PULSES/STEPS**
120 SP=ABS(SP)
130 IF(PEEK(CN)AND128)=128THEN130
140 IF(PEEK(CN)AND128)=0THEN140
150 SP=SP-1:IFSP>0THEN130
160 REM**TURN OFF MOTOR**
170 POKECN,0:GOTO60
```

Program. Both these programs are written for the Vic-20, but will work with a Commodore 64 by changing the value of CN in line 30 to 56577.


PRINT
ENTER

TOY ANDROID



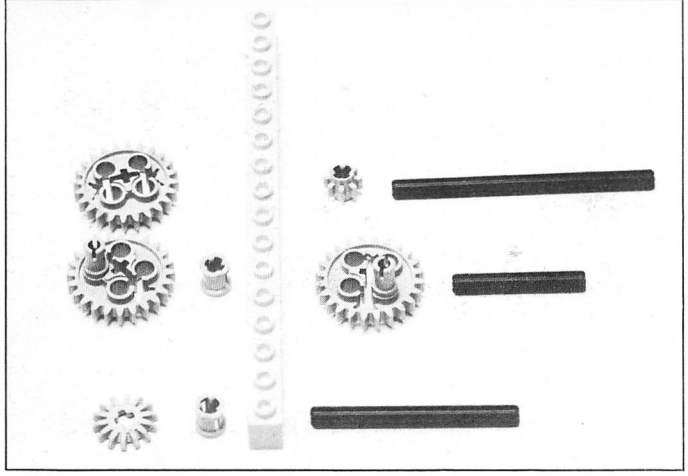
Robot toys have been popular since the 1950s, and indeed some of the early Japanese models now fetch considerable sums of money. Though based on crude structural elements stamped from sheet metal, the mechanics of these models were very intricate, labour costs being less of a consideration in those days. Is it possible to construct a similar type of design using standard kits such as Lego? The answer is yes, and this project shows how.

The toy androids in the photograph stand around 20cm (8in) tall. It is constructed entirely from Technical Lego, except for the conventional Lego roof bricks, which are used in the robot's feet. With the addition of a motor and the roof bricks, the robot can be constructed entirely from the standard Lego tractor kit. Although driven by a single motor, the robot walks, swings its arms marching style and moves its head from side to side, all at the same time. This is achieved by some ingenious but quite simple mechanisms inside the trunk of the body, the design of which may give you inspiration for other models – don't think that robots can't be built with less than four motors. Having only one motor restricts you to one type of independent movement, but that movement can be complex and have several branches.

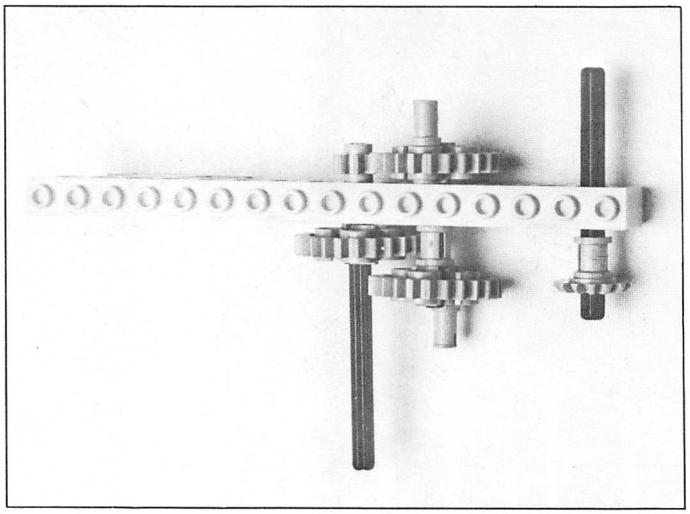
The motor itself can be driven from a Lego battery box fitted with a reversing switch or it can be coupled to a computer with the aid of a relay block. As this is one of the simplest projects in the book from an electrical viewpoint, we have shown the wiring diagrams and driving programs for three different computer systems.

As the photographs show, the robot is not a biped but a triped – the two outer legs are driven together. Though not a true walking mechanism, this is very effective for small models and will work in both directions. The skeleton of the robot will support a variety of different aesthetic designs for the head, arms, legs and even body. Indeed, the mechanical design may well give rise to a whole family of related figures.

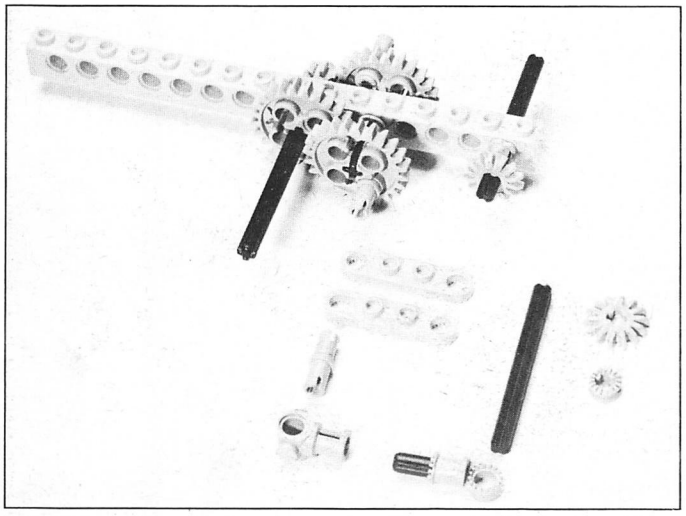
CONSTRUCTION



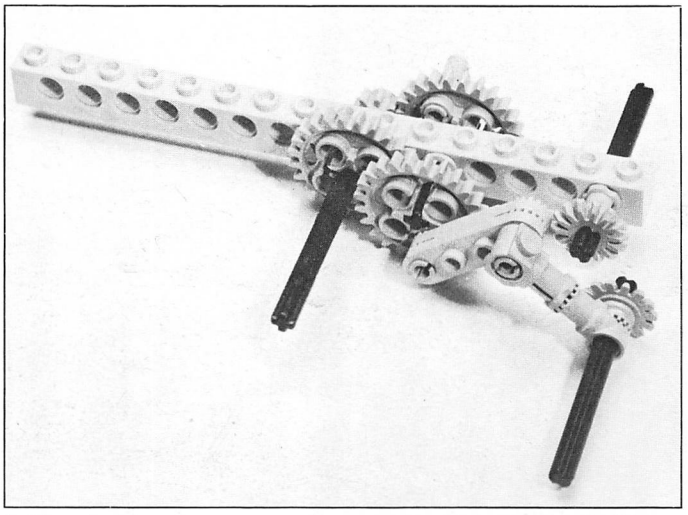
1 Components for the first stage laid out so as to reflect their order of assembly.



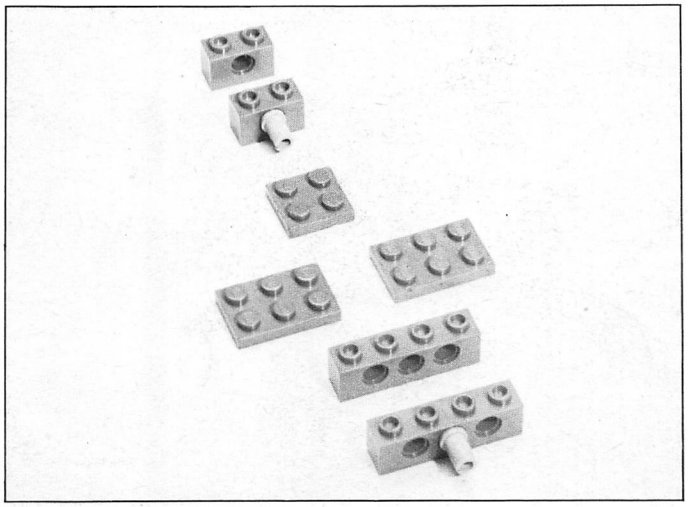
2 Slot the 4-, 6- and 8-unit-long axles into the 16-unit holed beam. Two of the 24-tooth gears have pins in them and are fitted so that the pins are diametrically opposite each other.



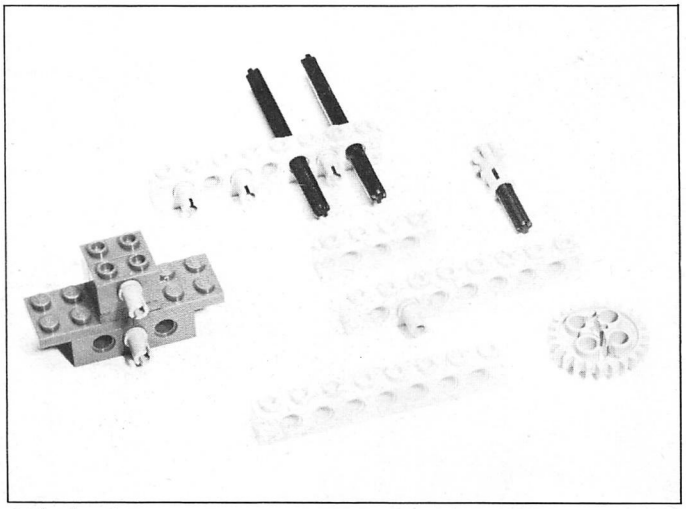
3 Parts normally used by Lego for steering gear are added to the assembly.



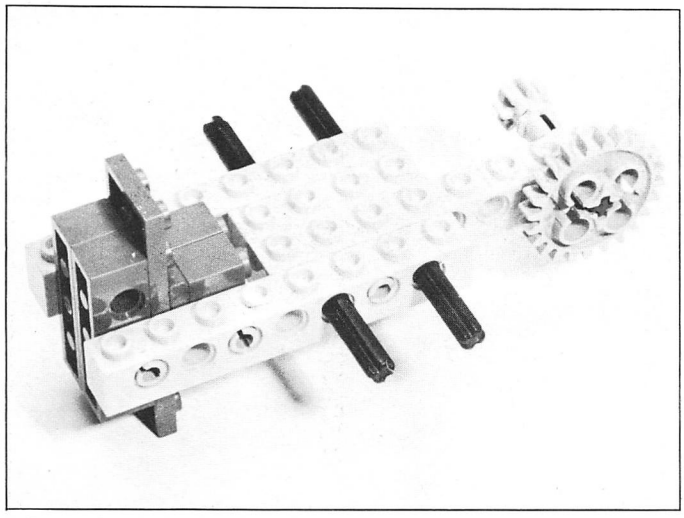
4 When the 24-tooth gear rotates, the new axle with the bevel gear will oscillate. This will move the head and arms.



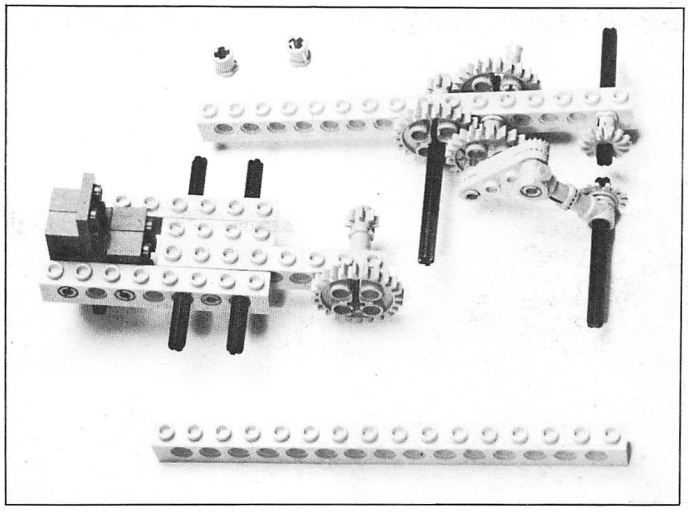
5 The top of the central foot is made from 2- and 4-unit bricks and plates and held in place by pins on either side.



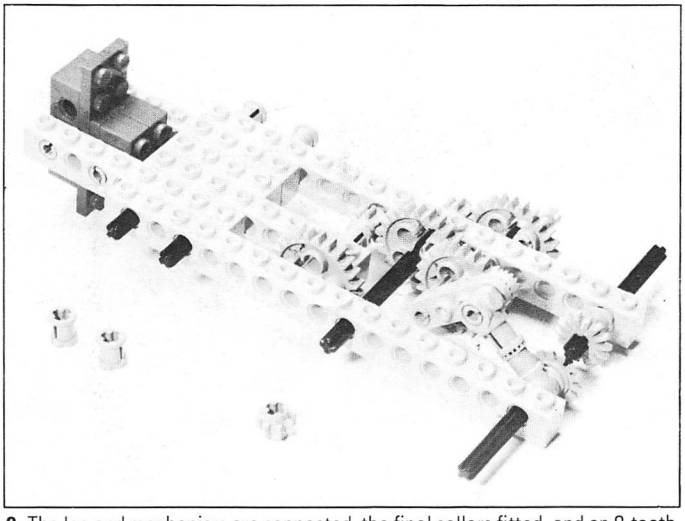
6 The foot lies between 8-unit beams. Two of the axles shown are 8 units long and the one with the two gear wheels is 4 units.



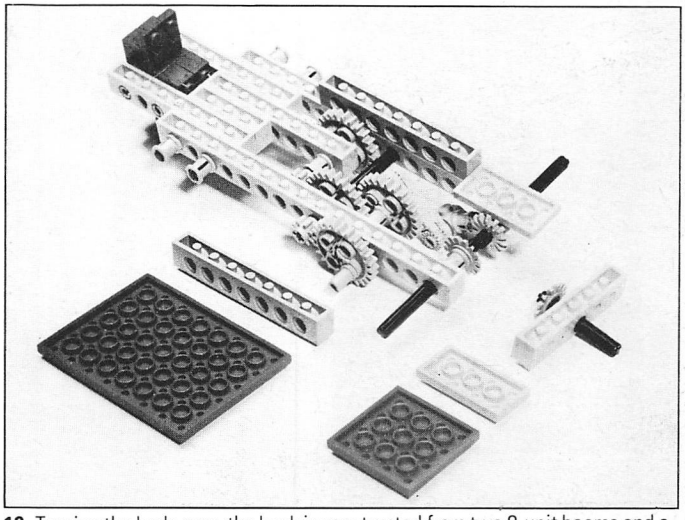
7 Ensure that all the pins shown have been inserted as these are needed for rigidity.



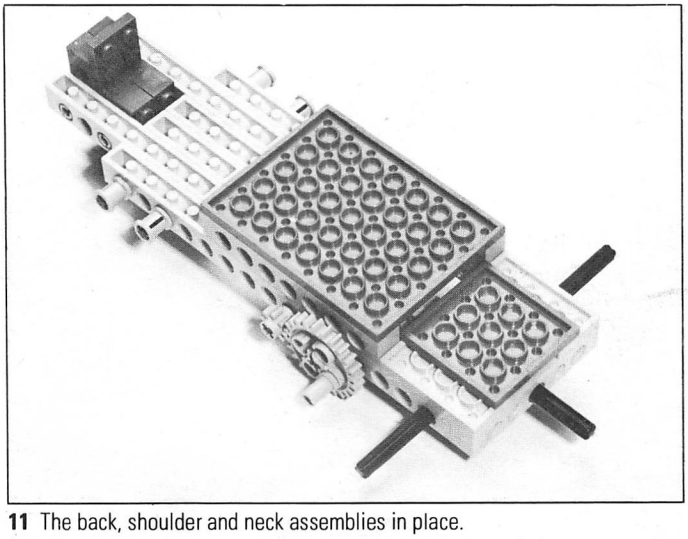
8 The central leg and the oscillating mechanism constructed previously. A second 16-unit beam and two more collars are added next.



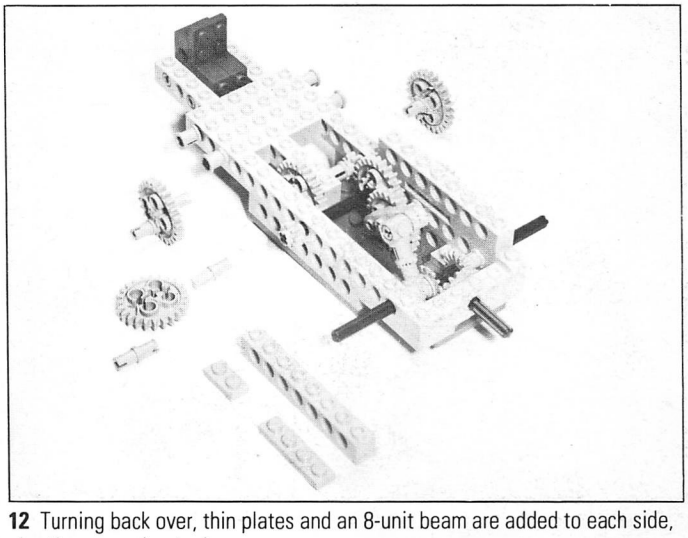
9 The leg and mechanism are connected, the final collars fitted, and an 8-tooth gear added.



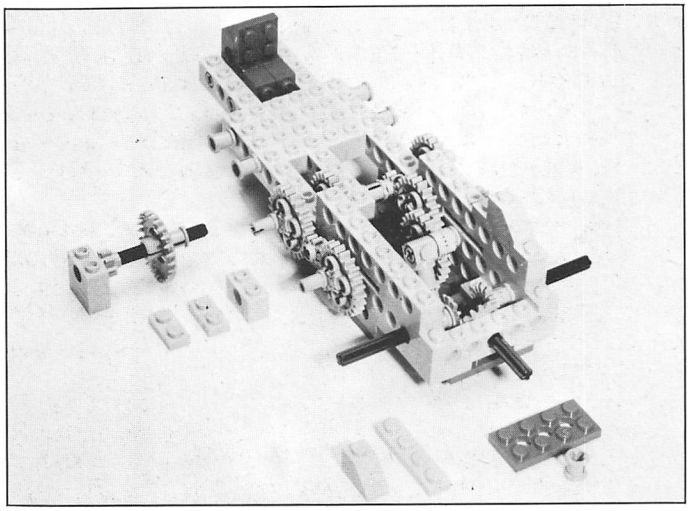
10 Turning the body over, the back is constructed from two 8-unit beams and a 6×8 plate. A 6-unit beam, two 4×2 plates and one 4×4 plate make the shoulders, with a 4-unit axle for the neck.



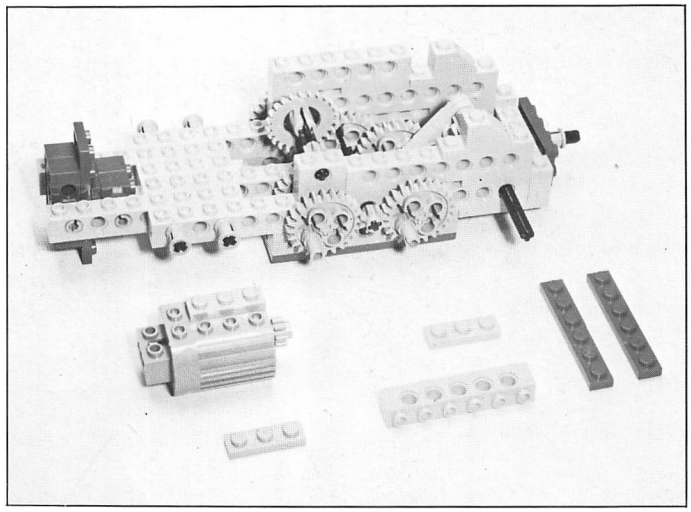
11 The back, shoulder and neck assemblies in place.



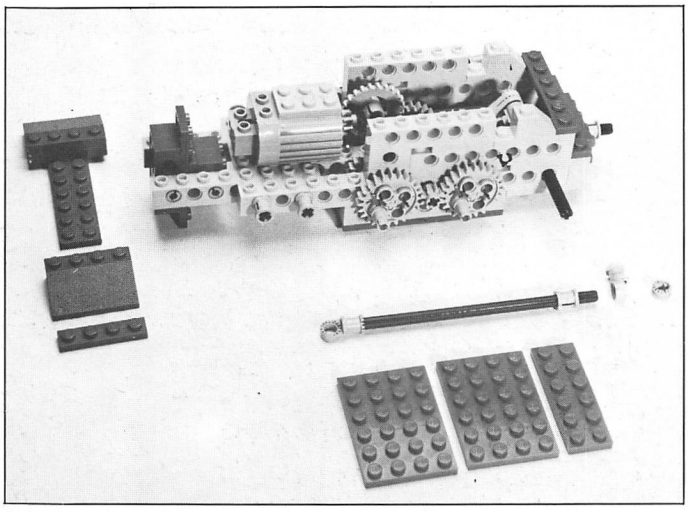
12 Turning back over, thin plates and an 8-unit beam are added to each side, plus the gear wheels shown.



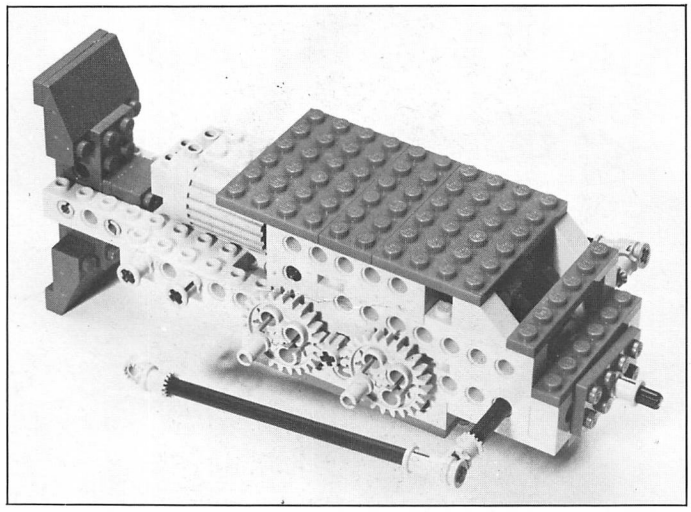
13 The crown wheel sits on a 6-unit axle, supported at each end on a 2×1 block and two plates. The assembly is mounted on the waist. Chest pieces, neck plate and collar are added.



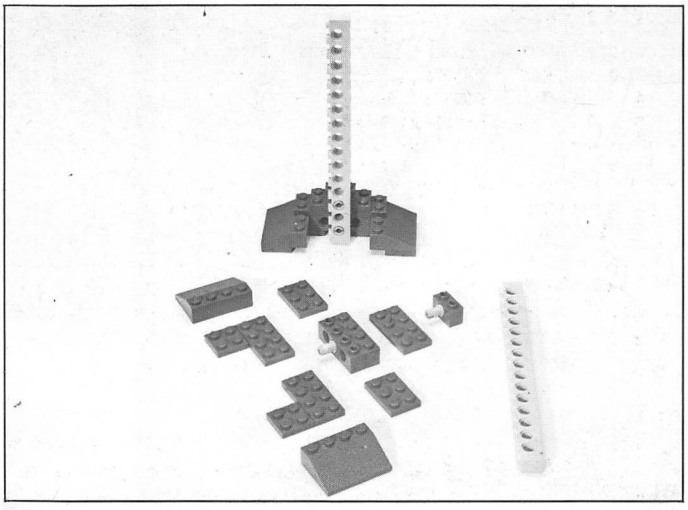
14 The motor features thin plates on top and an 8-tooth gear that engages with the crown wheel. Plates and beams complete the sides.



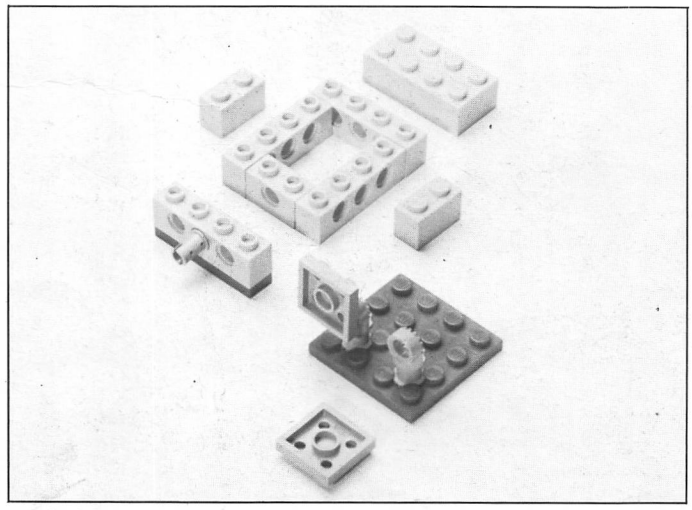
15 The sole of the central foot is made from Lego roof bricks, the arms are 12-unit axles fitted with hinges, and the front of the body comprises three large plates.



