#153 April 2003

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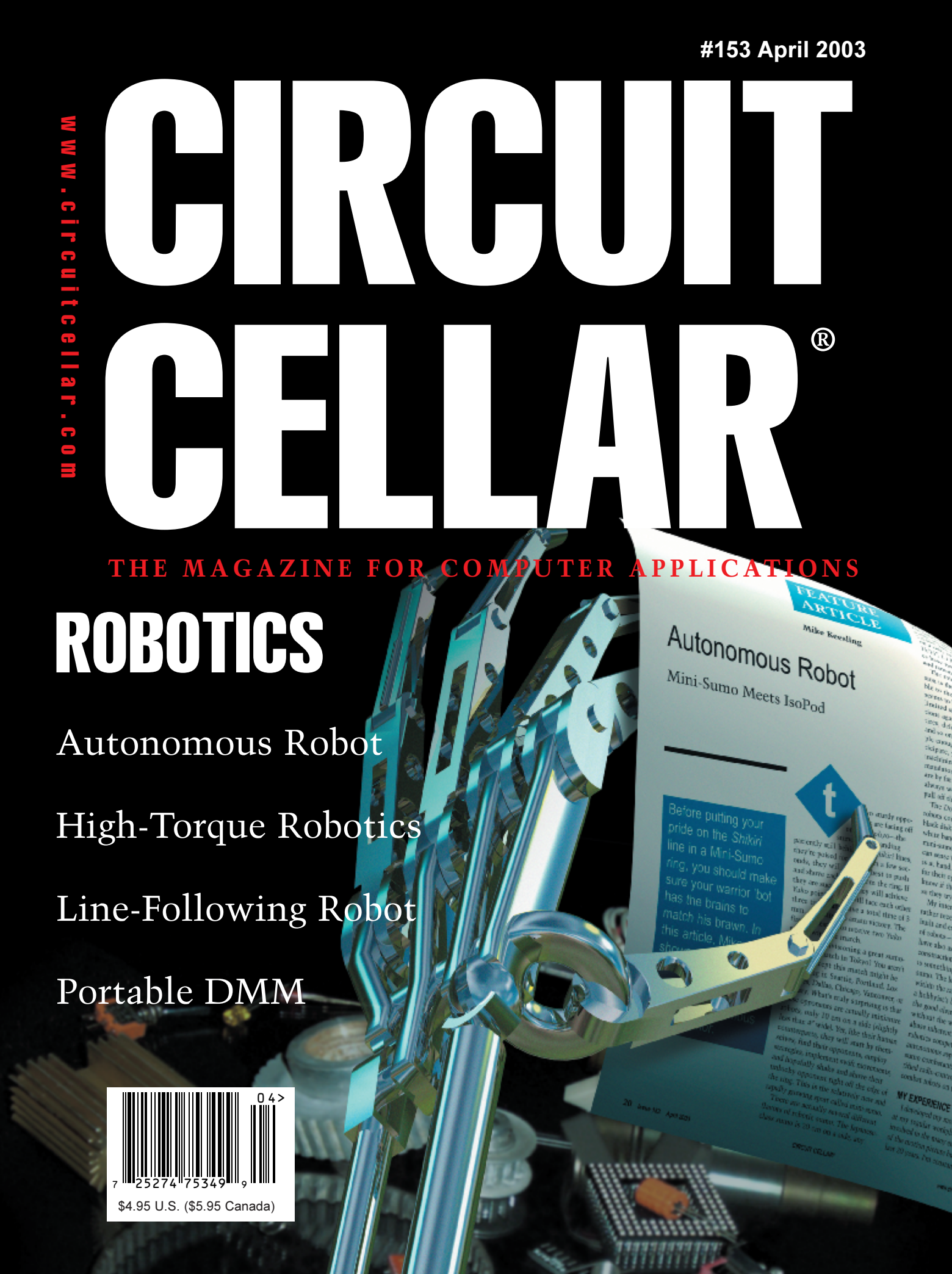
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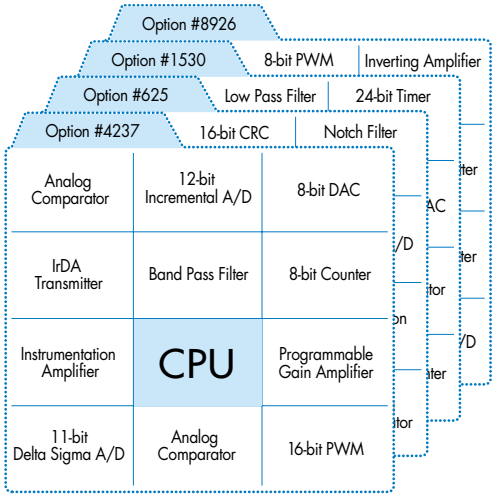
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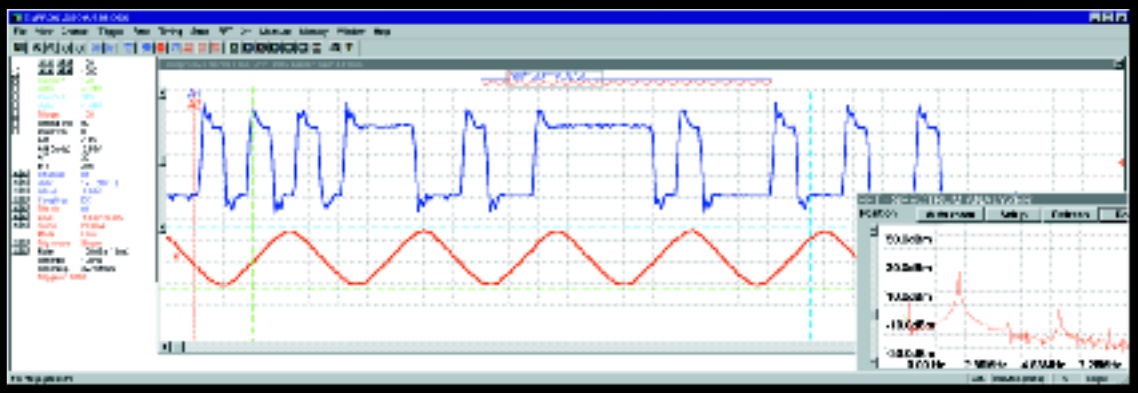
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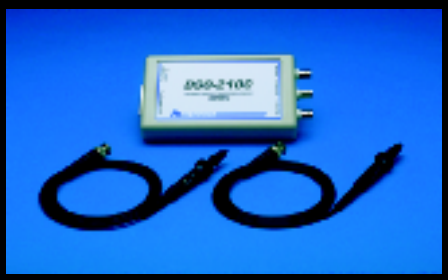
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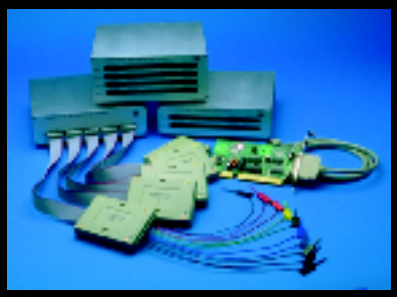