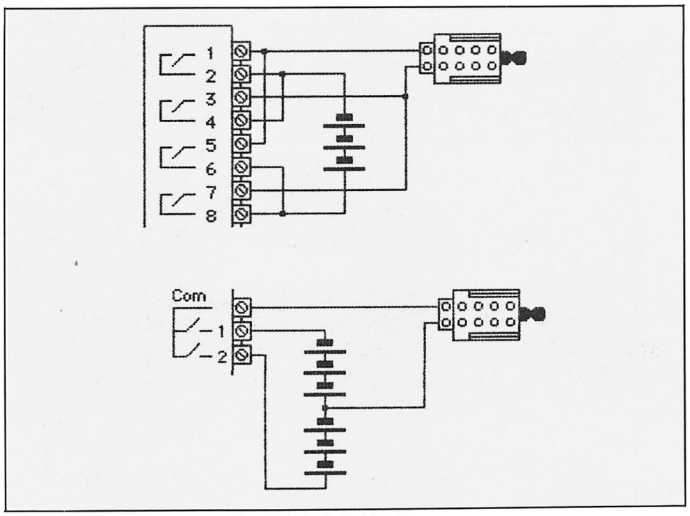
16 The pins on the exterior gears should line up and be in the same position on either side of the body.

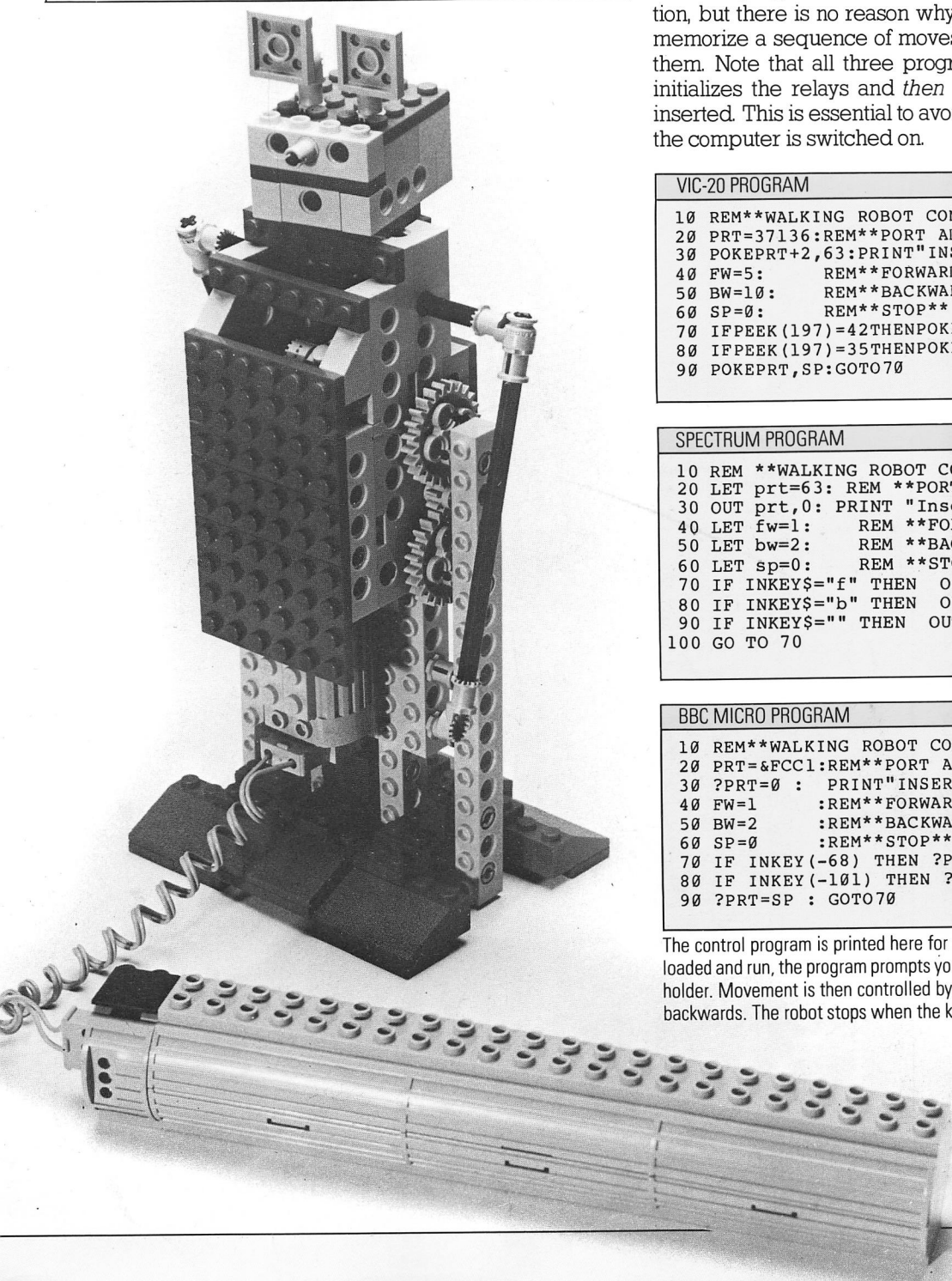


17 The two outer feet are constructed in the same way, each from a 16-unit beam, bricks and plates, and are fitted to the legs with two pins.



18 The head can follow more-or-less any design, as long as it clips onto the 4×2 plate on the neck.





Programs and wiring

Shown left are two different ways of wiring the toy android to a computer. You can use these techniques to drive any other Lego model fitted with a single motor.

The first wiring diagram and program are for the Vic-20 computer fitted with a VicRel relay block. Because the relays on the VicRel are all independent, four of them can be wired as shown so that the motor can be driven in either direction. The model is controlled from the keyboard by means of the F (Forward) and B (Back) keys.

The second wiring diagram works for both the InterSpec and InterBeeb units, and it is therefore accompanied by listings for both Spectrum and BBC computers. However, because the four relays on these interfaces are all commoned together, the only way to drive a motor in both directions is to use two sets of batteries, as shown.

All the programs listed here are for simple keyboard operation, but there is no reason why they cannot be expanded to memorize a sequence of moves in an array and then repeat them. Note that all three programs start with a routine that initializes the relays and *then* requests the batteries to be inserted. This is essential to avoid burning out batteries when the computer is switched on.

VIC-20 PROGRAM

```
10 REM**WALKING ROBOT CONTROLLER**
20 PRT=37136:REM**PORT ADDRESS**
30 POKEPRT+2,63:PRINT"INSERT BATTERIES"
40 FW=5:      REM**FORWARD**
50 BW=10:     REM**BACKWARD**
60 SP=0:      REM**STOP**
70 IFPEEK(197)=42THENPOKEPRT,FW:GOTO70
80 IFPEEK(197)=35THENPOKEPRT,BW:GOTO70
90 POKEPRT,SP:GOTO70
```

SPECTRUM PROGRAM

```
 10 REM **WALKING ROBOT CONTROLLER**
 20 LET prt=63: REM **PORT ADDRESS**
 30 OUT prt,0: PRINT "Insert Batteries"
 40 LET fw=1:     REM **FORWARD**
 50 LET bw=2:     REM **BACKWARD**
 60 LET sp=0:     REM **STOP**
 70 IF INKEY$="f" THEN  OUT prt,fw
 80 IF INKEY$="b" THEN  OUT prt,bw
 90 IF INKEY$="" THEN  OUT prt,sp
100 GO TO 70
```

BBC MICRO PROGRAM

```
10 REM**WALKING ROBOT CONTROLLER**
20 PRT=&FCC1:REM**PORT ADDRESS**
30 ?PRT=0 :  PRINT"INSERT BATTERIES"
40 FW=1      :REM**FORWARD**
50 BW=2      :REM**BACKWARD**
60 SP=0      :REM**STOP**
70 IF INKEY(-68) THEN ?PRT=FW : GOTO70
80 IF INKEY(-101) THEN ?PRT=BW : GOTO70
90 ?PRT=SP : GOTO70
```

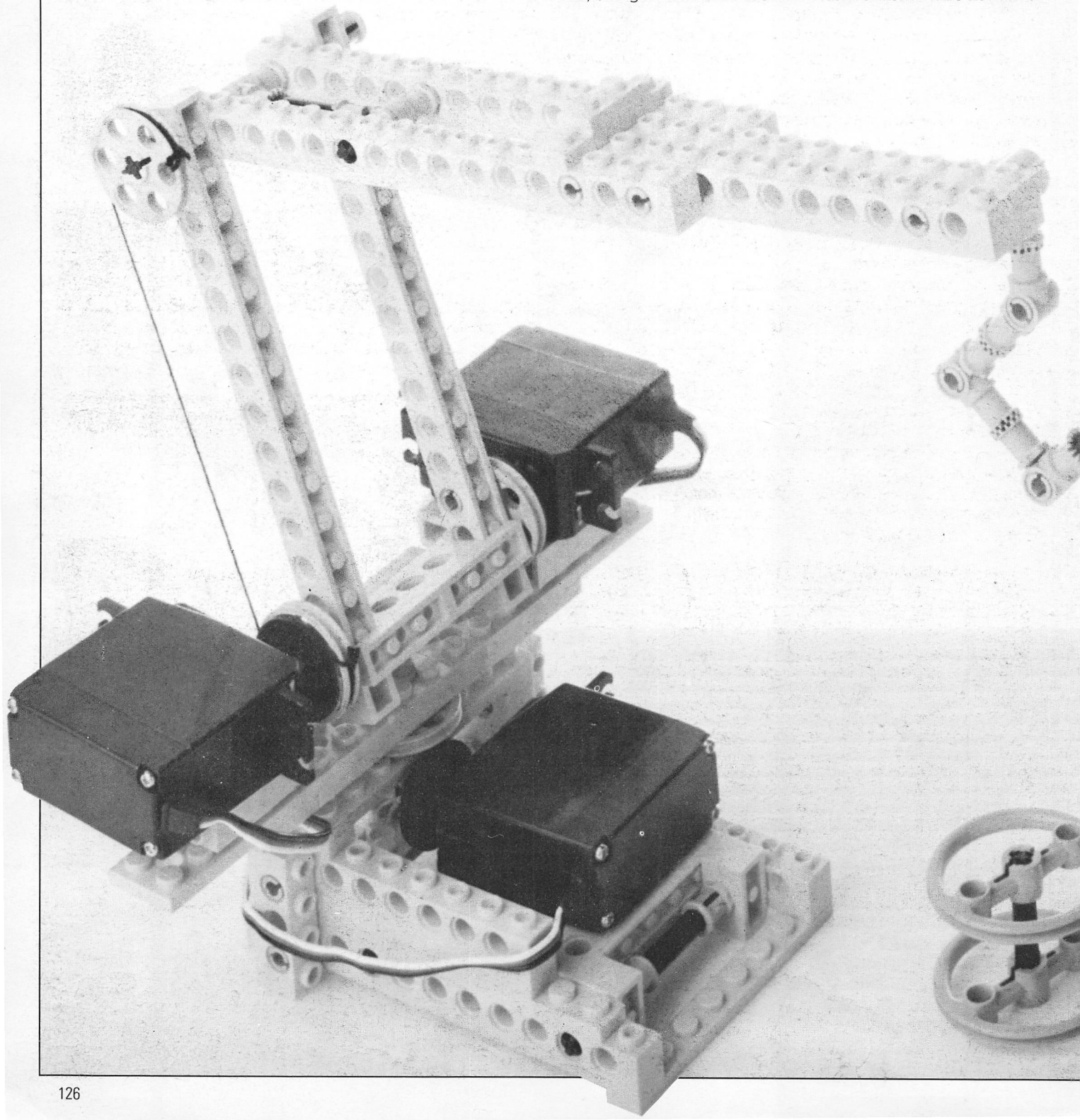
The control program is printed here for the Spectrum, BBC and Vic-20. Once loaded and run, the program prompts you to insert the batteries into the battery holder. Movement is then controlled by pressing F for forwards, B for backwards. The robot stops when the keys are released.

19 On the completed figure, the outer legs should line up and move in synchronization. The motor can be driven from a battery box, as shown here, or from a computer, as shown in the wiring diagrams.

THREE-AXIS ARM

The majority of industrial manipulators, especially the smaller ones, are driven by electric servo motors. A servo motor comprises four parts: a DC (direct current) electric motor, a gearing-down mechanism to reduce speed and increase torque (see page 68), a sensor for measuring the position of the output shaft, and some electronic circuitry. A servo motor can be instructed by the robot's control computer to rotate to a specified position and at a particular speed; the servo's internal feedback mechanism will then handle the details of the operation.

The small servo motors used by aeromodellers and radio-control enthusiasts work in the same way and therefore make excellent building blocks for small-scale robots. The Beasty is an interface unit that allows up to four such servos to be controlled from a BBC microcomputer (the UK manufacturers, Commotion, will be producing the same device for other home computers also). To the servos, the Beasty produces the same signals as would the receiver in a radio-controlled model, though in this case the link is conventional wire not radio.



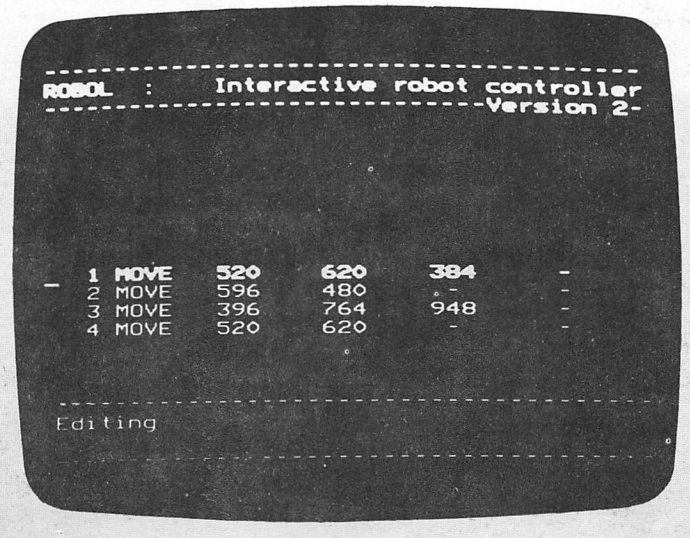
The servos are controlled via a simple form of robot programming language called ROBOL, supplied on cassette with the Beasty. Each of the servos is assigned a pair of keys on the computer's keyboard, and pressing these will rotate the output shaft in either direction. At any instant, the position of the four servos can be logged into the computer's memory in the form of a 'point'. By specifying a sequence of such points, and then playing them back by means of another command, a complex programme of movements can be built up.

These types of servo motors range in cost from around £12 each to over £50, according to their torque and turning range. The cheapest units have a turning range of only 100 degrees or so (servo motors are not therefore suitable for driving the wheels on a buggy), but have quite sufficient torque for driving the joints in a robot arm without further gearing down.

Commotion can supply a kit for building a simple robot arm using the Beasty, but this project shows how to build quite a sturdy design from Lego. It is a three-axis arm, meaning that it can rotate at the waist, shoulder and elbow, with a simple hook as an end effector. The arm is controlled using the ROBOL software, so no additional programming is needed, and movement is remarkably accurate. There is some free play at the end effector because of the tolerances at each joint and the slight elasticity of string, but far less than designs relying on Lego gears. String may not look like an elegant solution, but it is one of the most efficient means of transferring power to the relevant joint in a robot arm.

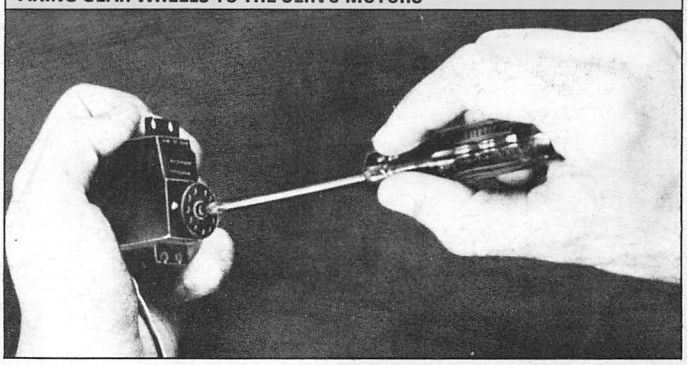
It is necessary to glue a couple of Lego gears onto the flange plates mounted on the servos, but the servos themselves can still be removed and used for other applications. The weight of the arm itself is borne by two of the servo motors, a neat solution, but one that would be inadvisable if the arm was much heavier, as this would put too much strain on the shafts. So, at the waist joint, the weight is borne by a Lego structure, not by the servo driving that joint.

If you have access to four servos, then you could replace the hook with a proper robot gripper, or alternatively an electromagnet could be used to manipulate metallic objects. The repeatability and programmability of this arm make it suitable for many types of experiments.

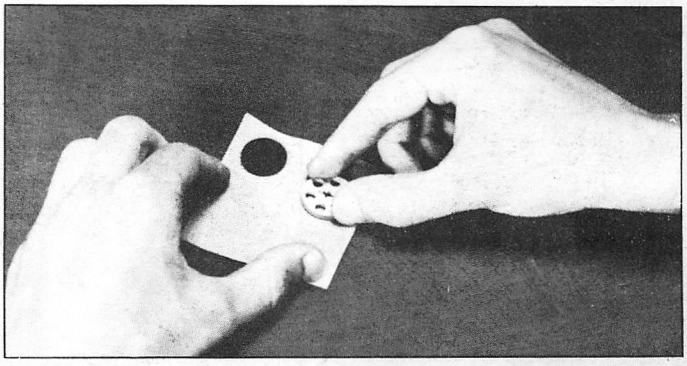


Using ROBOL. Each line on the screen represents a point that has been logged into the computer's memory (points 1, 2, 3, etc.). The four values in each row are the positions of the four servos at that point. The value 0 means the servo is at one extreme of rotation, 996 is the other extreme. In this model, the fourth servo is simply not connected.

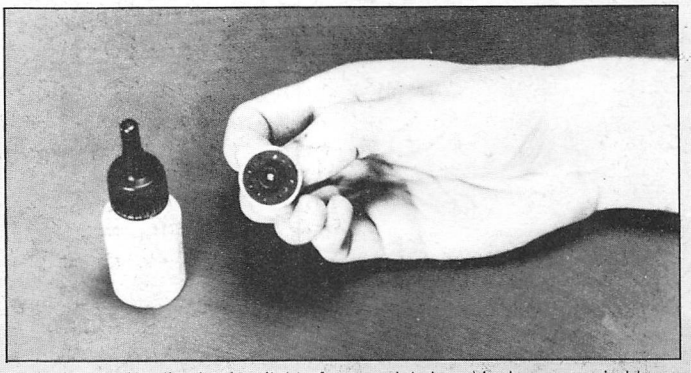
FIXING GEAR WHEELS TO THE SERVO MOTORS



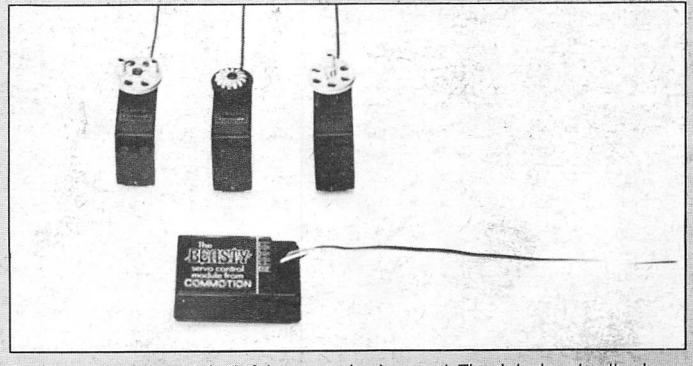
1 After removing the small screw, the flange plate can be pulled off the drive shaft. Most servos come with a variety of flange plates for different applications.



2 Using a piece of medium-grade sandpaper, both the flange plate and the gear wheel to be fitted should be sanded smooth. Clean off any dust before gluing plate and wheel together.

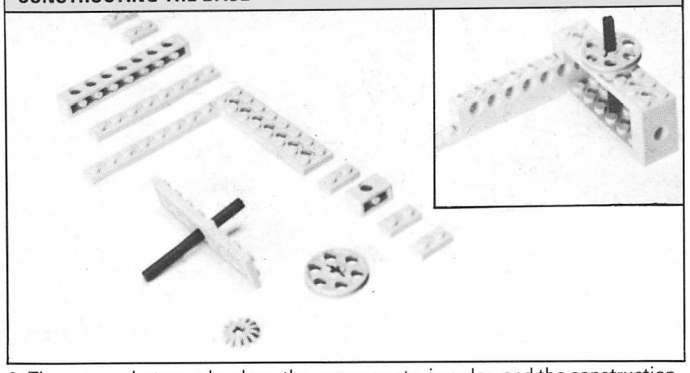


3 Liquid plastic adhesive (available from model shops) is the most suitable, though very fast acting. The centres of the flange plate and gear wheel must align exactly.



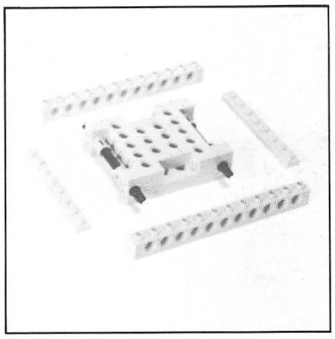
4 The motor pulley on the left has two pins inserted. The right-hand pulley has one central, splined pin. The bevel gear on the central motor can simply be screwed in place.

CONSTRUCTING THE BASE

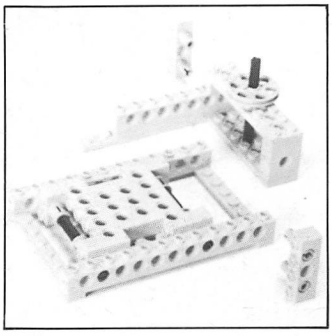


1 These two photographs show the components, in order, and the construction of the main bearing for the waist joint. A bevel gear is mounted on the 6-unit axle, to mesh with a similar gear on the servo motor.

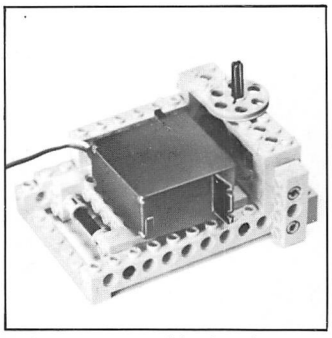
2 These beams, made from 6×1 and 4×1 units, are laid on their sides to provide a flat base for mounting the waist servo motor. The axle end units will hold the beams together.



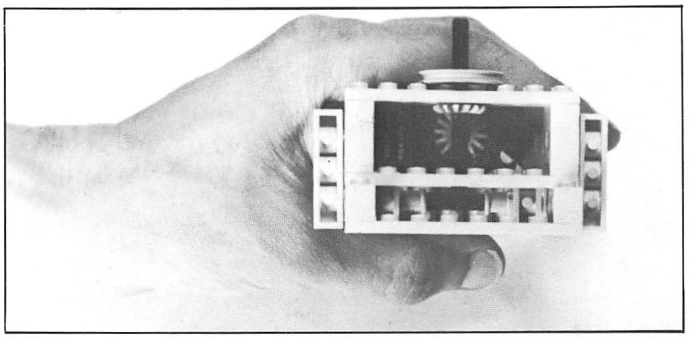
3 The beams are placed one above the other and the axle units added. Two side members are now fitted over the axles and held by 8×1 plates. Note that the axles are 8 units long.



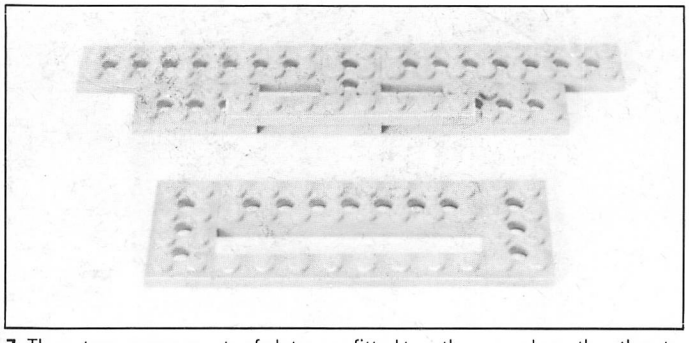
4 The two units are coupled together, the main bearing above right, and held by a pair of 4×1 beams with pins for extra rigidity.



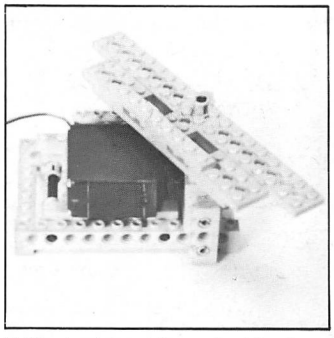
5 A servo motor with a bevel gear glued or screwed to its flange plate is mounted centrally on the base.



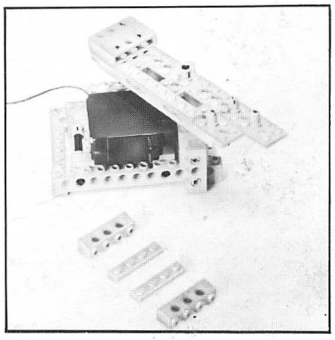
6 The complete unit is held end-on to show that the motor gear meshes with the bevel gear on the axle. Double-sided sticky tape holds the servo in place.



7 These two arrangements of plates are fitted together, one above the other, to be mounted on to the waist axle.

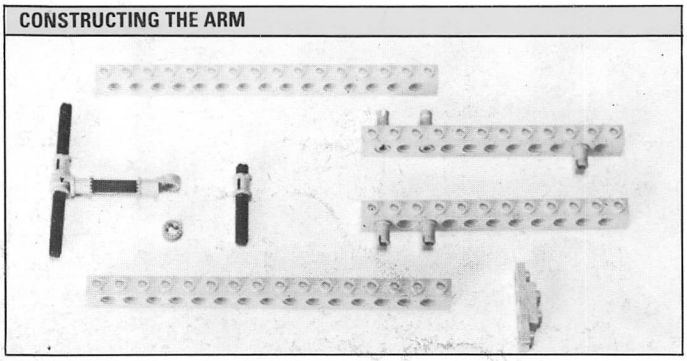


8 The bush must be pushed firmly down so that it engages with the bumps on the topmost plate.

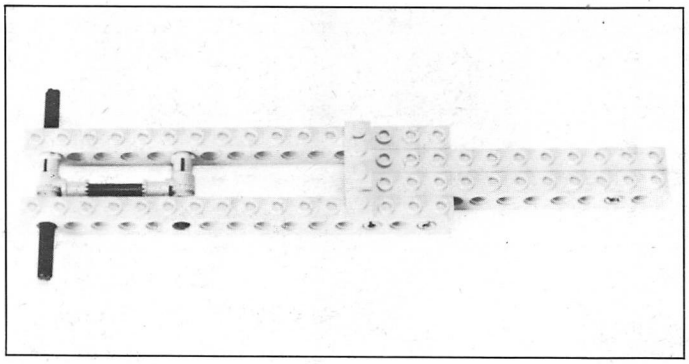


9 Two bases are built to take the other servos, and affixed to the plate structure with three pins each.

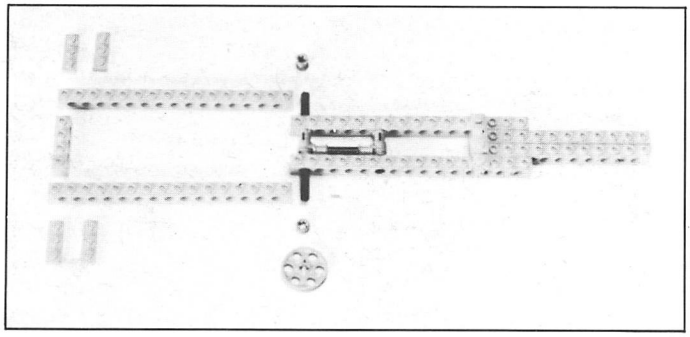
CONSTRUCTING THE ARM



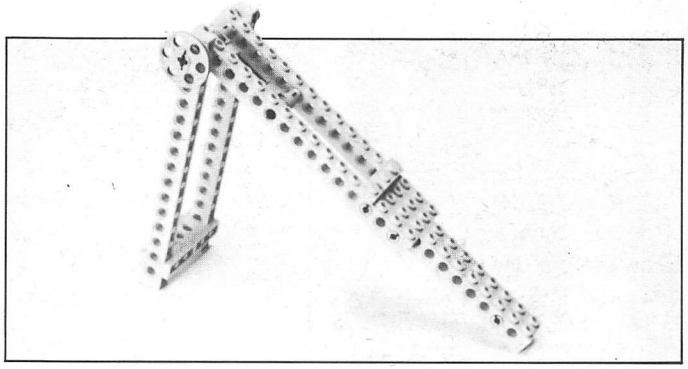
10 The forearm consists of two 16-unit-long and two 12-unit-long beams, held together by pins. The axles are 4, 6 and 8 units long.



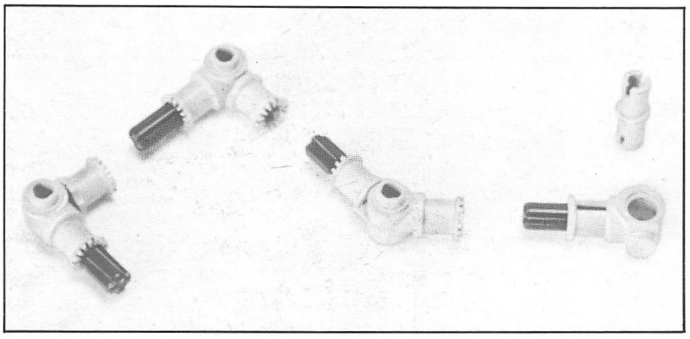
11 The components are fitted together. The axle arrangement provides positive drive at the elbow.



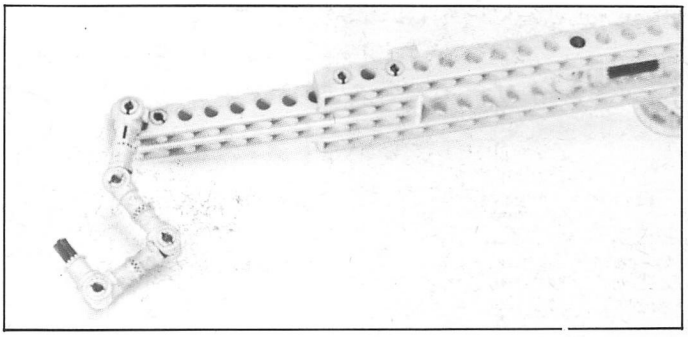
12 The upper arm, consisting of two 16-unit-long beams, is fitted onto the forearm. At the elbow joint, a thin bush is fitted between the pulley wheel and the beam for spacing.



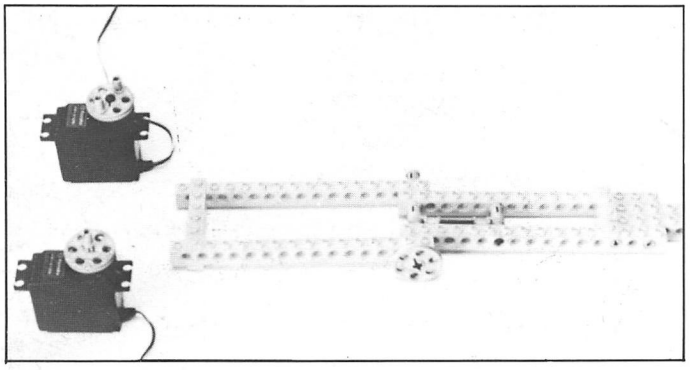
13 The arm, bent at the elbow joint and complete except for the end effector.



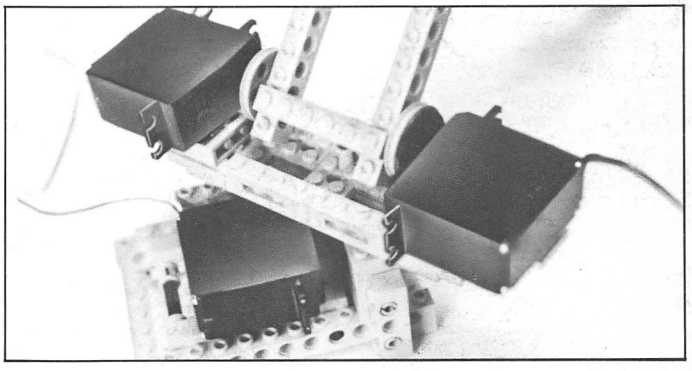
14 The hook is constructed from four 2-unit axles, held together with toggle joints in the arrangement shown.



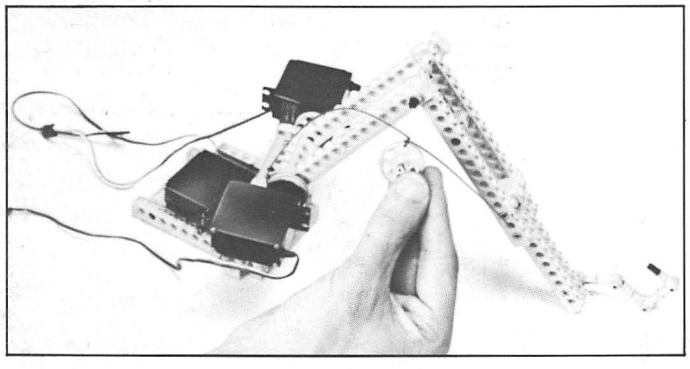
15 The hook is mounted onto the end of the forearm with a pin and should swing freely.



16 Both servos are fitted with a pulley wheel, one with two pins inserted, the other with one central pin.

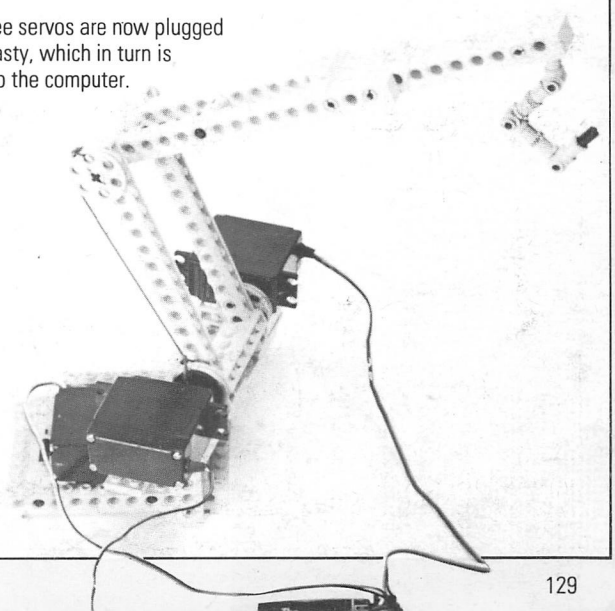


17 The two servos engage with the beams, and the assembly is fixed to the base with double-sided tape.



18 Before stringing up the arm, it is advisable to check the operation of the servos, using the computer. If the range of movement of the servos does not fit the requirements of the arm, the flange plates should be gently eased off the servos, the shafts rotated slightly, and the flanges replaced. A piece of string can now be tied between the two pulleys as shown; you may need to experiment to find the right length.

19 The three servos are now plugged into the Beasty, which in turn is plugged into the computer.



X-Y (DRAUGHTS-PLAYING) ROBOT

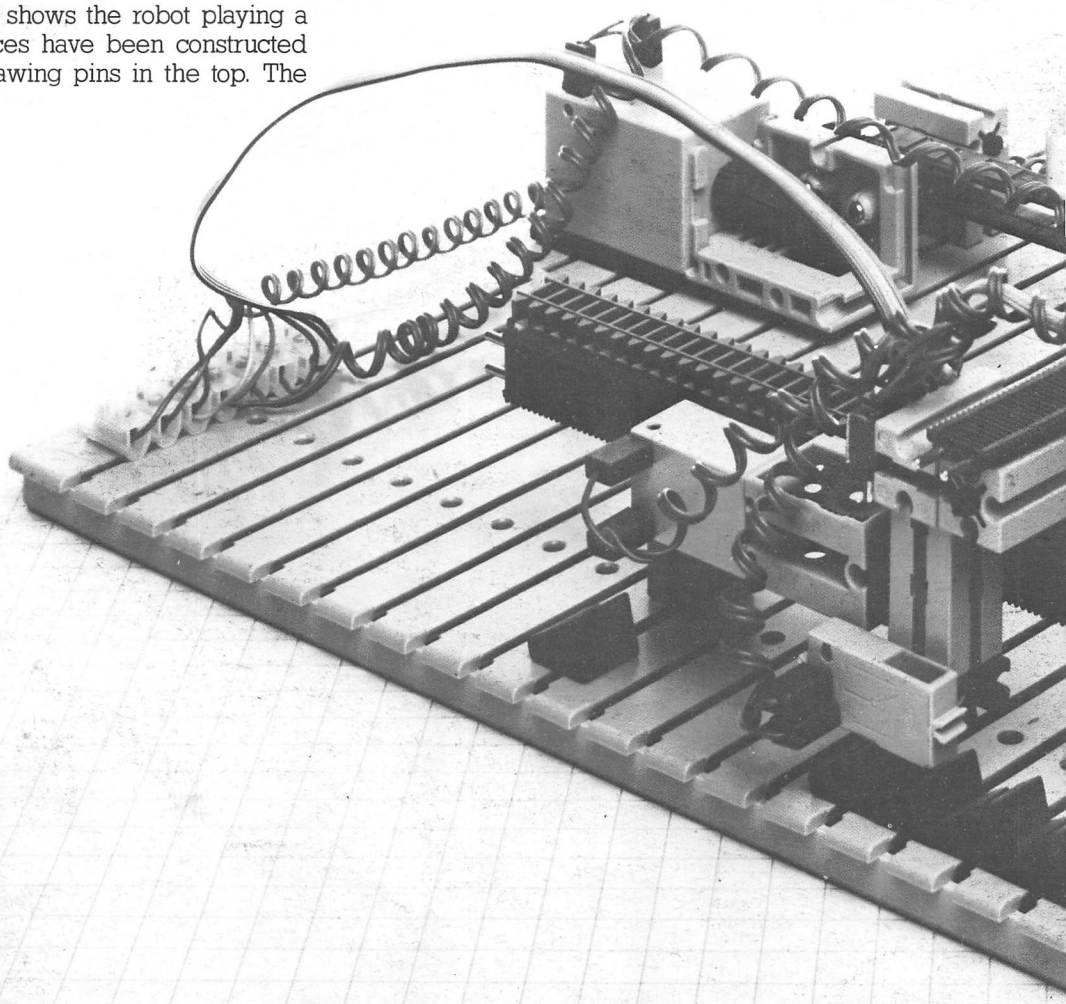
Robots constructed around the Cartesian system of co-ordinates (sometimes therefore called X-Y-Z robots) are less common than the jointed-arm type. They may not fulfil everyone's expectation of what a robot ought to look like, but for many industrial applications they are the most suitable design. The electronics industry uses small-scale X-Y robots (i.e. with only two axes of movement) for inserting the silicon chips into printed circuit boards, and much larger versions looking more like overhead gantry cranes form the basis of fully automated warehouses.

This project shows you how to build an X-Y robot from Fischertechnik and control its movement from a micro-computer. The model shown here is really a chassis upon which a great many experiments and further projects could be based. The techniques explained should also enable you to develop quite different robots based on Cartesian co-ordinates.

The photograph on this page shows the robot playing a board game. The draughts pieces have been constructed from wooden doweling with drawing pins in the top. The standard Fischertechnik electromagnet then makes an excellent end effector. Supplied with this project are a series of subroutines for moving the end effector to any desired co-ordinates and then activating or de-activating the magnet. From these subroutines you can construct your own programs for playing board games, setting the computer up against human opponents or against itself.

Start with simple games first, such as noughts and crosses. You will discover that there isn't sufficient clearance for pieces to be jumped over each other, so your program will have to keep track of the state of the board and move new pieces around existing obstacles. It may even be necessary for the robot to clear a path temporarily and then restore the pieces to their correct positions after the move has been made. This calls for considerable skill in programming, but the X-Y robot provides a highly rewarding way of learning about such problems.

Game playing is not the only application. A miniature conveyor belt has been included in the design so that a warehousing robot can be simulated. The subroutine supplied will advance the conveyor belt until the light beam at the end is broken. That means that the next item is ready for collection by the robot. You can try labelling the draughts pieces to



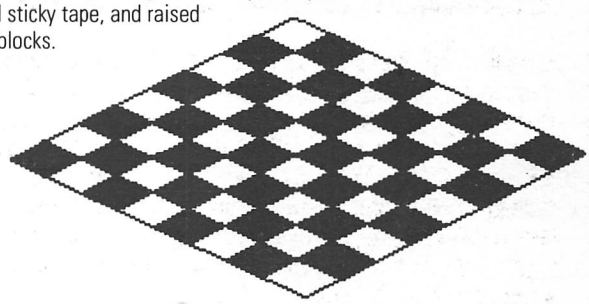
represent different stock items, then write a program that accepts an item from the conveyor, together with a label typed in on the keyboard, and stores the item somewhere on its floorspace. On request from the keyboard, the conveyor is reversed and the robot retrieves the appropriate item.

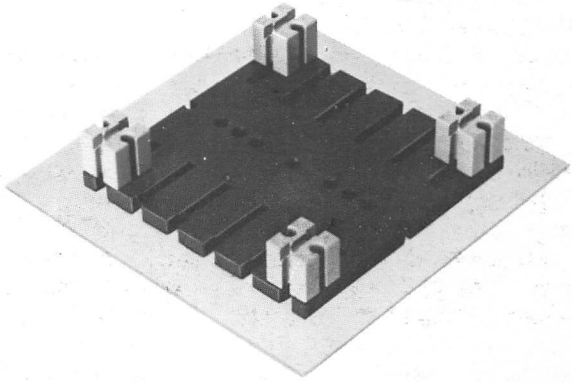
Fundamental to the design of this robot is the positional feedback employed on both axes, without which it would be impossible to position the end effector accurately. A microswitch passes over a line of angled bricks and the computer keeps track of position by counting the closures of the switch. You can alter the spacing of the angled bricks to suit the application and fit as many or few as you need. When the computer is instructed to move to co-ordinates 4,7, it will move the end effector to the fourth angled brick along and the seventh one across, so it doesn't even matter if their spacing is unequal.

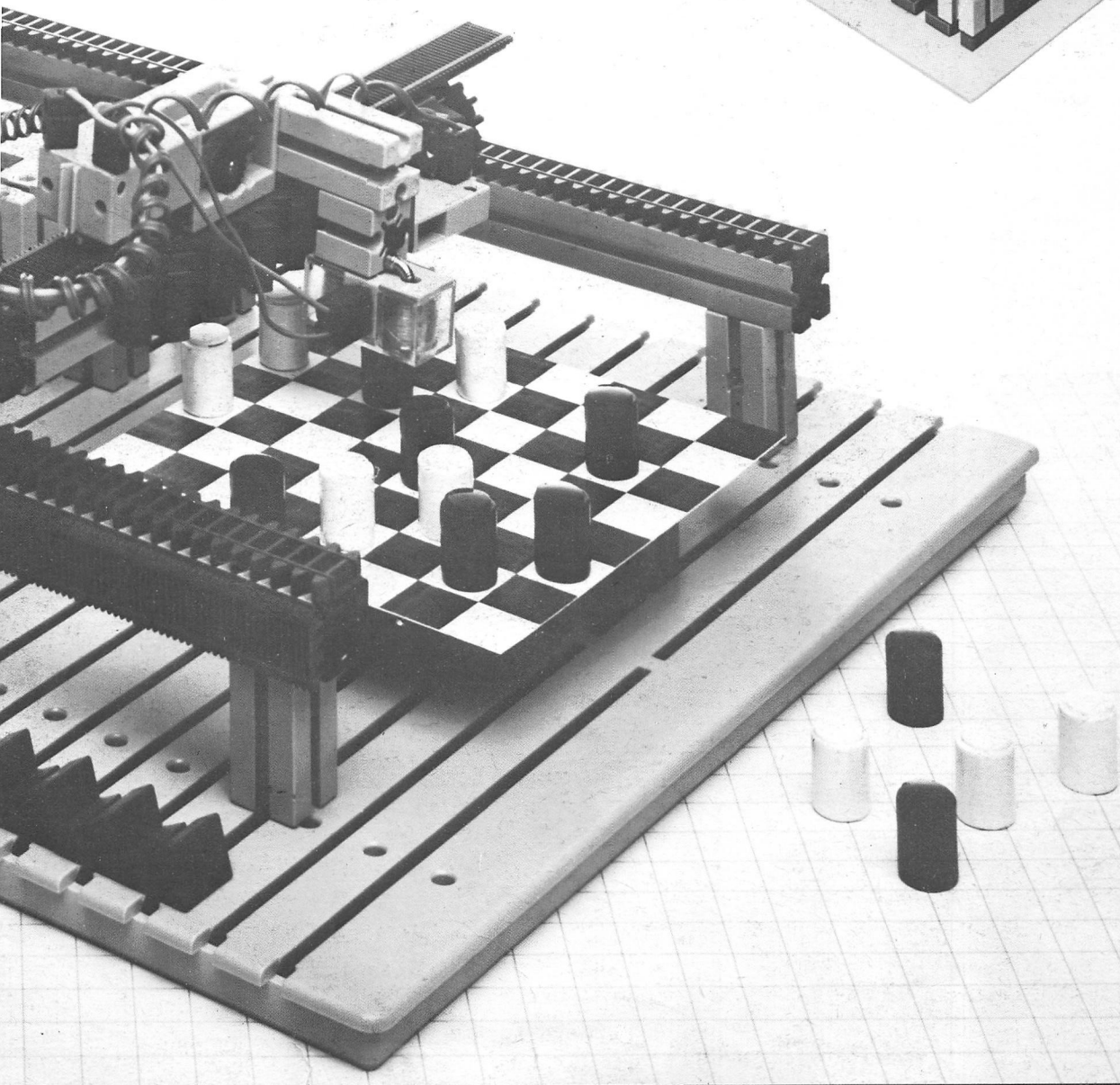
Once you've exhausted these possibilities, you can add to the basic chassis. If you have a third minimotor, then a Z axis to raise and lower the end effector would be a boon. Alternatively, you could replace the electromagnet with a hook or a mechanical end effector. Finally, you can extend the warehouse concept by adding another conveyor. Individual items arrive on one, the robot stacks them into neat piles, and then ships the loaded pallets out the other end.

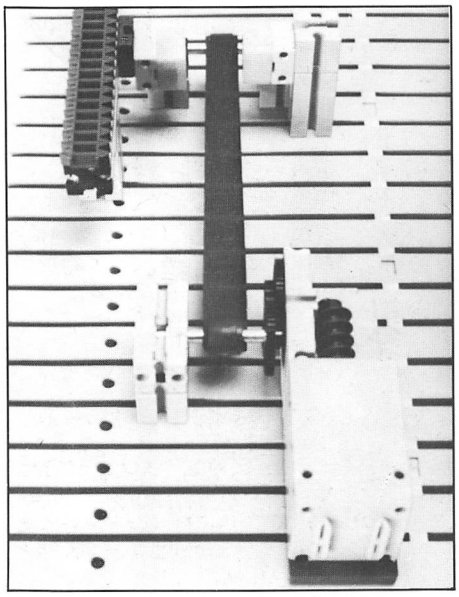
Making the chessboard. Mark out the board on a piece of stiff card, with the size of the squares identical to the width of a standard building block (15mm). The board is then mounted onto a square baseplate, using double-sided sticky tape, and raised on four half-blocks.

Playing pieces. A rod of 1cm (⅖in) thick doweling is sawn into pieces of equal length. A drawing pin (of the kind that can be picked up by magnet) is inserted into each, and the group of pieces painted or labelled as required.

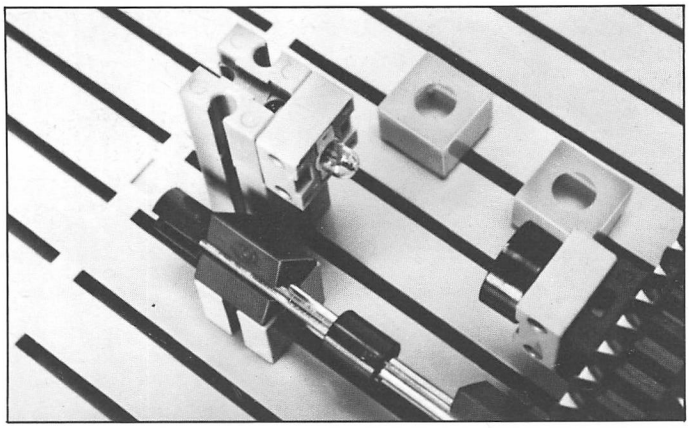






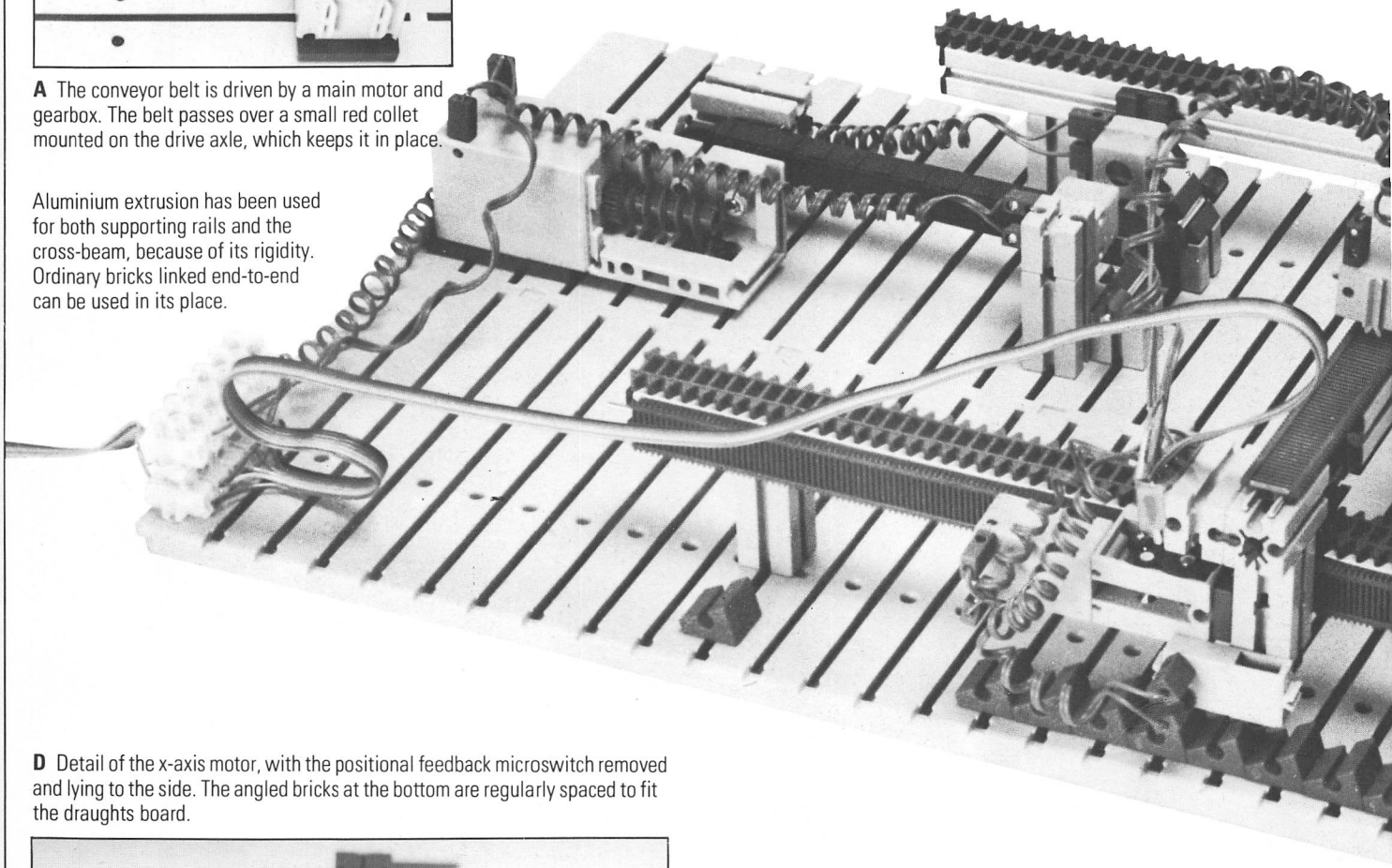


A The conveyor belt is driven by a main motor and gearbox. The belt passes over a small red collet mounted on the drive axle, which keeps it in place.

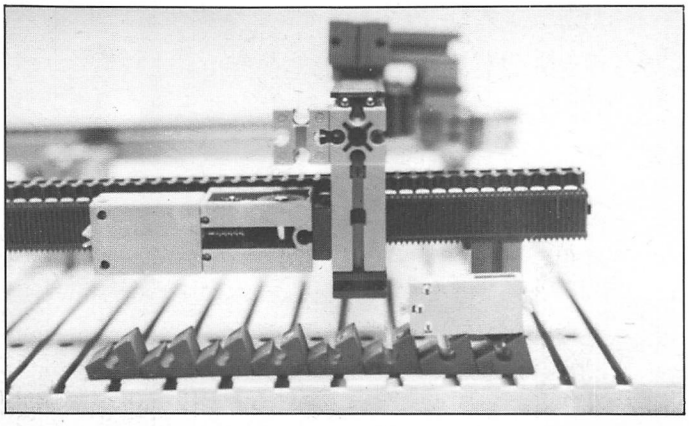


B The caps supplied must be fitted over the light bulb and light detector. The system may still be prone to extraneous light, in which an additional cap, made from cardboard and with a small hole in the end, should be constructed and placed over the light detector.

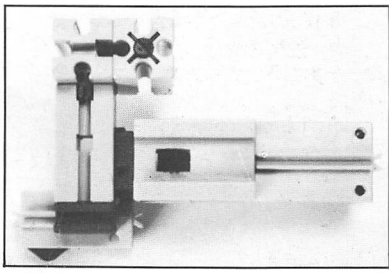
Aluminium extrusion has been used for both supporting rails and the cross-beam, because of its rigidity. Ordinary bricks linked end-to-end can be used in its place.

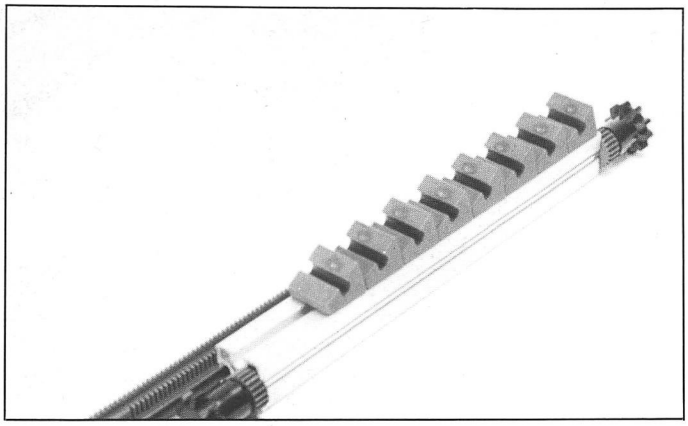


D Detail of the x-axis motor, with the positional feedback microswitch removed and lying to the side. The angled bricks at the bottom are regularly spaced to fit the draughts board.

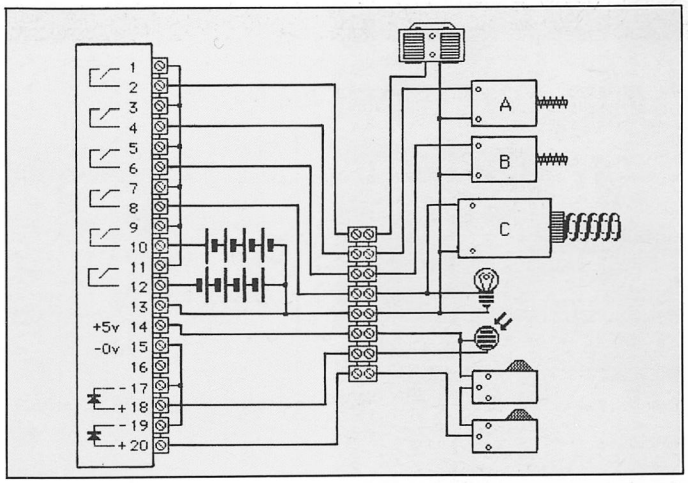


E The x-axis motor and microswitch removed, shown from the reverse side.

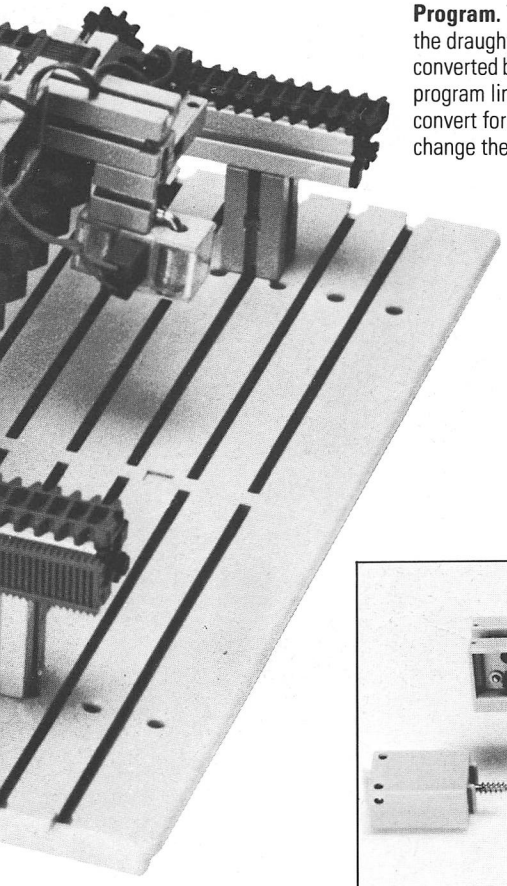




C The two black pinions at either end of the cross-beam are locked tight onto an axle that passes through the length of the beam. They engage with the racking on the top surface of the two supporting rails, and their function is to ensure that the cross-beam remains perpendicular to the rails.

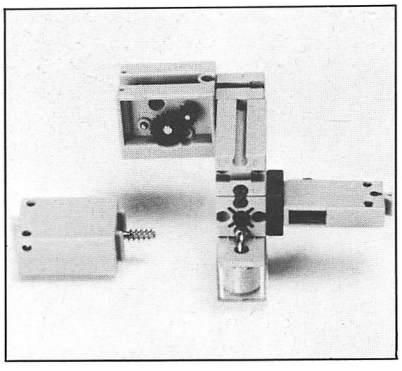


Wiring diagram. The two microswitches are wired up in series so that they can be read by a single input line (the other is for the light cell). So one of the switches must be held closed for the other one to be read. Our program stops one axis with the switch closed before moving the other. If your relay block has more lines available, or you omit the conveyor belt, feed each microswitch to a separate input. Note, too, that the light bulb is in parallel with the conveyor motor, because the two are always activated together.

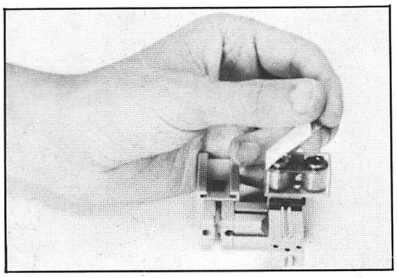


Program. This automatically sets out the draughts board. It can be easily converted by rewriting or adding more program lines between 150–1000. To convert for use on Commodore 64 change the value of PRT to 56577.

```
10 REM**DRAUGHTS ROBOT CONTROLLER**
20 REM**INITIALIZE**
30 PRT=37136:POKEPRT+2,63
40 PRINT"INSERT BATTERIES"
50 REM VARIABLES
51 MG=0  :REM MAGNET FLAG
52 MX=2  :REM MOTOR X
53 MY=4  :REM MOTOR Y
54 M=8   :REM CONVEYOR MOTOR
55 D1=16 :REM DIRECTION 1
56 D2=32 :REM DIRECTION 2
57 OFF=0 :REM TURN OFF MOTORS
60 REM**USER SETS TO 1,1**
70 PRINT"USE CURSOR KEYS TO SET TO 1,1"
80 PRINT"AND THEN PRESS RETURN"
90 GETA$:IFA$=""THEN80
100 IFA$=""THENX=2:X1=1:GOSUB1000
110 IFA$=""THENY=2:Y1=1:GOSUB1100
120 IFA$<>CHR$(13)THEN90
130 X=1:Y=1
150 REM**SET UP BOARD**
160 FORI=1TO24:READXP,YP:GOSUB1200
170 X1=1:Y1=0:GOSUB1000:GOSUB1100
180 GOSUB1300
190 X1=XP:Y1=YP:GOSUB1100:GOSUB1000
200 GOSUB1350
210 NEXTI:END
1000 REM**DRIVE X TO X1**
1010 IFX1>80RX1<1THEN1080
1020 DX=SGN(X1-X)
1030 IFDX=-1THENPOKEPRT,MX+D2+MG:GOTO1050
1040 POKEPRT,MX+D1+MG
1050 IF(PEEK(PRT)AND64)=0THEN1050
1060 IF(PEEK(PRT)AND64)=64THEN1060
1070 X=X+DX:IFX<>X1THEN1050
1080 POKEPRT,OFF+MG+D1:RETURN
1100 REM**DRIVE Y TO Y1**
1110 IFY1>80RY1<0THEN1180
1120 DY=SGN(Y1-Y)
1130 IFDY=-1THENPOKEPRT,MY+D2+MG:GOTO1150
1140 POKEPRT,MY+D1+MG
1150 IF(PEEK(PRT)AND64)=0THEN1150
1160 IF(PEEK(PRT)AND64)=64THEN1160
1170 Y=Y+DY:IFY<>Y1THEN1150
1180 POKEPRT,OFF+MG+D1:RETURN
1200 REM**FEED CONVEYOR**
1210 POKEPRT,M+D1+MG:GOSUB1400
1220 IF(PEEK(PRT)AND128)=0THEN1220
1230 POKEPRT,OFF+MG+D1:RETURN
1300 REM**MAGNET+FLAG ON**
1310 GOSUB1400
1320 MG=1:POKEPRT,MG+D1:GOSUB1400:RETURN
1350 REM**MAGNET+FLAG OFF**
1360 GOSUB1400
1370 MG=0:POKEPRT,MG+D1:GOSUB1400:RETURN
1400 REM**SLIGHT PAUSE**
1410 FORTD=0TO100:NEXTTD:RETURN
10000 DATA8,8,6,8,4,8,2,8,7,7,5,7,3,7,1,7
10010 DATA8,6,6,6,4,6,2,6,7,3,5,3,3,3,1,3
10020 DATA8,2,6,2,4,2,2,2,7,1,5,1,3,1,1,1
```



F Detail of the end effector, the y-axis motor and positional feedback microswitch, which can be finely adjusted for position when mounted on the cross-beam.



G A small piece of paper is stuck on the bottom surface of the electromagnet with adhesive tape. Without this, the drawing pins are likely to become permanently magnetized.

LEGO ROBOT ARM

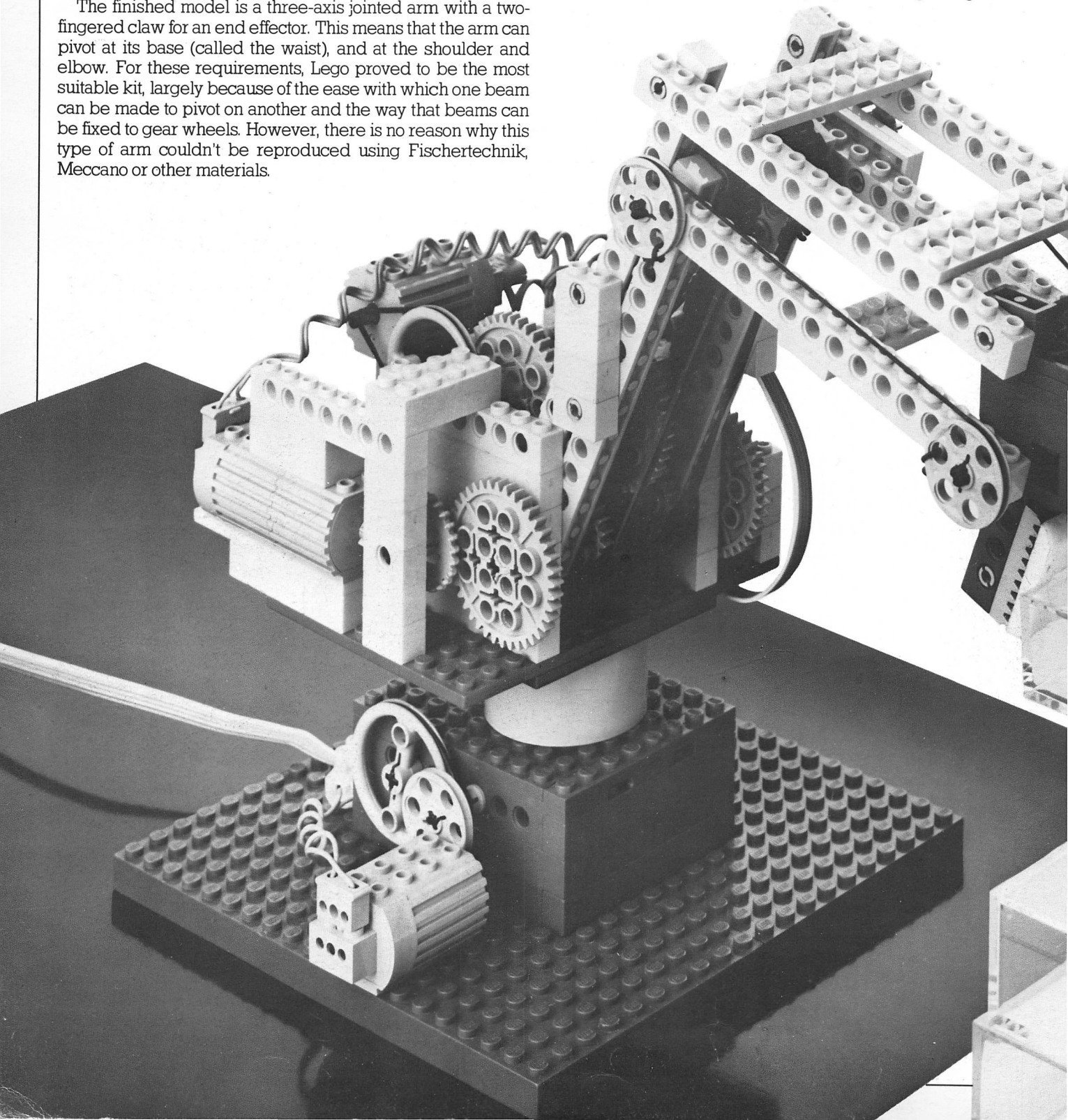
Manipulating a small-scale robot arm under the control of a computer is the ideal way of learning how industrial robots operate, as well as being great fun. Purpose-built educational robot arms, however, can cost £500 or more, but this project shows how a similar type of device can be built from a standard construction kit.

The finished model is a three-axis jointed arm with a two-fingered claw for an end effector. This means that the arm can pivot at its base (called the waist), and at the shoulder and elbow. For these requirements, Lego proved to be the most suitable kit, largely because of the ease with which one beam can be made to pivot on another and the way that beams can be fixed to gear wheels. However, there is no reason why this type of arm couldn't be reproduced using Fischertechnik, Meccano or other materials.

The arm can be driven through battery boxes and switches, or interfaced to a computer, as shown overleaf. It must be stated, though, that its operation falls somewhat short of the more expensive off-the-shelf products. Specifically, the working envelope of this robot – the volume of space that its end effector can reach – is very restricted. It can lift only very light loads and, most important, it lacks any form of feedback, so precise control is difficult.

Nevertheless, this project demonstrates several very important principles in the construction of robot arms, and these will help you to design your own models, employing more axes of freedom or using a quite different geometry.

Firstly, it demonstrates the very high level of gearing down



needed to obtain useful torque and controllable speed. Using a combination of Lego gearboxes plus trains of conventional gear wheels, the motor powering the end effector is geared down by 300:1, the shoulder by 250:1, and the elbow by 500:1. These arrangements would be far too clumsy for an industrial robot, which is why they employ the harmonic drive (see page 117).

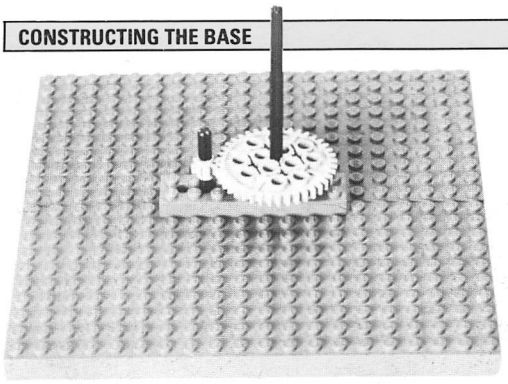
Secondly, the base unit highlights the need for proper bearings that can provide relatively friction-free rotation and, at the same time, structural support – the weight of the extended arm exerts a considerable bending moment (turning force) on the axis of rotation. Our model uses a large roadwheel to bear the load, but a professional design would employ ball bearings or a proper turntable.

A third feature of importance is the way that power is transmitted through an arm that changes in shape. At both the shoulder and elbow, the power drive (consisting of chains and string belts) passes through the axis of the joint so that rotating one limb will not cause movement in another.

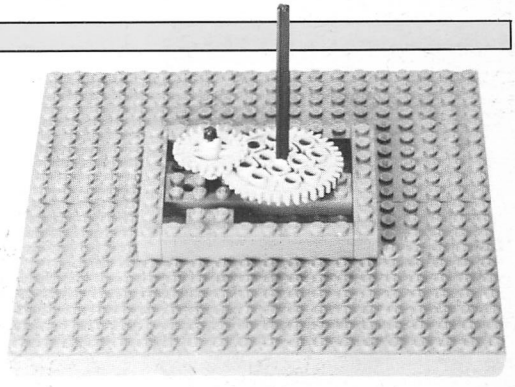
Finally, note the way that rubber bands have been used on both the forearm and upper arm. They counteract the weight of the robot's own limbs, without adding further mass as a traditional counterbalance would. Without some form of counterbalance, almost all of the motor's effort would be taken up with lifting the arm itself, rather than any useful load at the end effector.

As stated before this project is more about construction techniques than about control systems. You could write a computer program that memorized a sequence of movements and then played them back, but it wouldn't be very accurate. The program printed allows the arm to be controlled from the computer's keyboard in live mode, and you can set yourself various exercises, such as stacking building blocks or playing noughts and crosses.

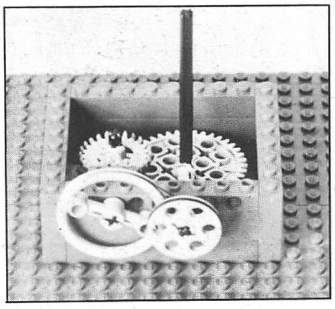
CONSTRUCTING THE BASE



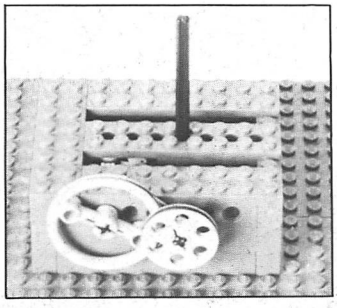
1 Two rectangular baseboards are held together using two 8×2 holed plates. The 40-tooth gear wheel is mounted on a 12-unit-long axle, the 8-tooth gear on a 4-unit-long axle.



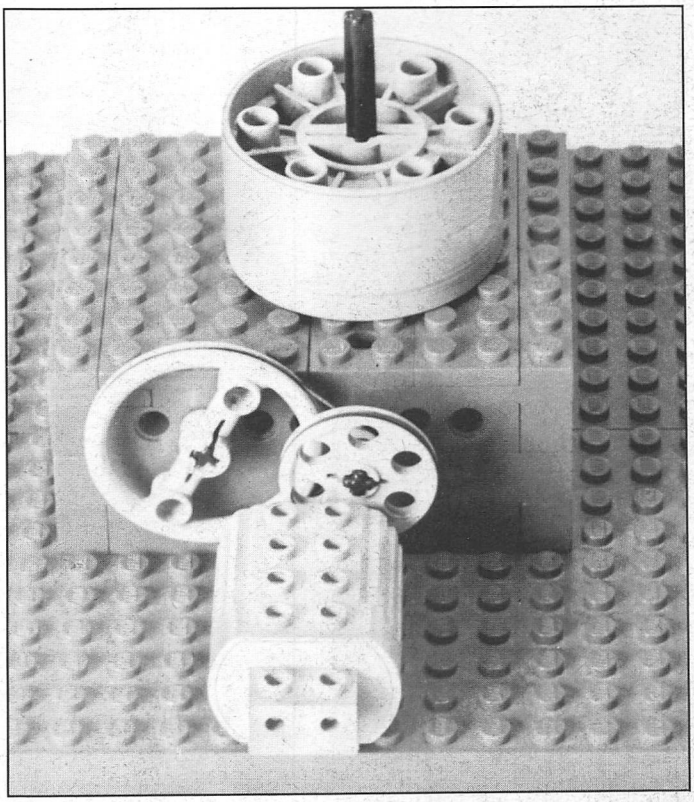
2 A 24-tooth crown wheel is fitted onto the shorter axle, and the first layer of the base housing is added. Note the location of the 2×1 brick inside the casing.



3 Two pulley wheels are mounted on 4-unit axles. An 8-tooth gear wheel on the left-hand axle meshes with the crown wheel. The other axle has a bush either side of the wall.

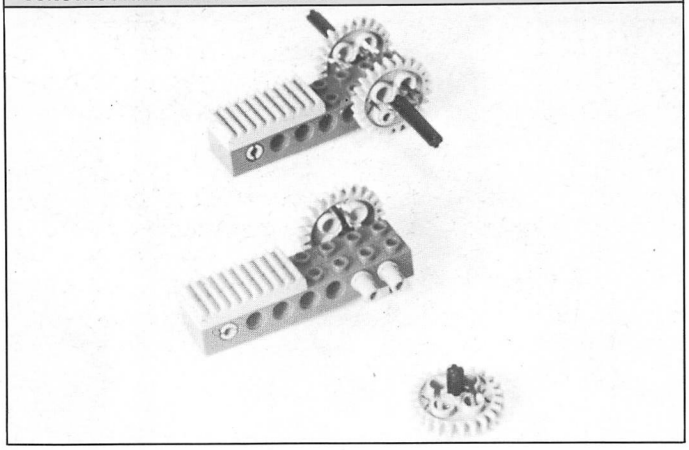


4 The first layer of 8×2 top plates is added. Rubber belts are fitted to both pulleys, the left-hand one passing over the bush on the right-hand axle.

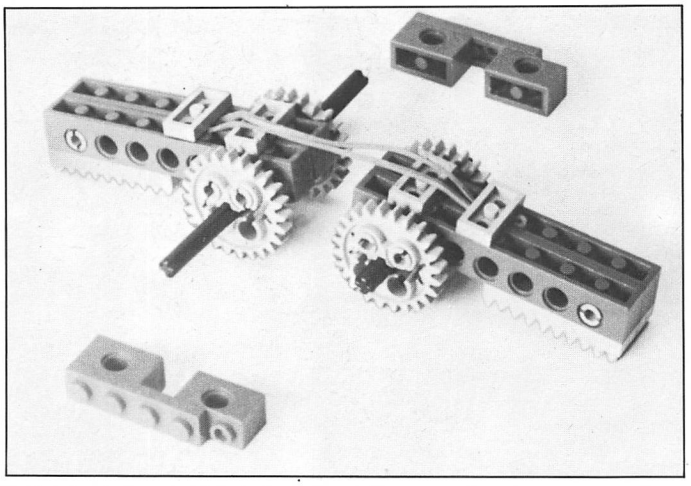


5 A second layer of plates is added, followed by the inner part of a large tractor-type wheel to act as a bearing. The second rubber belt links motor (in foreground) and smaller pulley.

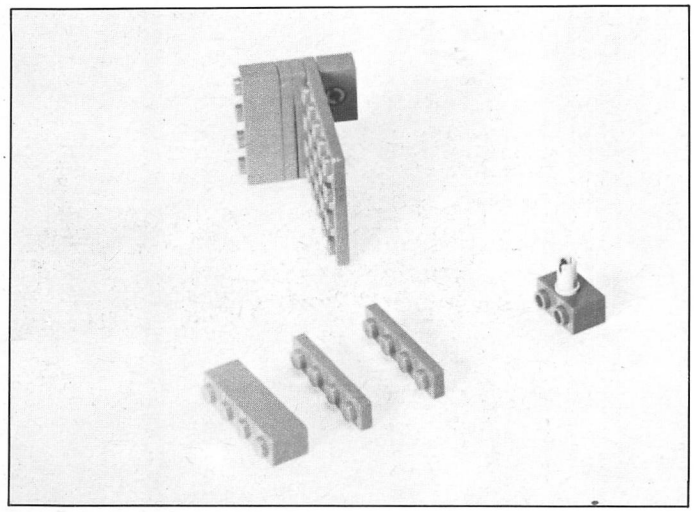
CONSTRUCTING THE END EFFECTOR



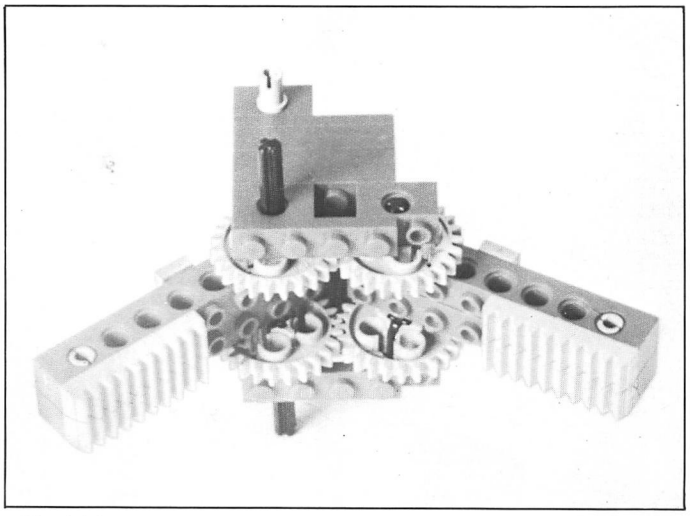
6 The two fingers of the end effector are identical, except that one (below in picture) features 2-unit-long axles, where the other has 4-unit-long axles. All four gear wheels have 24 teeth.



7 Two 2×1 plates hold the halves of each finger together, the outermost plate also securing a thin elastic band, the purpose of which is to spring the two fingers apart. On each side two 2×1 holed bricks and a 4×1 cross plate are used to link the fingers.

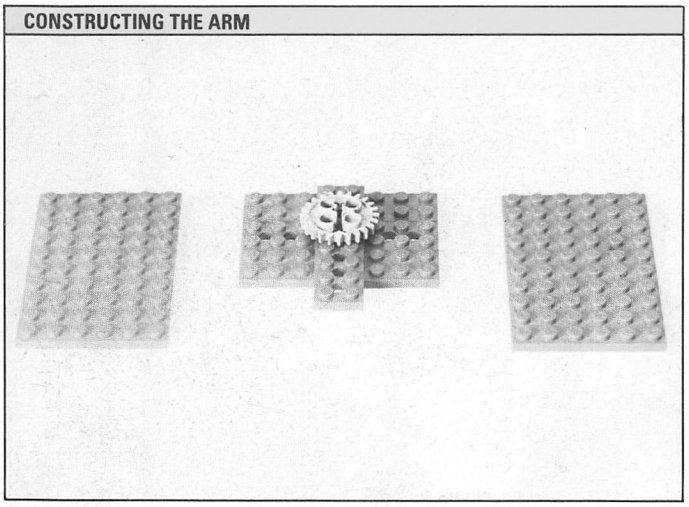


8 The two sides of the end effector housing, completed using 4×1 plates and bricks, fit onto a 6×4 plate. Connector pins are fitted into the two 2×1 holed bricks on the top surface to join onto the arm.

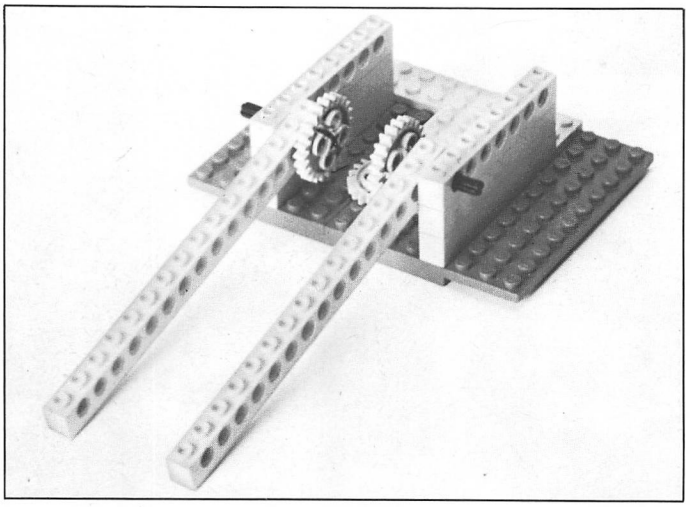


9 The finished end effector. Check that the jaws open and close smoothly, and that the elastic band runs across the top of the jaws, providing moderate tension when closed.

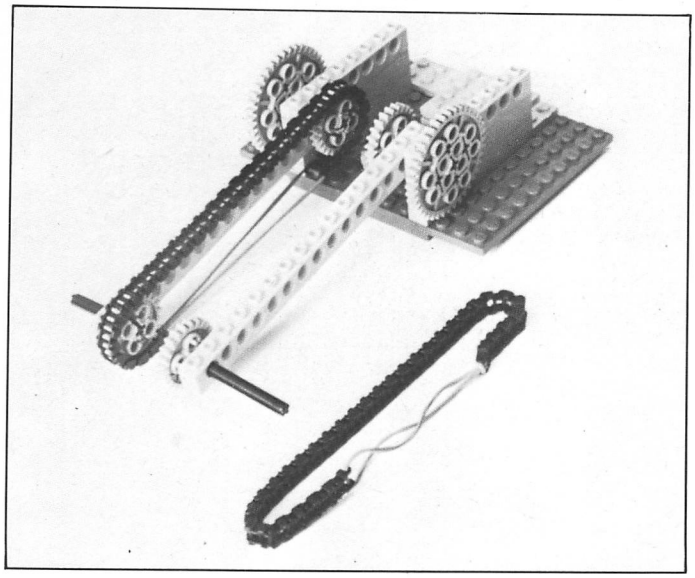
CONSTRUCTING THE ARM



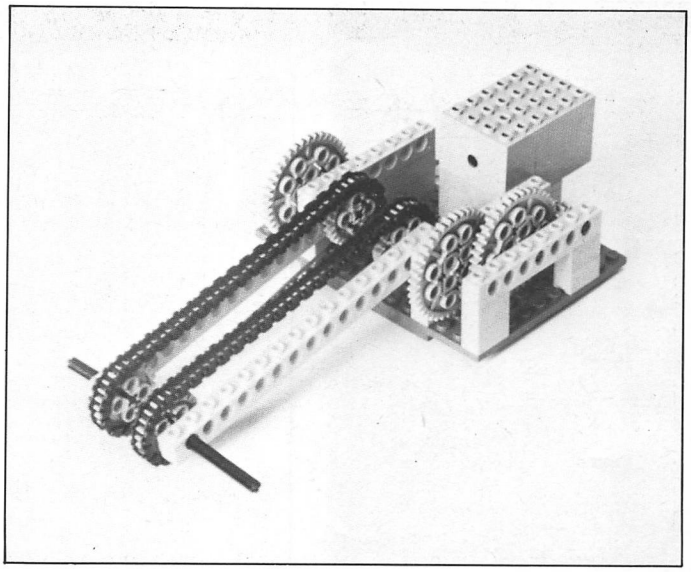
10 The baseplate consists of two 6×10 plates and four 2×8 plates, two of which have holes. A 24-tooth gear wheel fits over the common hole, to take the turntable axle.



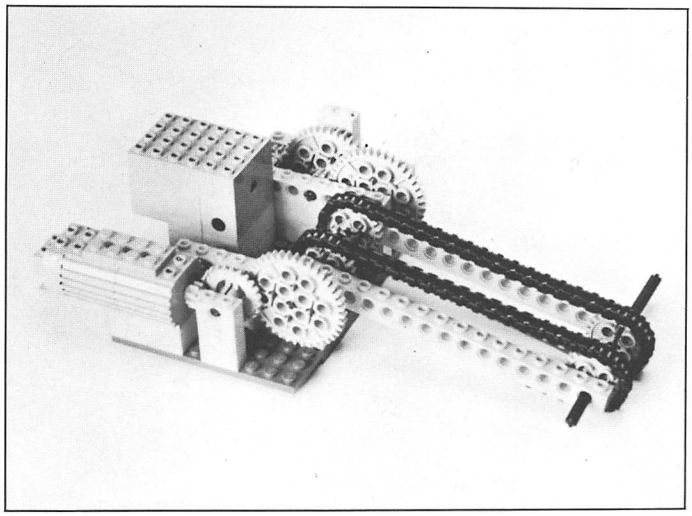
11 The side walls are three layers high. A 4-unit axle, bearing a 24-tooth gear wheel and a 16-unit-long holed beam, is fitted to the front of each side. A single 8×2 plate goes behind the two sides.



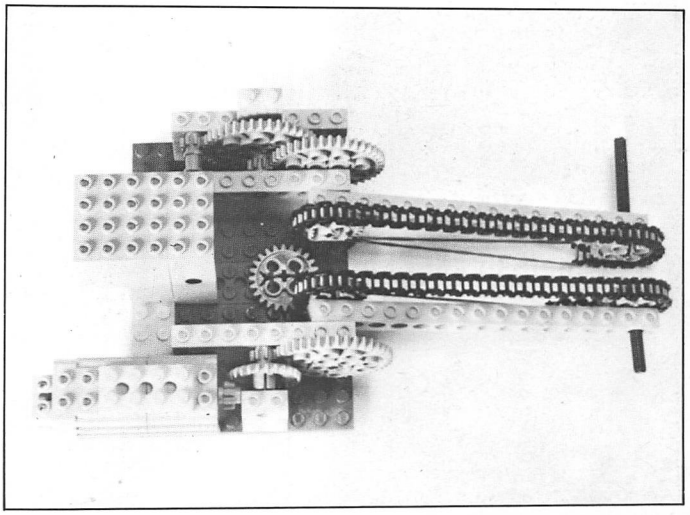
12 A 4-unit axle and a 6-unit axle, both fitted with 24-tooth gears, form the elbow joint. The drive chains are lengthened with rubber bands, which also provide tension. A 4×2 and a 4×4 plate are added to support the gearbox.



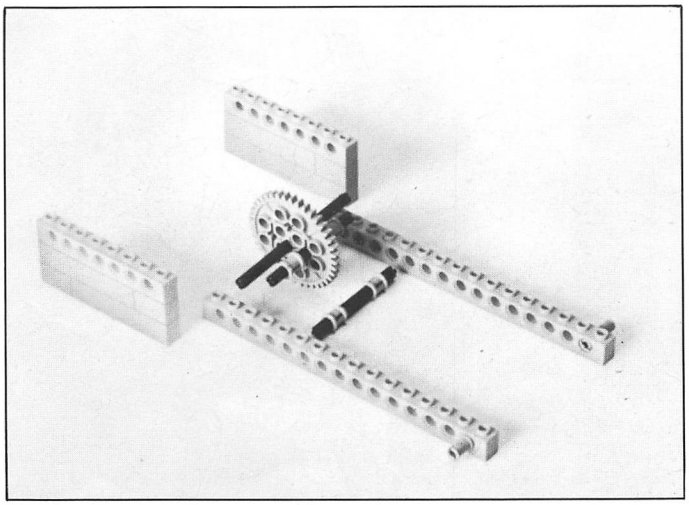
13 The gearbox is mounted on a total of three sets of plates and one course of bricks. A 6-unit axle passes from the box through the side into a train of 8- and 40-tooth gears supported by a raised 8×1 holed beam.



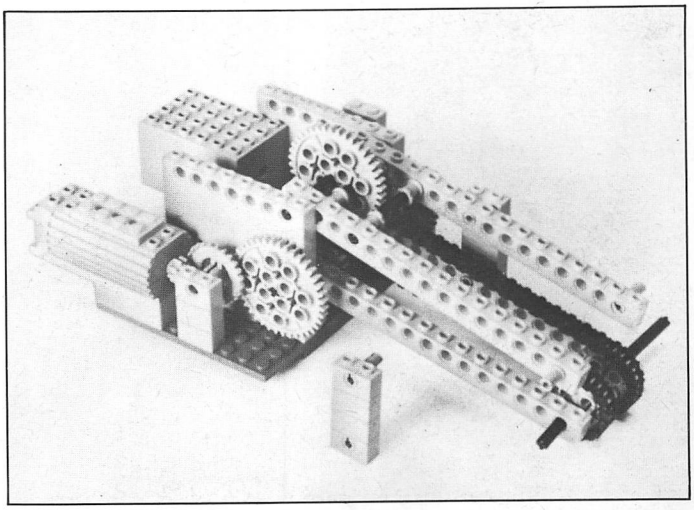
14 The second motor used in the project also drives through a 20:1 gearbox to an 8-tooth gear wheel. This meshes with a crown wheel, mounted on a 4-unit axle along with another 8-tooth gear (not visible in this picture).



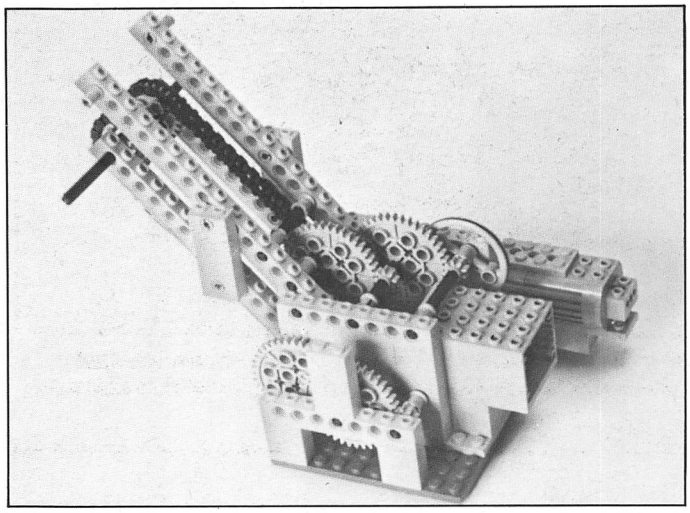
15 This shows the detail of the gear trains on both sides of the main housing. Note that once the gearboxes are mounted, neither of the sets of gears should be forced.



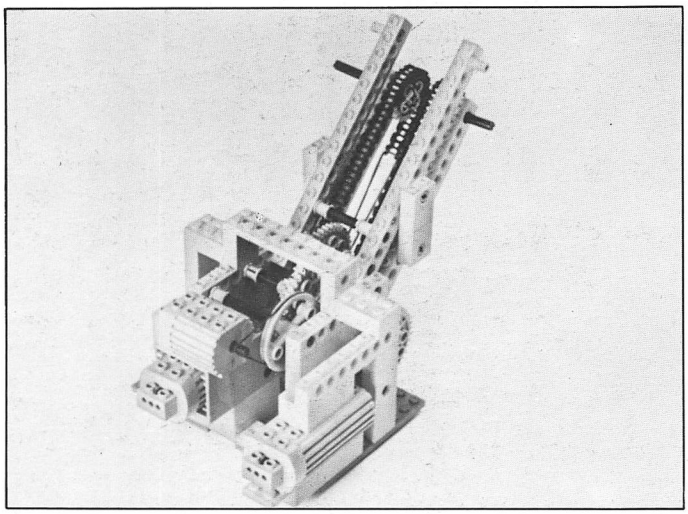
16 The upper body and arm are constructed from 8-unit- and 16-unit-long beams respectively. Two 6-unit axles bridge the arm, while one 8-unit axle bearing a 40-tooth gear locates the arm in the two sides.



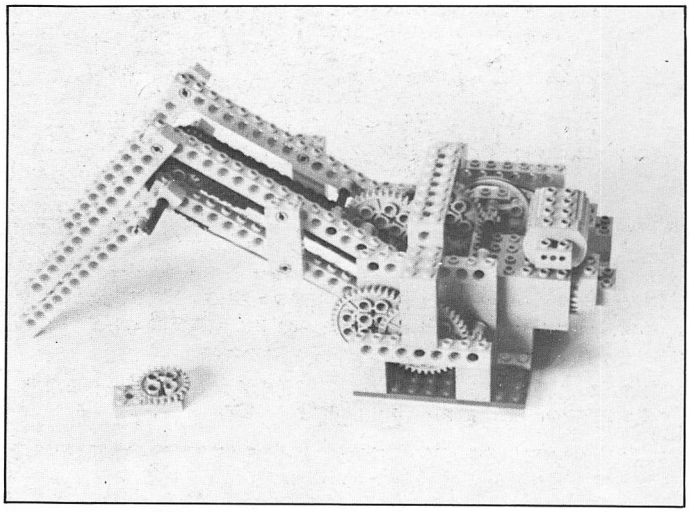
17 After mounting the new structure on the main body, two side pieces are fitted, to keep the main beams parallel. Each consists of four 2×1 bricks with two connecting pins.



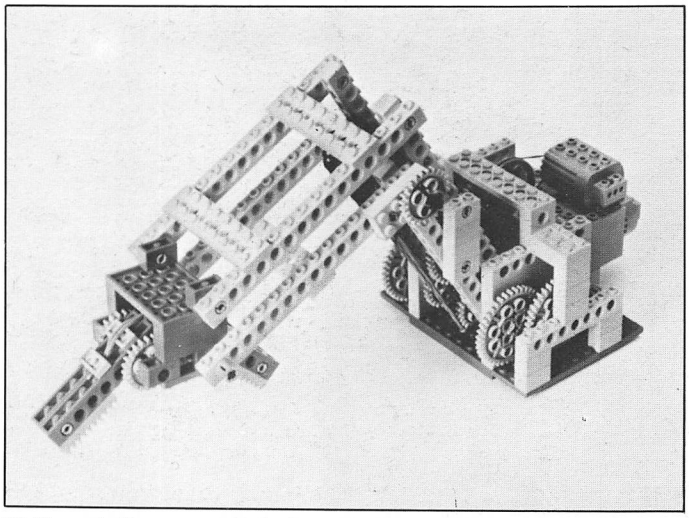
18 Two more 8-unit axles, one above the main gearbox and one centrally, bridge the main body, with a train of 8- and 40-tooth gears mounted on them. The large pulley has already been fitted with a rubber belt.



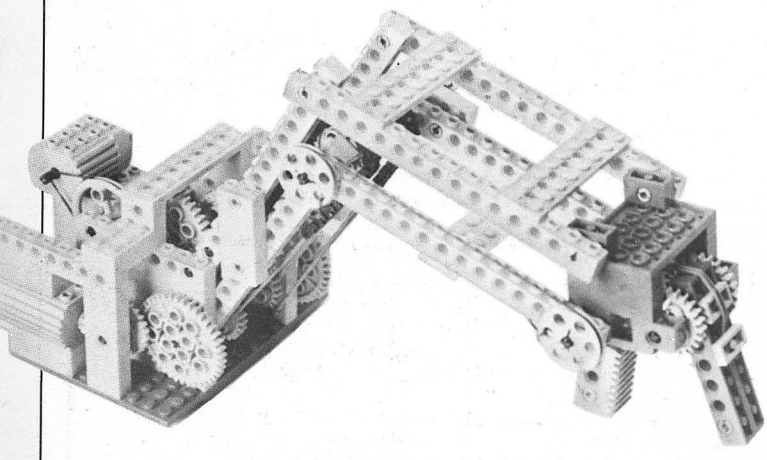
19 The top motor, placed above the main gearbox, is now engaged with the rubber belt, and the remaining motor inserted into its gearbox. A supporting bridge of plates and bricks strengthens the structure.



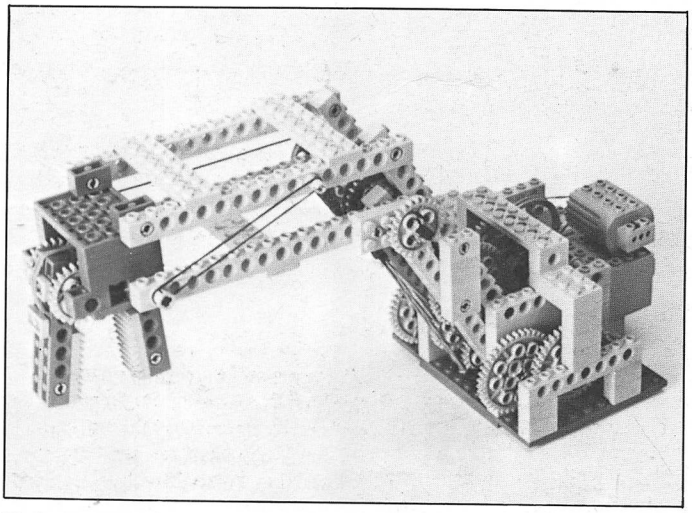
20 Four 16-unit-long beams make up the forearm. An 8×2 holed plate bearing a 24-tooth gear is fitted over the longer of the protruding axles and secured via the peg.



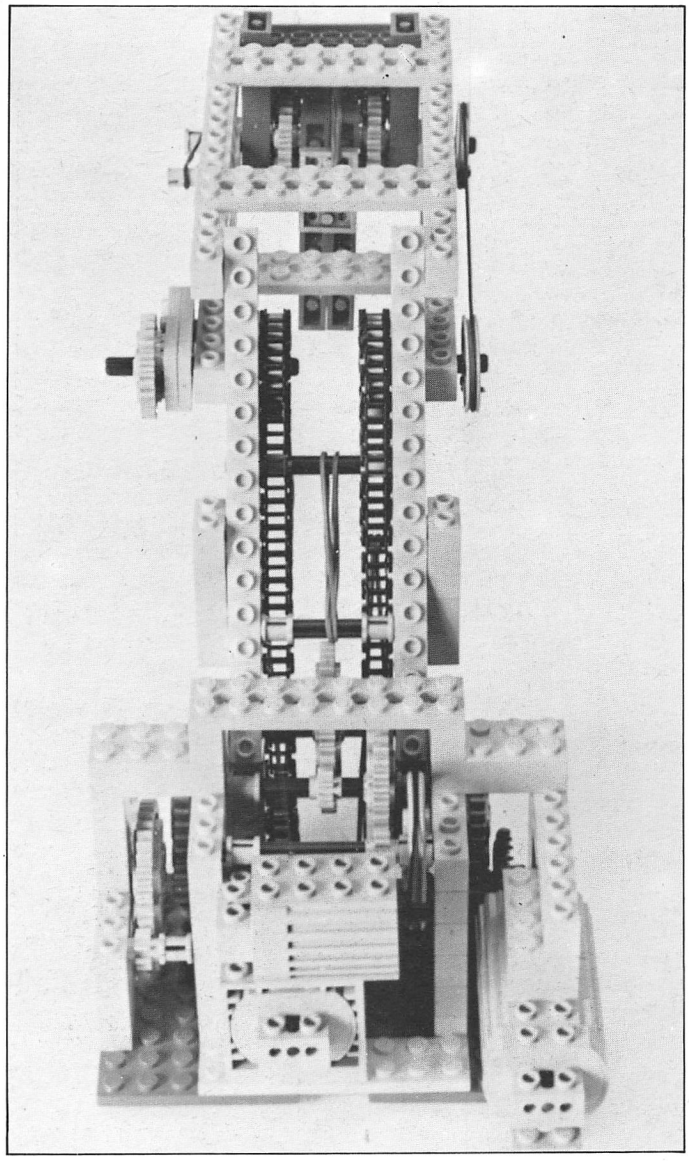
21 The end effector can now be fixed to the forearm and secured with a bush one side and a pulley wheel the other. Three 8×2 plates placed transversely make the arm more rigid.

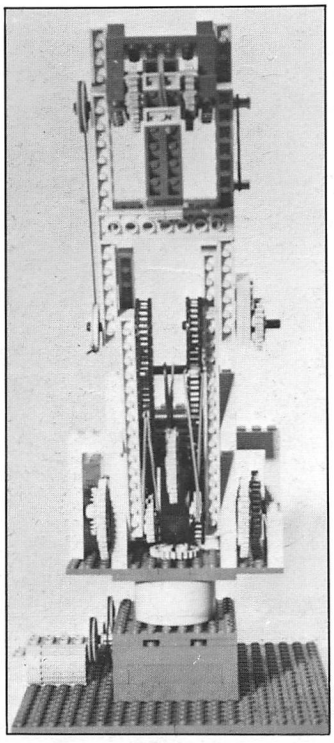


22 A piece of string is tied between two pulley wheels, one placed on the elbow, one on the wrist. Experiment with the length of the string so that the motor can open and close the jaws fully.



23 A rubber band is fitted to the forearm using an additional pin. It should bear the weight of the arm, but not force it upwards so that the drive chain becomes slack.

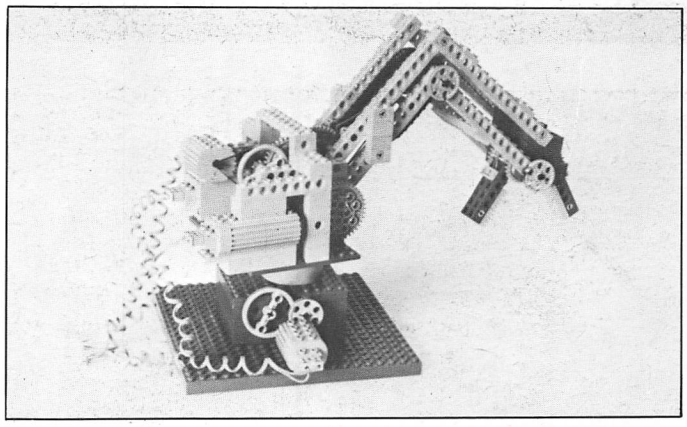




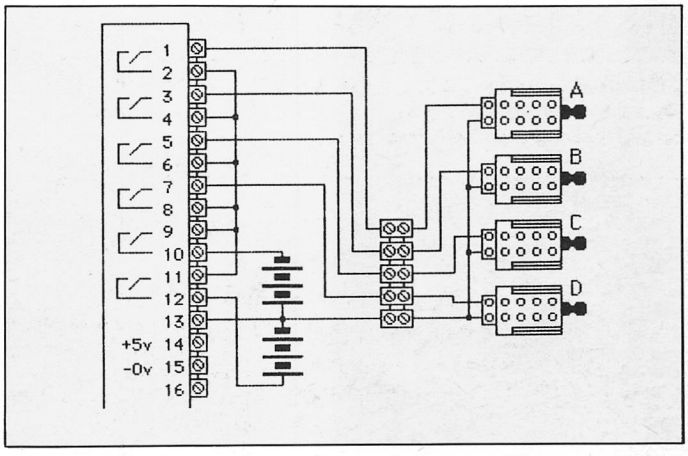
24 The complete arm, seen from behind. A second rubber band, this one doubled up, and placed centrally, counterbalances the weight of the upper arm. The new, 6-unit axle, is fitted between the two lower beams in the upper arm, near to the elbow joint.

25 The arm is now fitted to the base unit. The protruding axle passes through the baseplate and engages with the gear wheel. The body must be pushed down as far as possible.

Program. After initializing the interface block, the movements of the arm are controlled with eight keys: 1 and Q rotate the base in either direction, 2 and W the shoulder, 3 and E the elbow, 4 and R the gripper. Written for the Vic-20, the program can easily be modified for the Commodore 64.



26 The arm is now ready for wiring up, to either four battery boxes and switches or a computer. The wires can be coiled and screwed into a connection block for neatness.



Wiring diagram. One wire is common to the four motors, and they are driven from four relays. Using two sets of batteries and two further relays, it then becomes possible to drive each motor in either direction.

WARNING: LOAD AND RUN THE COMPUTER PROGRAM BEFORE INSERTING THE BATTERIES INTO THE BATTERY HOLDER.

```
10 REM**ARM CONTROLLER**
20 REM**INITIALIZE**
30 PRT=37136:POKEPRT+2,63
40 PRINT"INSERT BATTERIES"
50 DIMKEY(8):FORI=1TO8:READKEY(8):NEXTI
60 MA=1:MB=2:MC=4:MD=8:D1=16:D2=32:OFF=0
100 REM**CONTROL**
110 SCAN=PEEK(197):T=9:FORI=1TO8
120 IFSCAN=KEY(I)THENT=I:I=9
130 NEXTI:IFT=9THENPOKEPRT,OFF:GOTO110
140 ONTGOSUB200,250,300,350,400,450,500,550
150 POKEPRT,OFF:GOTO110
200 REM**SHOULDER UP**
210 POKEPRT,MA+D1:GOSUB1000:RETURN
250 REM**SHOULDER DOWN**
260 POKEPRT,MA+D2:GOSUB1000:RETURN
300 REM**FOREARM UP**
310 POKEPRT,MB+D1:GOSUB1000:RETURN
350 REM**FOREARM DOWN**
360 POKEPRT,MB+D2:GOSUB1000:RETURN
400 REM**BASE CLOCKWISE**
410 POKEPRT,MC+D1:GOSUB1000:RETURN
450 REM**BASE ANTICLOCKWISE**
460 POKEPRT,MC+D2:GOSUB1000:RETURN
500 REM**OPEN GRIPPER**
510 POKEPRT,MD+D1:GOSUB1000:RETURN
550 REM**CLOSE GRIPPER**
560 POKEPRT,MD+D2:GOSUB1000:RETURN
1000 REM**DELAY**
1010 FORTD=0TO20:NEXTTD:RETURN
10000 DATA0,56,1,57,48,9,49,10
```

CARD-DEALING ROBOT

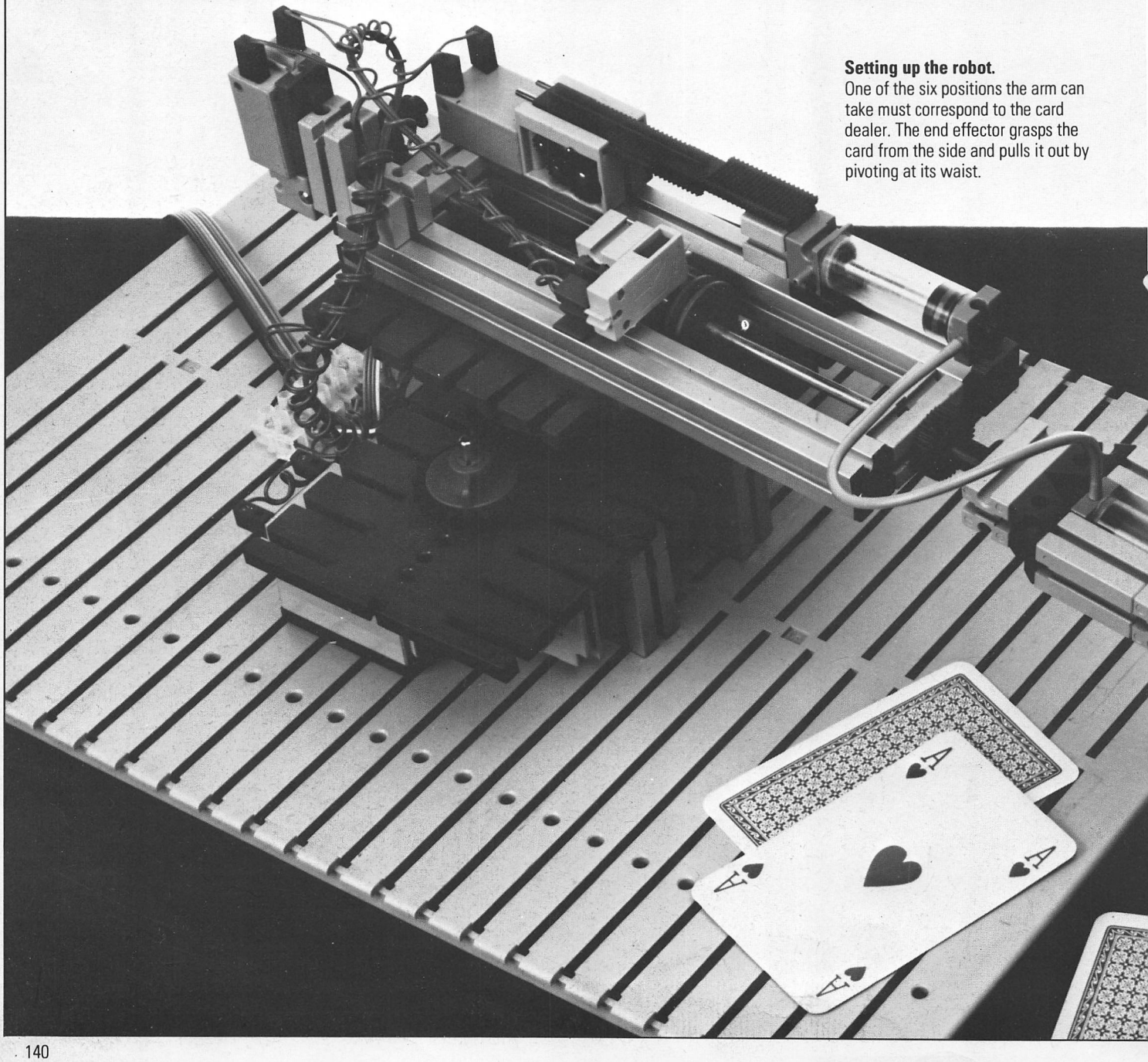
Problem: design a robot that can deal cards. So simple for a human to perform, this function nevertheless represents quite a challenge for a robot. The model pictured here, made from Fischertechnik, can deal cards from a shuffled pack, face-up or face-down, to any of five players, and with reasonable reliability. For those who like to be one up on the Joneses, this device could be worth a lot of merit points, but the real purpose of the project is to demonstrate how the robot designer goes about tackling an awkward application.

One of the keys to solving this problem, for example, is knowing when to mimic the human method of working and when to pursue a quite different solution. So, looking at a human dealing cards, the first thing to note is that it is a two-handed operation. The pack is held in the right hand, say, and cards are pushed off the top (or bottom if the dealer is unscrupulous) one at a time. The left hand grasps the extended card and pivots around to the appropriate player before releasing it, or turning it face up and then releasing it.

The job of the left hand should be well within the capabilities of a conventional robot arm. It need only have two degrees of freedom: the main pivot and the ability to rotate the end effector. It will need positional feedback to locate each of the players consistently, but this can be achieved with a microswitch.

Two flat fingers will suffice for the end effector, but the grip must be tight enough to prevent the card from falling out when the wrist rotates. The grip of plastic fingers can be improved by spreading on a little rubber-solution adhesive and letting it dry, but the best technique is to employ pneumatics because air is so compressible.

The job of the right hand is far more tricky to emulate using construction kit technology, though the problem has been solved in the form of sheet feeders in the printing industry.



Setting up the robot.
One of the six positions the arm can take must correspond to the card dealer. The end effector grasps the card from the side and pulls it out by pivoting at its waist.

Humans employ friction to slide off the top card from the pack, with pressure from the thumb. For a robot, a rubber tyre on a rotating wheel is the nearest equivalent. As each card is dealt the pack gets smaller, so the driving wheels will have to be pivoted on a supporting structure, to keep a constant pressure on the pack.

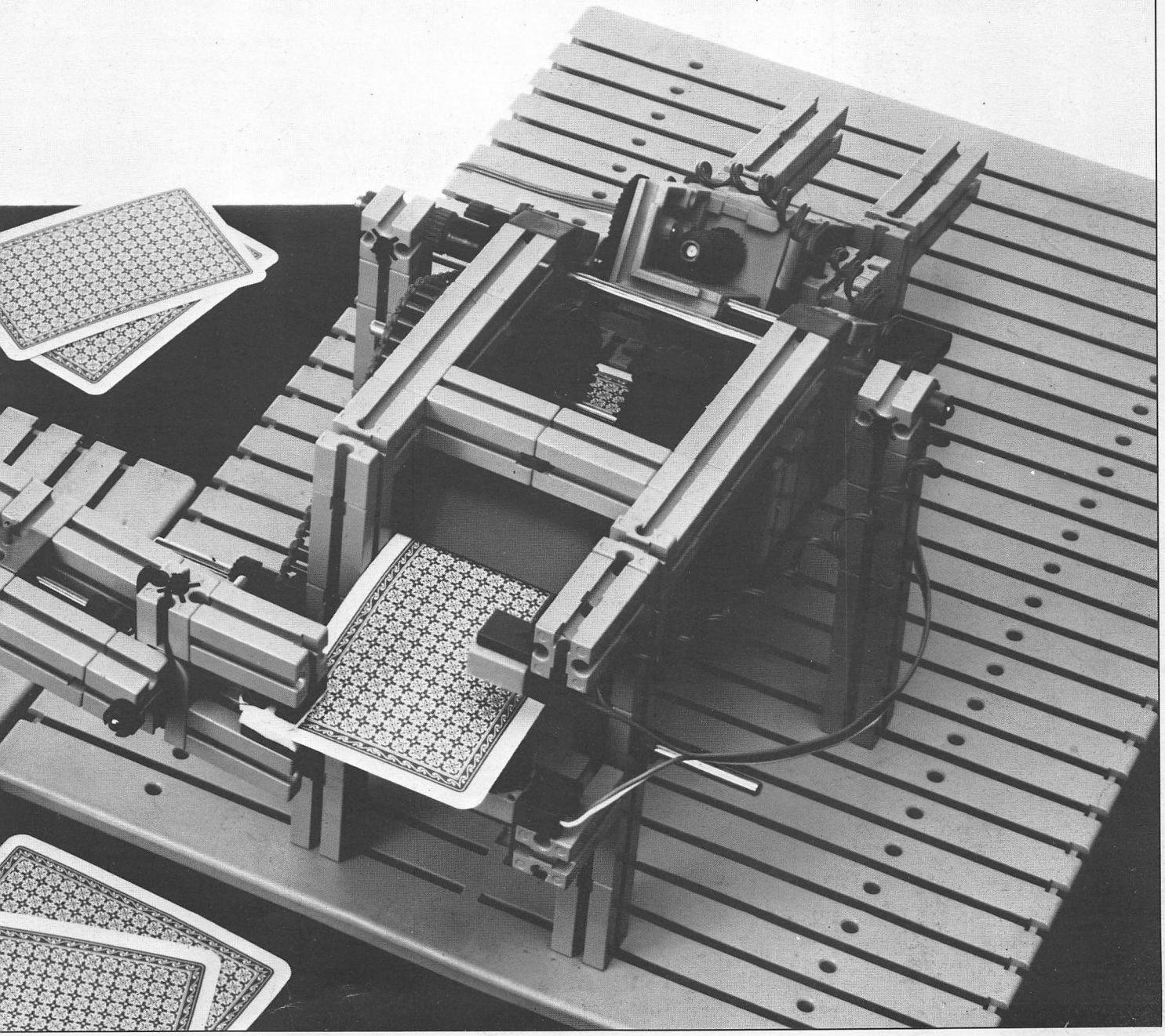
However, the cards will then come off the pack at different heights, which will cause a problem unless the robot arm is equipped with a vertical axis of movement. The solution to this problem demonstrates the technique of inverting the design: fix the driving wheels and pivot the pack of cards!

How is the delivery of cards off the pack to be co-ordinated with the movement of the robot arm, and indeed with the requirements of the players, which are presumably typed in on a computer keyboard? The supply of components to an industrial machine is often regulated using light beams and, fortunately, Fischertechnik can supply both light bulbs and light detectors. The motor can then drive a card off the pack until its front edge interrupts the beam, starting again when that card has been removed by the arm.

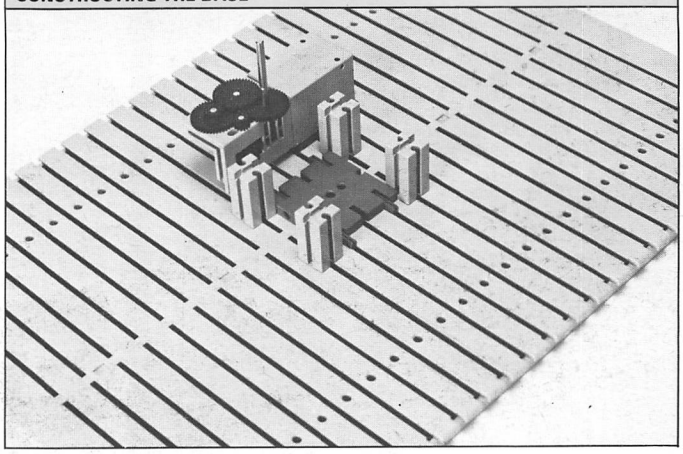
Based on this information you could proceed to build a device for dealing cards off a pack, but you would soon encounter the biggest problem of all: the stickiness of most playing cards will result in them coming off the pack in twos and threes. So how do humans cope with this? Well, while the thumb is pushing a card off the top, the four fingers are acting as a brake on the underneath – if more than one card is delivered, the movement of the fingers pushes the bottom ones back. We can simulate this on the robot with another rubber-rimmed wheel and a pair of deflector plates to guide the advancing cards over it.

When you build this project, you will find that several parts of the model must be finely adjusted to make it work – you may even have to try a couple of different packs of cards. We don't claim that the dealing works 100 per cent of the time, but building the robot is a very rewarding exercise.

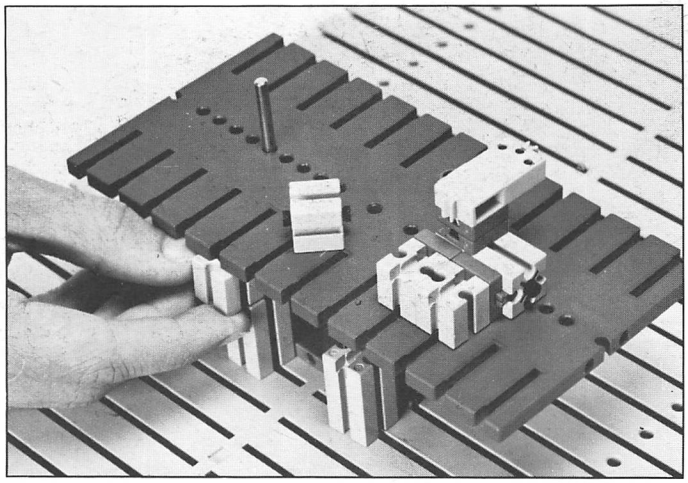
The program supplied consists of a series of simple sub-routines for dealing a card, operating the end effector and moving the arm. From these you can write your own applications programs, for card games such as pontoon, where each player can buy or twist cards from the pack.



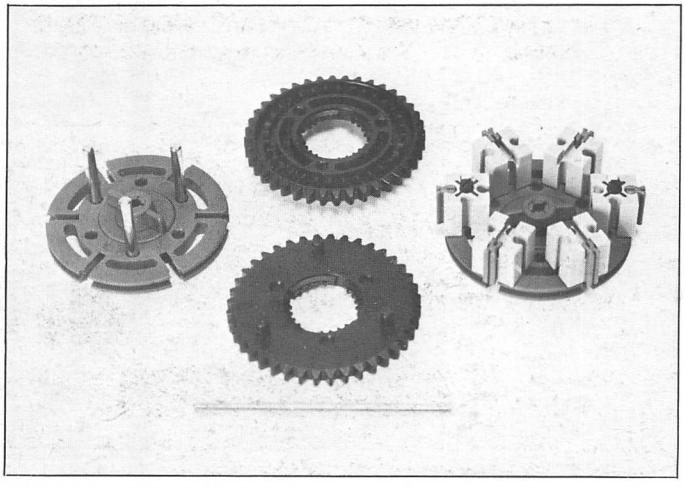
CONSTRUCTING THE BASE



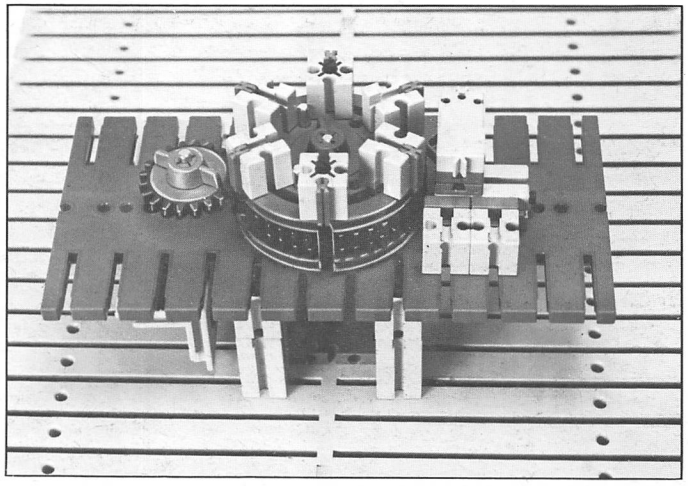
1 The motor and gearbox are mounted directly onto the large baseboard. The small red plate in the centre, between four legs, is to anchor the main turntable shaft. (If you don't have such a plate, use an arrangement of bricks.)



2 The large rectangular plate is fitted over the gearbox axle and fixed to the legs with four half-bricks. Next, the supporting structure for the microswitch is added. The switch measures rotation of the arm.

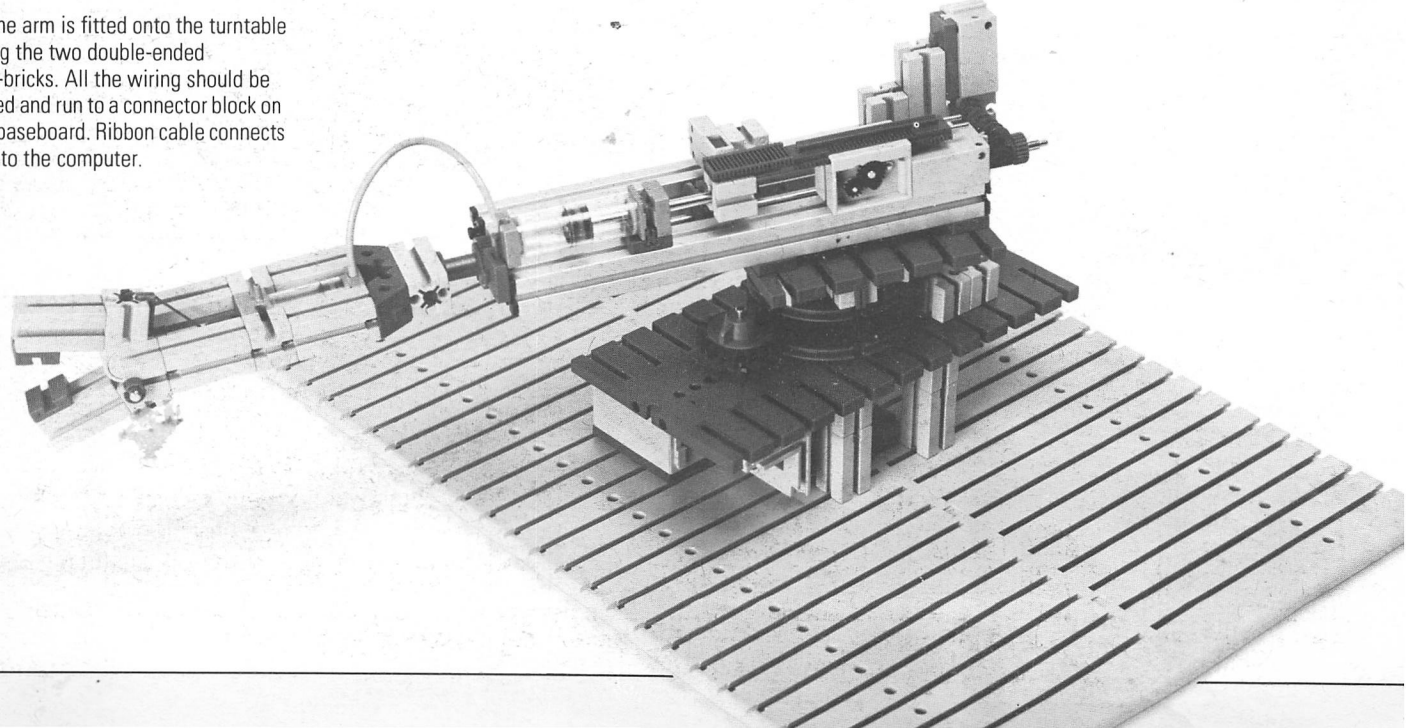


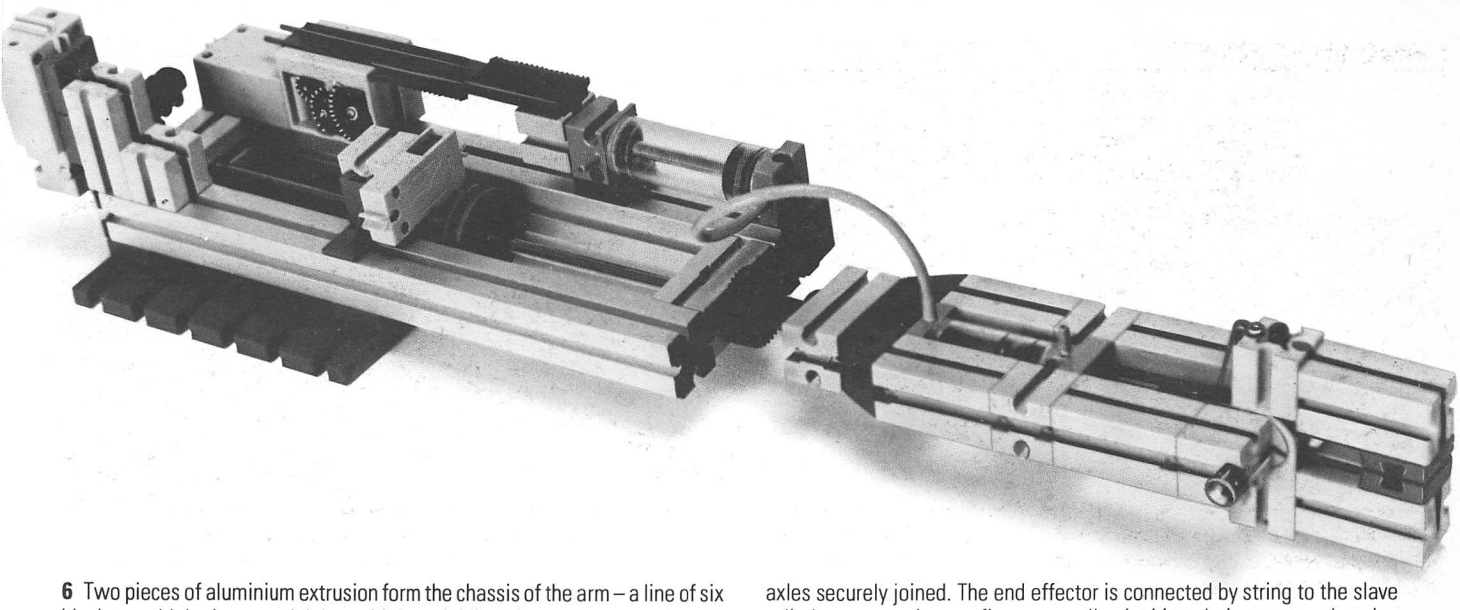
3 This rather complex structure for the turntable is needed for rigidity. If you have the Fischertechnik computer kit, a special turntable component is included. Two of the six half-bricks are double-ended.



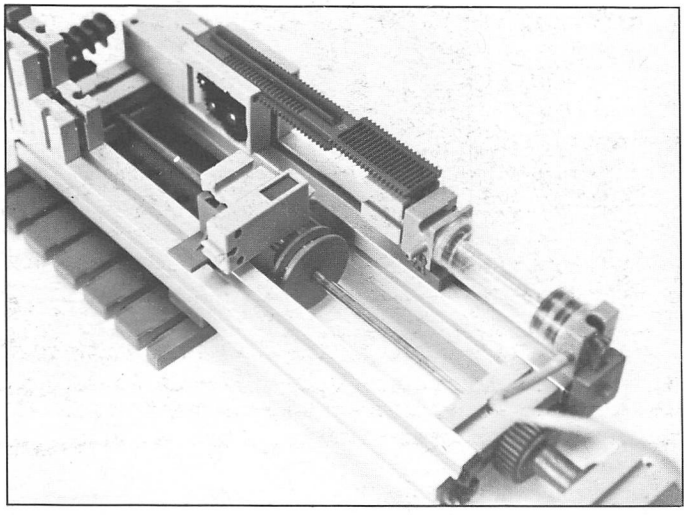
4 The microswitch is adjusted so that the six red connectors in the half-bricks close the switch as they pass by. Now the driving gear can be fitted to the axle shaft, so that it engages with the turntable.

5 The arm is fitted onto the turntable using the two double-ended half-bricks. All the wiring should be coiled and run to a connector block on the baseboard. Ribbon cable connects this to the computer.

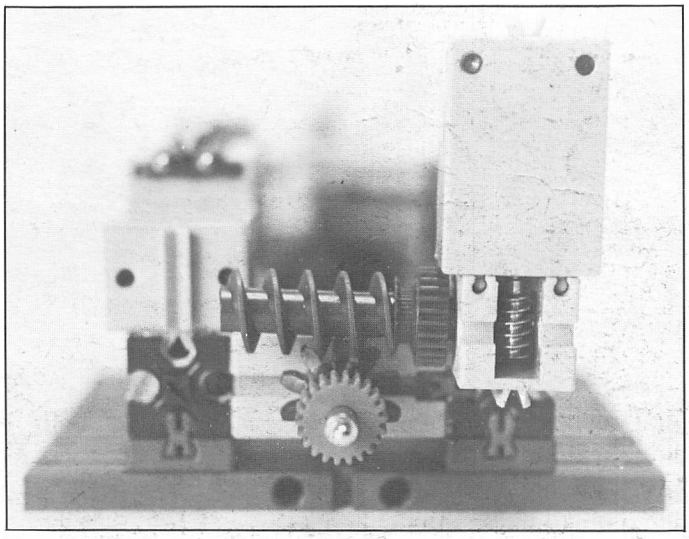




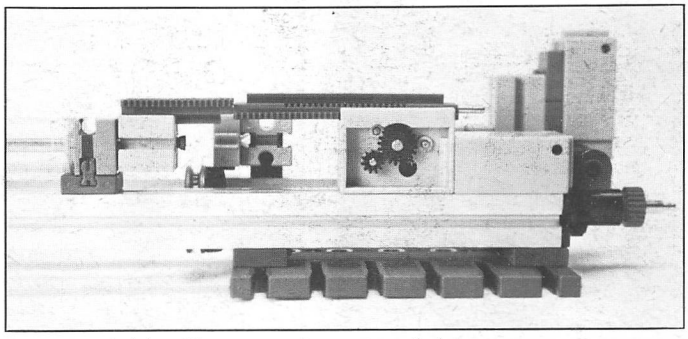
6 Two pieces of aluminium extrusion form the chassis of the arm – a line of six blocks would do the same job but with less rigidity. They are supported on the square baseplate with red quarter-bricks and red connectors, then all the other components slide between them from one end or are mounted on the top. The wrist is rotated by a minimotor at the rear, so you will need a long axle, or two axles securely joined. The end effector is connected by string to the slave cylinder to open the two fingers equally, the hinge being sprung closed. A microswitch is mounted half-way along the extrusion, to engage with the wing-nut on a standard wheel. This ensures that the wrist rotates exactly half a turn.



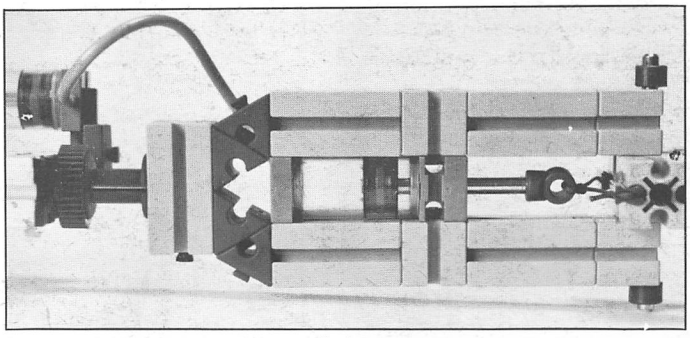
The flange on the central pulley wheel activates the microswitch.



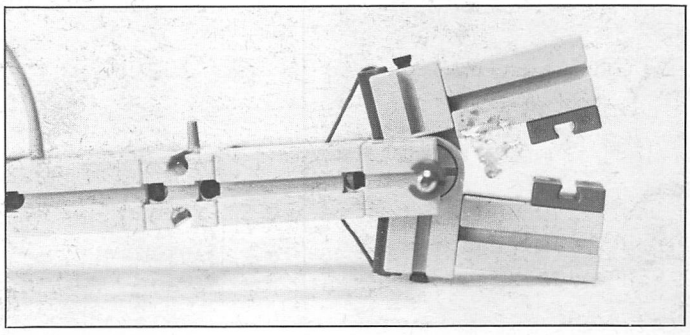
The wrist motor is mounted at the back of the arm.



The rack and pinion drive powers the master cylinders.

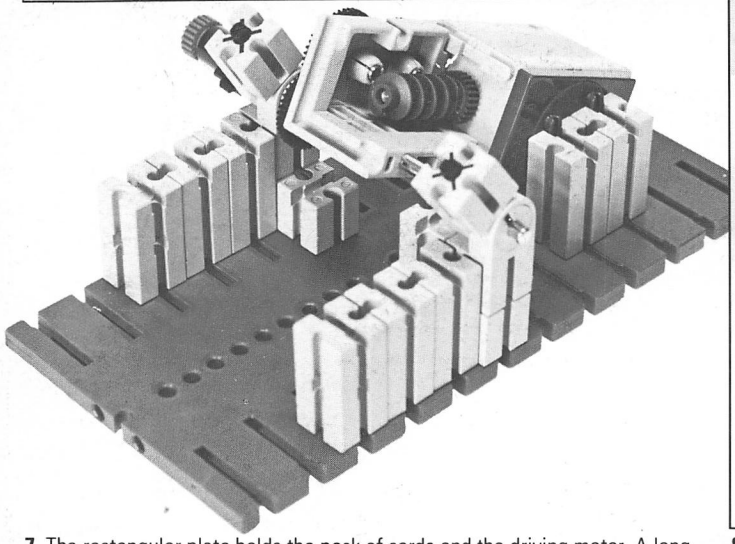


Detail of the wrist joint and slave cylinder.

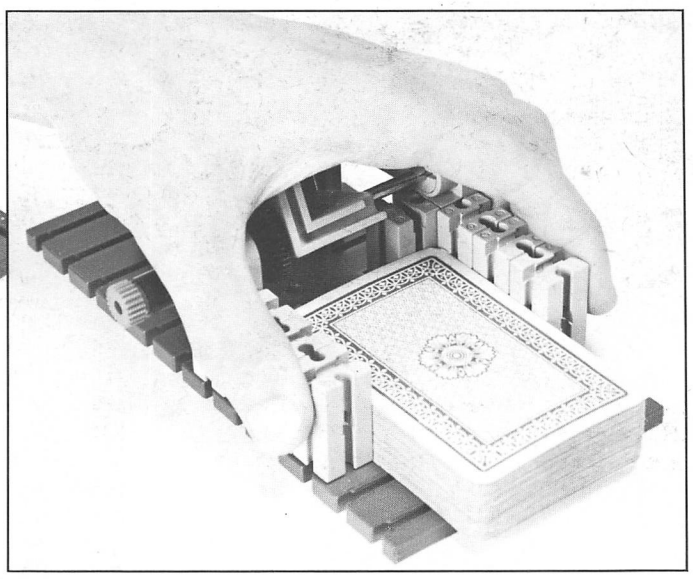


The hinge joint is sprung to close the gripper.

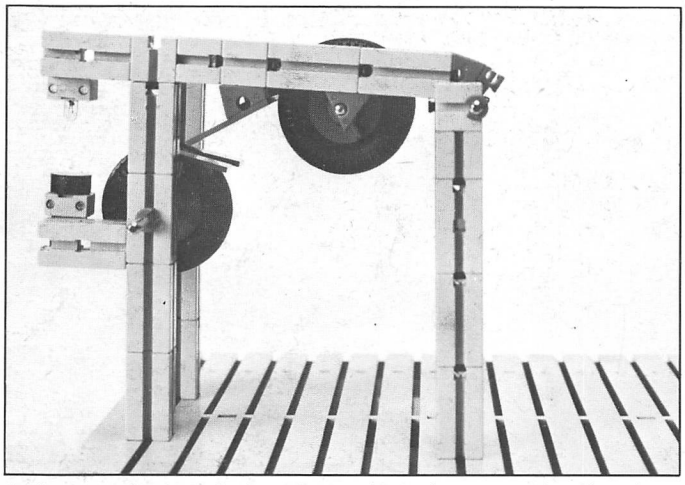
CONSTRUCTING THE DEALER



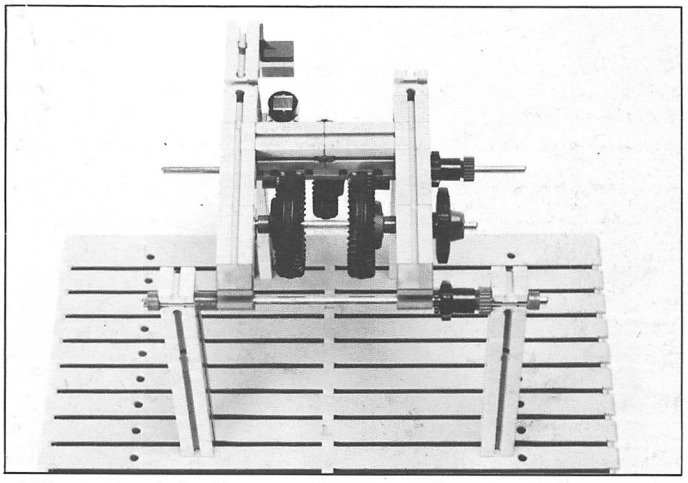
7 The rectangular plate holds the pack of cards and the driving motor. A long axle is used as the output from the gearbox, and this passes through the two hinges to a small black gear on the far side.



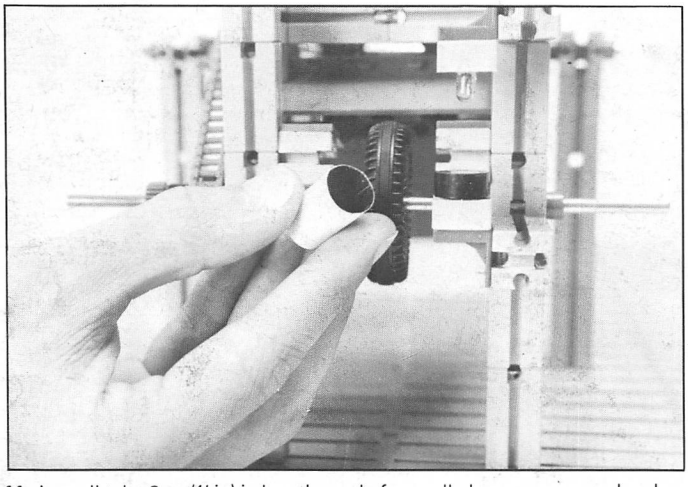
8 The blocks on either side should be squeezed together to provide the maximum grip on the pack of cards when it is in place. The less sticky the cards are, the better this robot will work.



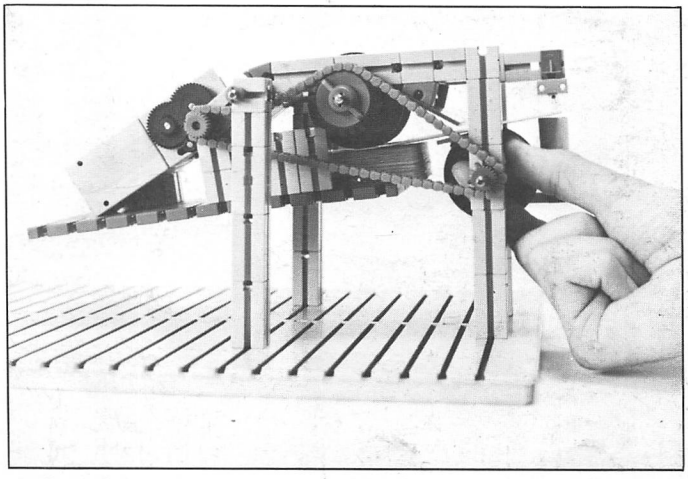
9 The supporting frame is shown here and in 10 from two angles. Note the mounting of the light bulb and detector, and the deflector plates for guiding the card over the frontmost wheel.



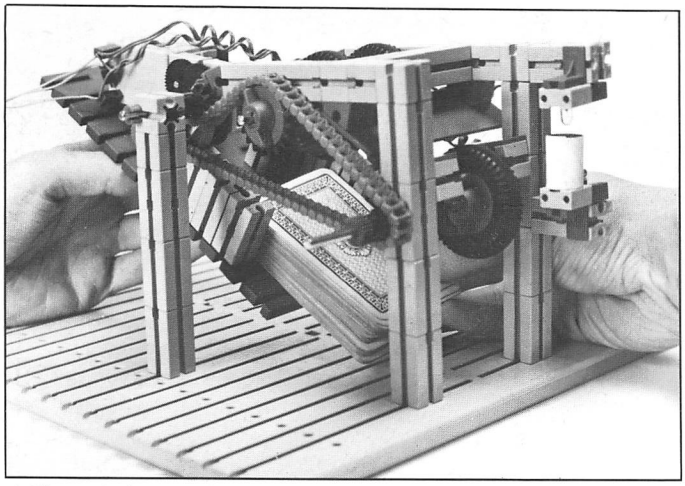
10 The top plate is fixed by two angled blocks, while the two smaller bottom plates are supported on two of the half-bricks that can rotate on their mountings (the ones with red protrusions). All wheels have rubber tyres fitted.



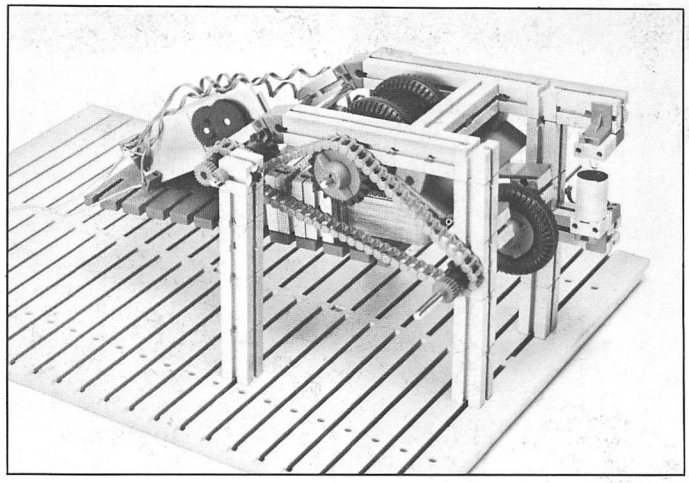
11 A small tube 2cm (⅘in) in length, made from rolled-up paper or card and coloured black on the inside, is mounted on the light detector. This makes the system less vulnerable to light from other sources.



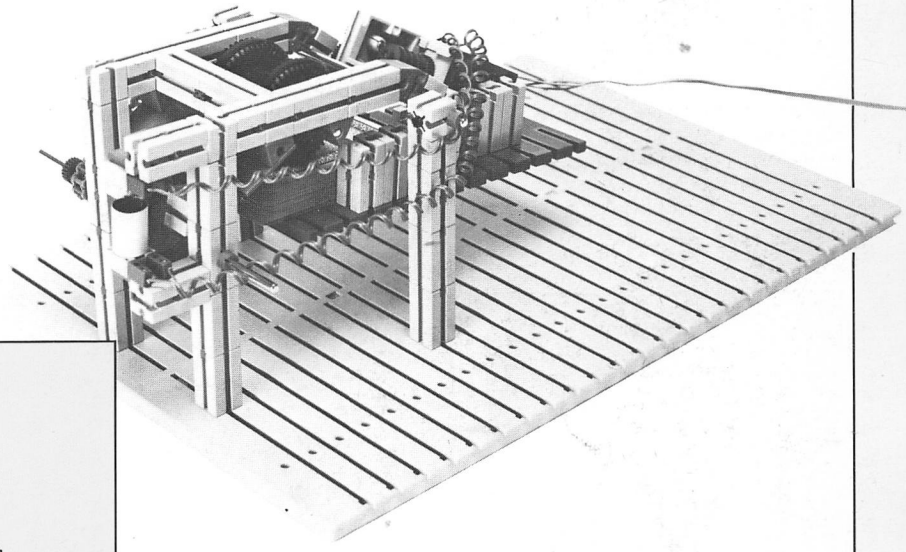
12 The chain is now mounted as shown, passing under the topmost black gear, which acts as a tensioner. The bottom deflector plates can be adjusted using finger and thumb, to guide the cards properly.



13 The pack of cards is inserted by pivoting the holder upright. You will probably find it necessary to weight down the back of the holder using Plasticine to provide enough pressure on the driving wheels.



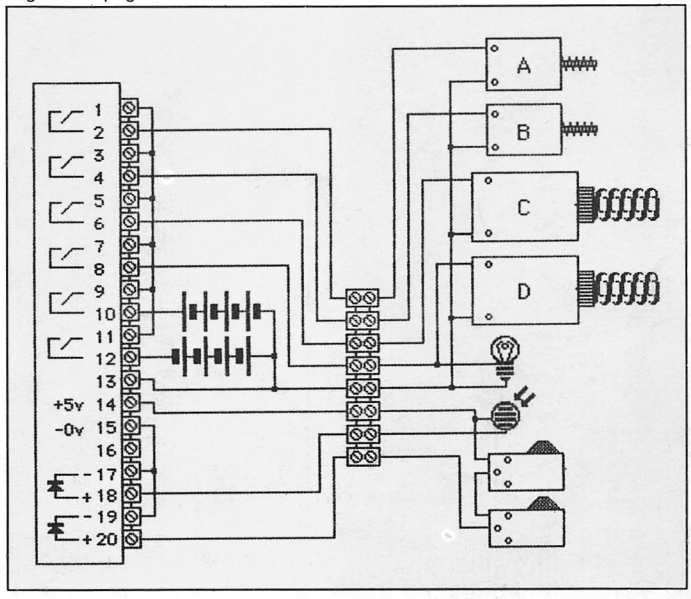
14 The finished dealer is wired up and its operation tested by hand before it is interfaced with the computer and the robot arm. The dealer can be mounted on a smaller baseplate if you have one.



Program. This was written for the Vic-20 but will work with the Commodore 64 by changing the value of PRT in line 30 to 56577. After initializing, the program prompts: PLAYER (1–5), TWIST (Y/N) ? Responding with 3,Y will result in a card being dealt face upwards to player number three.

```
10 REM**CARD DEALER**
20 REM**INITIALIZATION**
30 PRT=37136:POKEPRT+2,63
40 PRINT"INSERT BATTERIES"
50 D1=16:D2=32:OFF=0
60 MA=1:MB=2:MC=4:MD=8
100 REM**BASIC PLAY**
110 CP=0:GOSUB1200:GOSUB1400
120 INPUT"PLAYER (1-5),TWIST (Y/N)";NP,T$
130 GOSUB1300:GOSUB1000
140 IFT$="Y"THENGOSUB1100
150 GOSUB1200:GOSUB1300
160 IFT$="Y"THENGOSUB1100
170 NP=0:GOSUB1000:GOTO110
1000 REM**ROTATE ARM TO POS NP**
1010 DR=SGN(NP-CP):IFDR=0THEN1070
1020 IFDR=-1THENPOKEPRT,MC+D1:GOTO1040
1030 POKEPRT,MC+D2
1040 IF(PEEK(PRT)AND64)=0THEN1040
1050 IF(PEEK(PRT)AND64)=64THEN1050
1060 CP=CP+DR:IFCP<>NPTHEN1040
1070 POKEPRT,OFF:RETURN
1100 REM**SPIN HAND**
1110 IFHP=1THENPOKEPRT,MB+D2:HP=0:GOTO1130
1120 POKEPRT,MB+D1:HP=1
1130 IF(PEEK(PRT)AND64)=0THEN1130
1140 IF(PEEK(PRT)AND64)=64THEN1140
1150 POKEPRT,OFF:RETURN
1200 REM**OPEN HAND**
1210 POKEPRT,MA+D2
1220 DL=1200:GOSUB2000
1230 POKEPRT,OFF:RETURN
1300 REM**CLOSE HAND**
1310 POKEPRT,MA+D1
1320 DL=800:GOSUB2000
1330 POKEPRT,OFF:RETURN
1400 REM**FEED CARD**
1410 POKEPRT,MD+D1:DL=150:GOSUB2000
1420 IF(PEEK(PRT)AND128)=0THEN1420
1430 POKEPRT,OFF:RETURN
2000 REM**DELAY DL STEPS**
2010 FORTD=0TODL:NEXTTD:RETURN
```

Wiring. This circuit is very similar to the X-Y robot (pages 158–163), except that there is an additional motor (the one that drives the end effector) in place of the electromagnet. The reason for the two microswitches being wired in series is given on page 107.



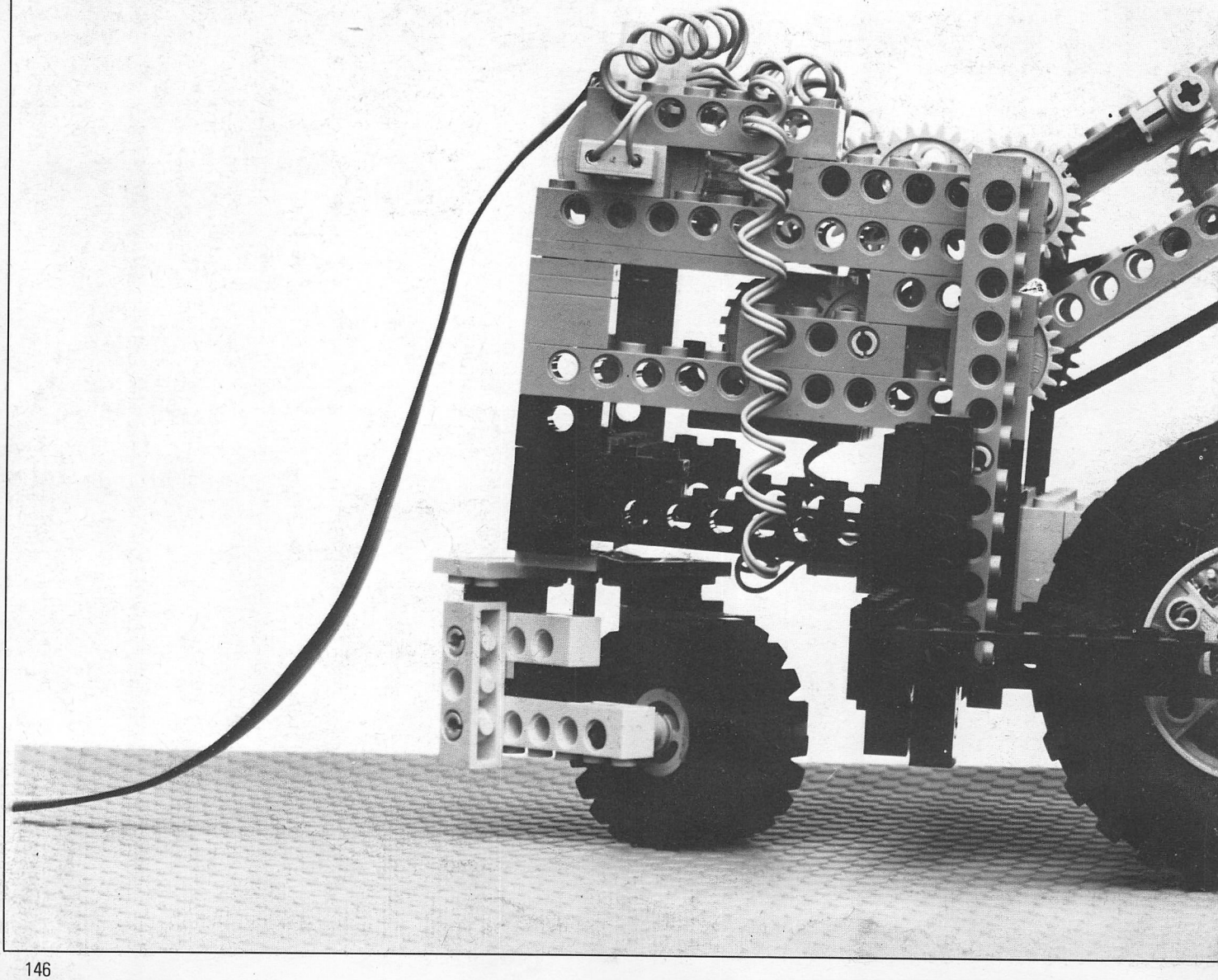
FREE-ROVING ROBOT

The intention of this project is to produce a general-purpose roving floor robot using Lego that can act as the base unit for a variety of robot superstructures. The first half of the project therefore shows how to construct the base unit, and this is followed by instructions for an elegant design of grabber arm that can be fitted to the base. However, the design of the base lends itself to many more possibilities, including a jointed arm, an android type of body and a vertical lifting arm like a fork-lift truck, and you can experiment with these ideas for yourself.

A general-purpose roving base has to be stable, controllable, rigid and easy to build onto. If it is to negotiate small steps, such as that at the edge of a carpet, then large rubber-tyred wheels and high ground clearance are mandatory. The design shown is constructed largely from the Lego tractor kit, with a few additional pieces that include four motors. The two large wheels are independently driven to permit forward, reverse and turning motions. The jockey-wheel at the rear provides stability and allows the robot to turn on its own axis. It is important to keep the centre of gravity of any superstructure well behind the axis joining the two main wheels.

A gear reduction of 180 to 1 was found to be the optimum for the driving wheels; higher reduction would give a greater torque and load-bearing capacity but would make the movement frustratingly slow. To reduce the size of the vehicle and the backlash that results from long trains of gears, the motors are fitted into standard Lego 20:1 gearboxes. Gearbox sets feature two different units so two sets will be needed, but the other two gearboxes can be used to very good effect on the grabber arm.

Rigidity is the other major consideration for the base. The chassis shown can withstand a fair battering, and the base can

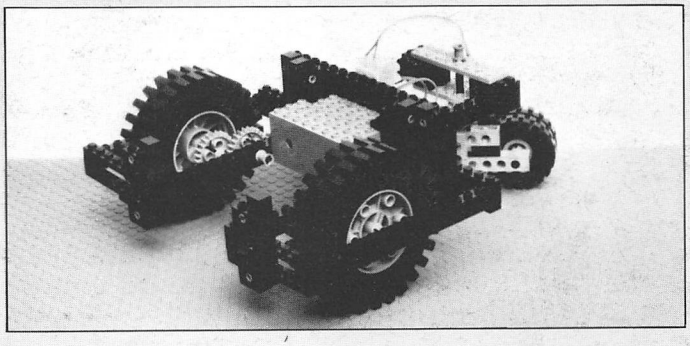


be grasped at any point without falling apart. This has been achieved by pinning anchor beams across the chassis at several points, a technique that can be extended to any Lego robot design.

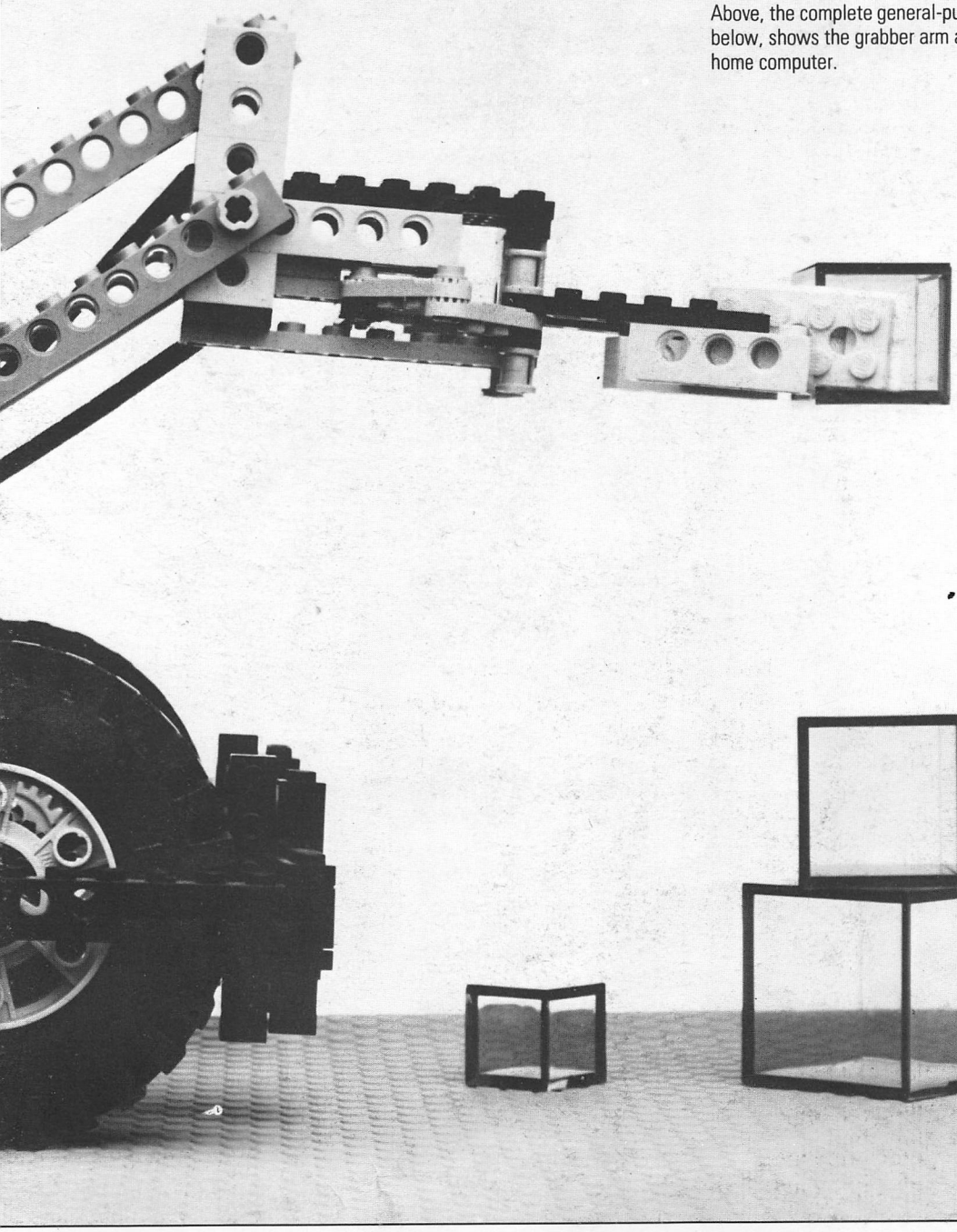
Though unusual, the shape of the resulting base unit is very versatile. Electronics enthusiasts can mount collision detectors or other sensors on the front bumpers, and the well between the wheels allows an arm to reach down to and operate at floor level.

The arm design shown here is based on parallelogram geometry, so that the end effector remains level as the arm is raised. Raising the arm requires a considerable amount of torque, and in fact the motor is geared down by 540 to 1 with the partial help of a gearbox. The gripper itself follows very closely the design of many industrial end effectors. Power is transmitted through a tensioned chain and thence via a rack and pinion. The gripper is built from standard Lego pieces that form the steering mechanism on the larger vehicle kits.

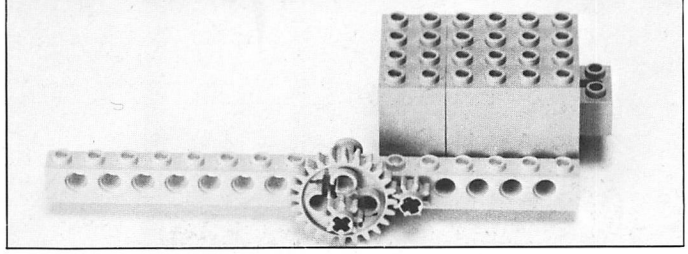
Once constructed, the roving robot with arm can be programmed to retrieve objects from anywhere in the room. Its main limitation is that it lacks any sensors or feedback, so precise movement cannot be achieved. The program listed is for controlling the robot live from the computer keyboard, but the subroutines for driving the motors could be built into a larger program that memorizes and repeats a sequence of moves of a complexity of your choice.

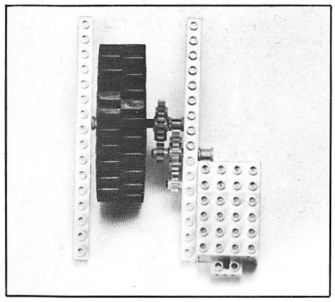


Above, the complete general-purpose roving floor robot. The main picture, below, shows the grabber arm attached to the roving base and wired up to a home computer.



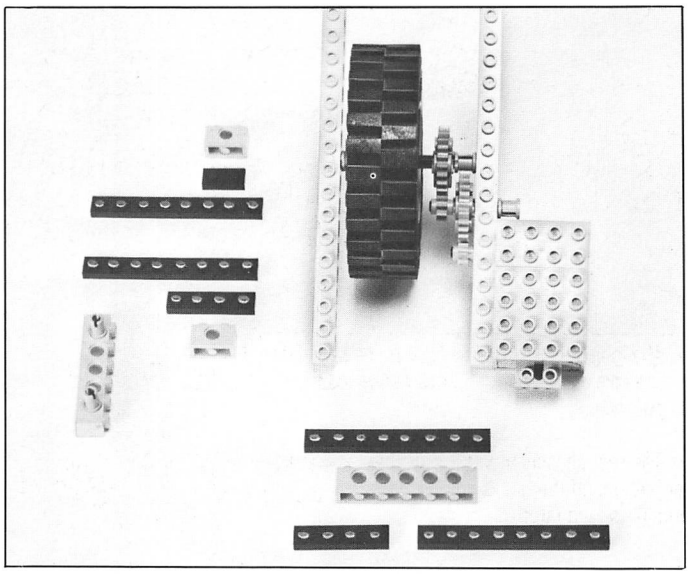
CONSTRUCTING THE BASE



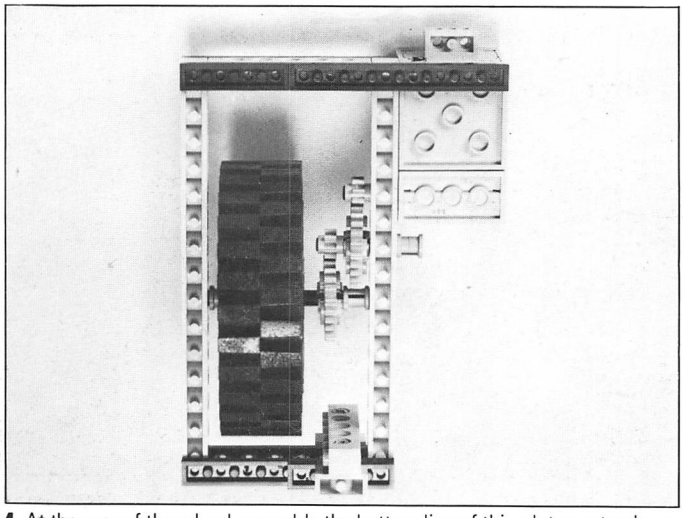


1 Above, a 6-unit-long axle fits into a square gearbox and motor and thence through a 16-unit-long beam. Gear wheels – 24- and 8-tooth – and bushes are added to axles as shown.

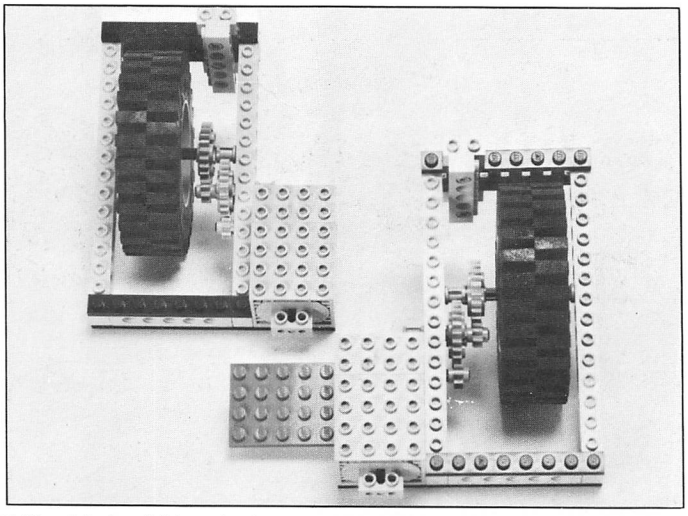
2 Left, the large tractor wheel sits on an 8-unit axle. The total gear reduction is 180 to 1.



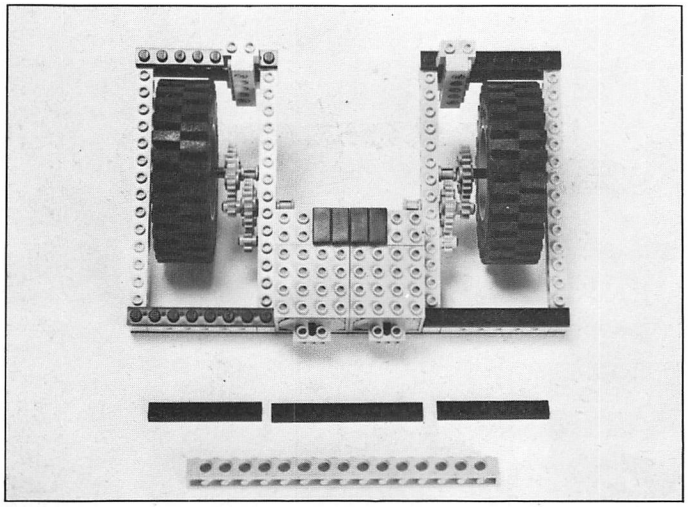
3 The front bumper of black plates is strengthened by a vertical 6-unit beam and two pins, shown in left of picture.



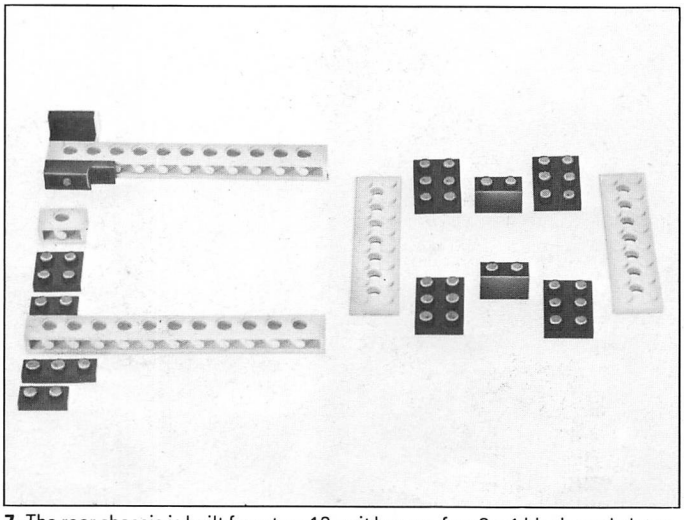
4 At the rear of the wheel assembly the bottom line of thin plates extends sideways to support the motor and gearbox unit.



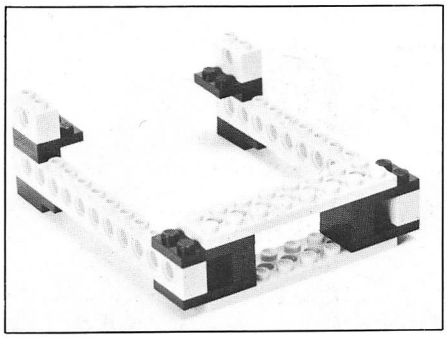
5 The right-hand drive wheel assembly is constructed as a mirror image. A 4×10 plate holds the two units together.



6 Long beams and plates fit underneath the motors. Small plates can be added on top to take a wiring block.

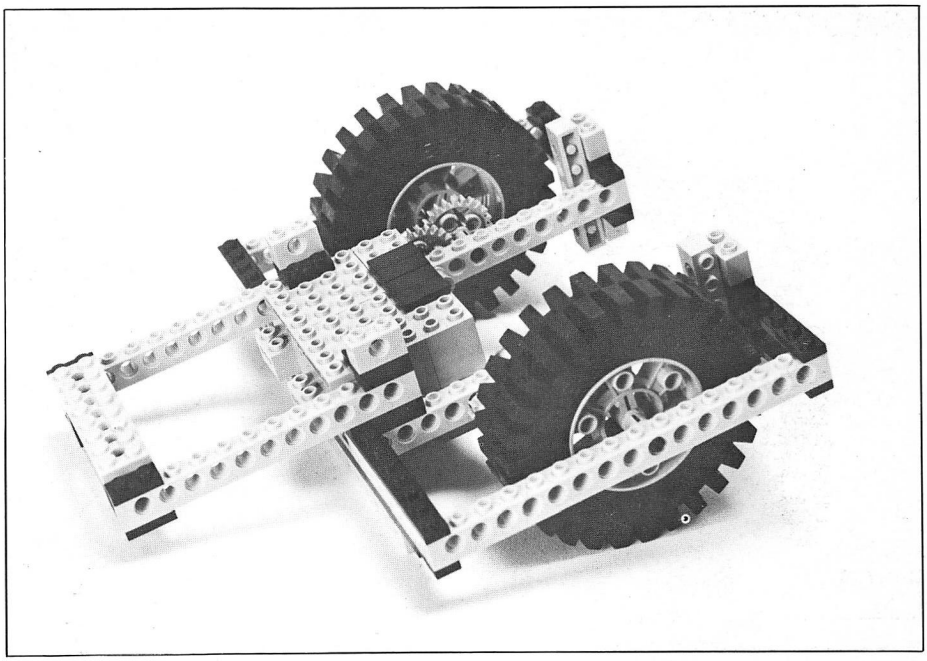


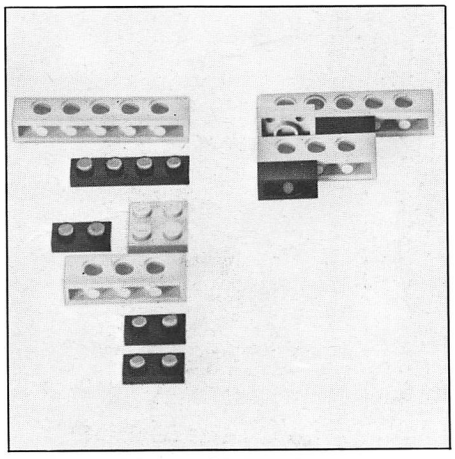
7 The rear chassis is built from two 12-unit beams, four 2×1 blocks and plates as follows: two 2×8, four 2×3, two 2×2, four 2×1 and two 3×1.



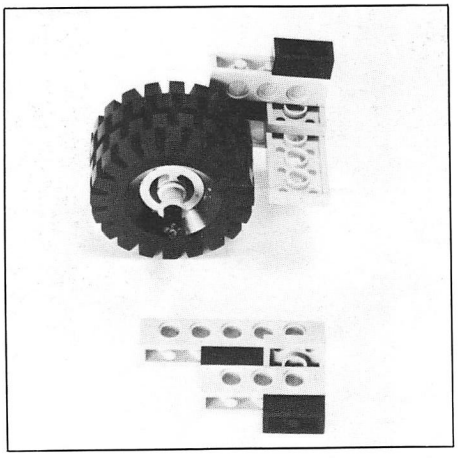
8 The long beams form the sides of the rear chassis, the blocks and plates the cross-beam and side supports.

9 The rear chassis then fits onto the main chassis, either side of the gearboxes. Further strengthening will be added later.

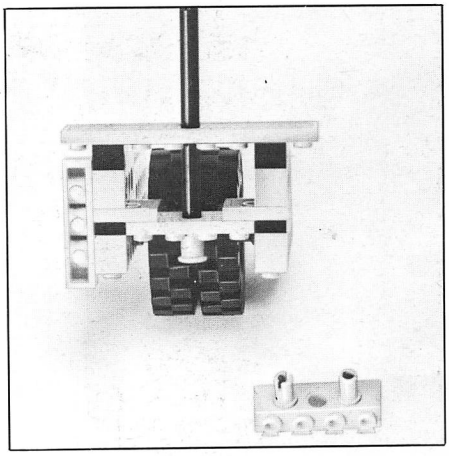




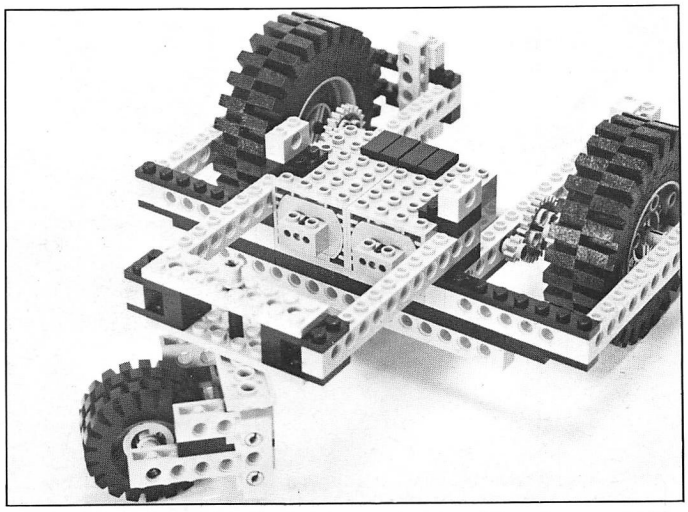
10 The two sides of the jockey-wheel support are constructed as mirror images, using beams and plates.



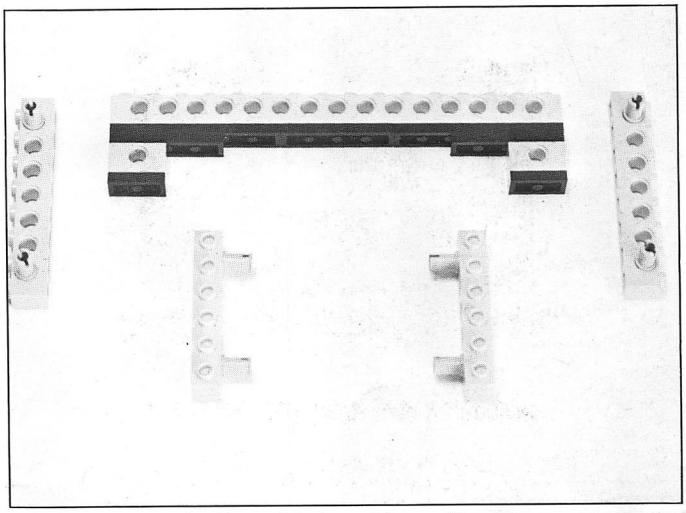
11 The two 44mm-diameter wheels fit on a 6-unit axle with two collars. A 4×2 plate holds the side supports together.



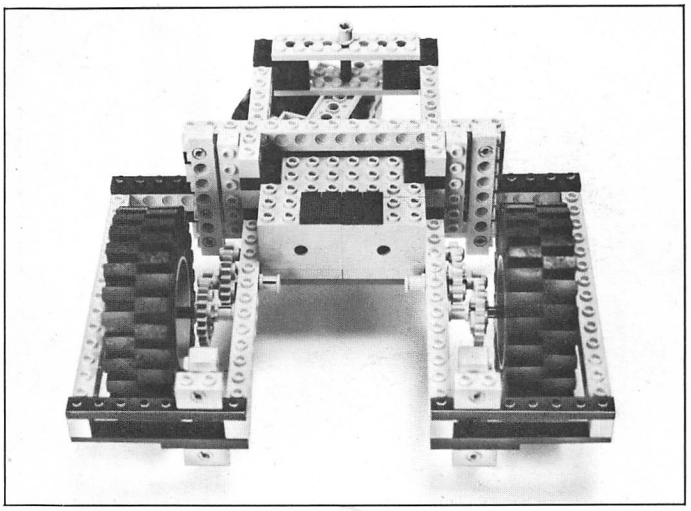
12 An 8×2 plate and an 8-unit axle complete the bearing. Two 4×1 strengthening beams are pinned to the sides.



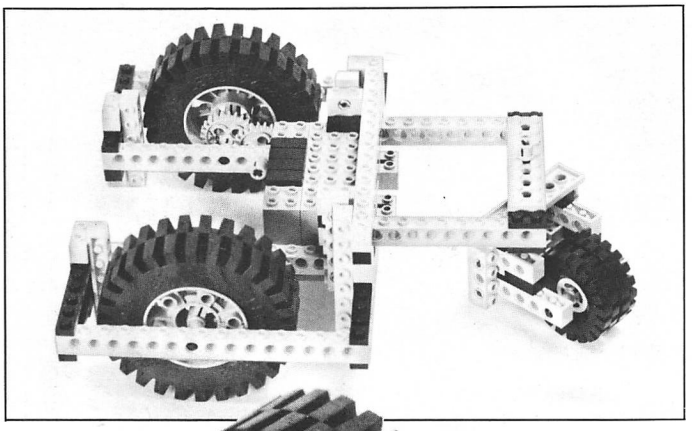
13 The jockey-wheel unit is fitted to the rear chassis and the axle secured with a collar, top and bottom.



14 A bridge across the drive unit is formed from a 16-unit beam and several layers of plates and bricks as shown. The two vertical beams are pinned on either side to strengthen the structure.

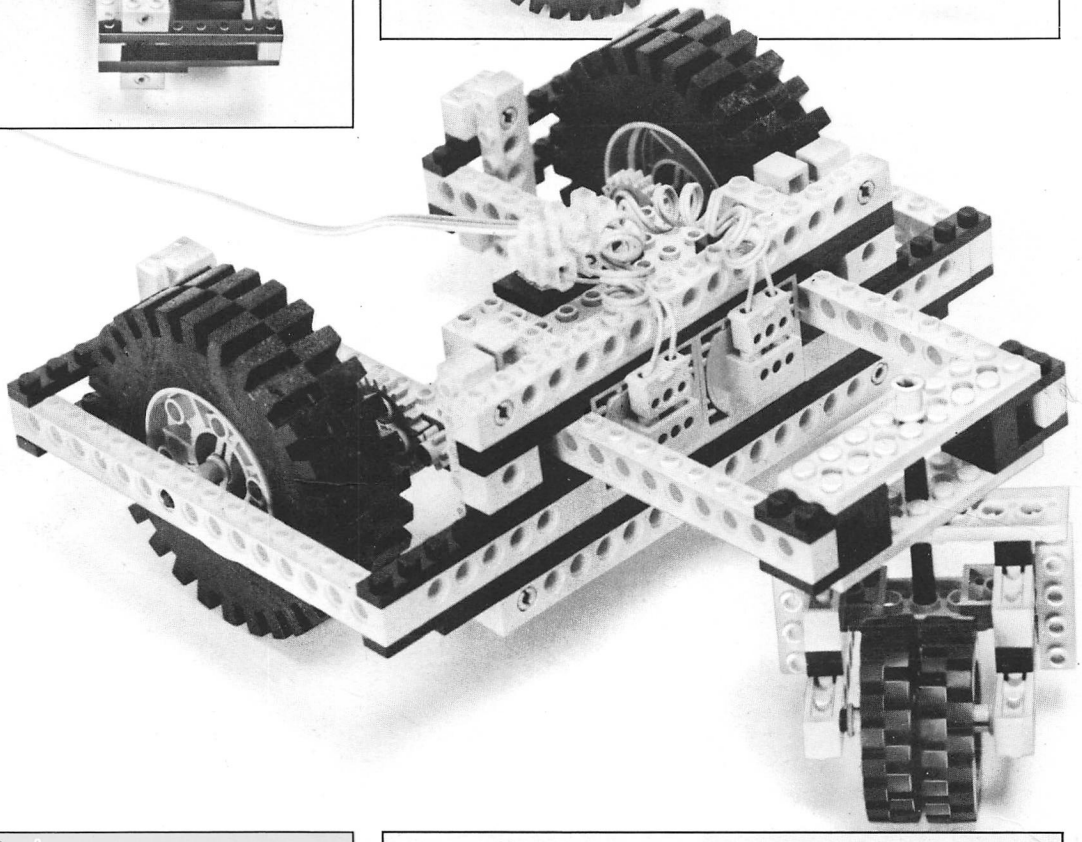


15 Above, the bridge in position, attached to the motor units and side supports of the rear chassis (see step 8).

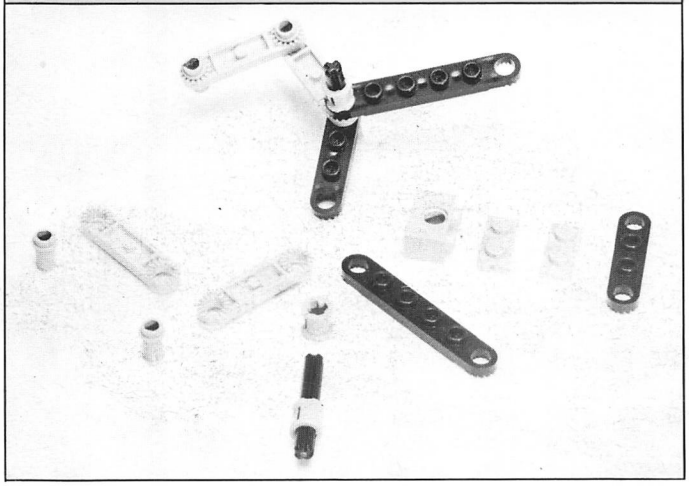


16 Above right, at this point the roving base, here seen from the side, is finished.

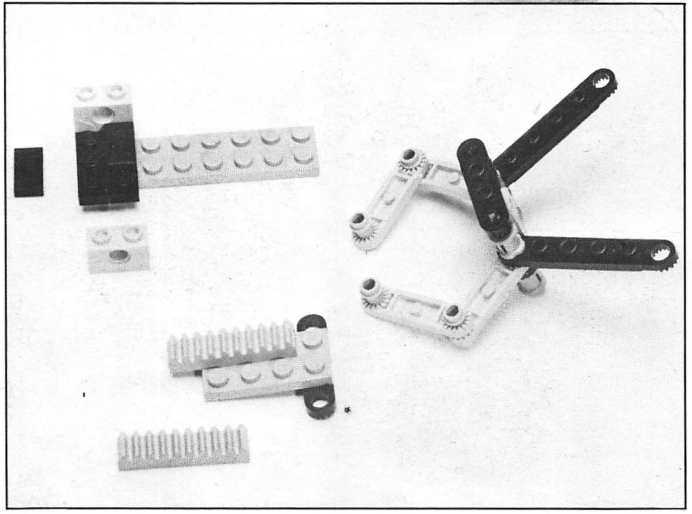
17 Right, the two driving motors can be wired up and the base used as a buggy. Alternatively, you can proceed to build on either a superstructure or the grabber arm shown in the following steps.



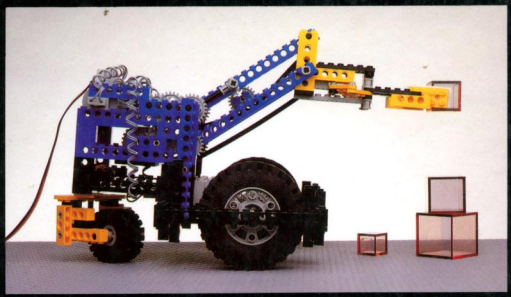
CONSTRUCTING THE END EFFECTOR



18 The fingers are made from steering links, which must all face in the directions shown here. One finger is shown made up, the other finger and the linkages as separate components.



19 Two smooth 2×1 plates sit on top of the black 4×2 plate for the racking to slide over. The bushes on the ends of the fingers push into holes in the 4×1 rounded plate.



THE ROBOT BOOK

☐ is a beginner's guide to the entire field of robotics, from fictional and toy robots, how robots work, robots used in education and industry, to the future of robots.

☐ is written in clear and simple language and assumes no mathematical, technical, electronic or computer knowledge.

☐ presents an up-to-date account of current robotics research and new robot products.

☐ provides full step-by-step constructional details for more than a dozen robots you can build yourself and control from a home computer. Most projects require no special tools or skills.

☐ is illustrated throughout with photographs, drawings and explanatory diagrams.

☐ is written by one of Britain's leading communicators in robotics and computing.

☐ will appeal to people interested in new technology, to home computer owners, hobbyists and those wishing to keep up with a changing society.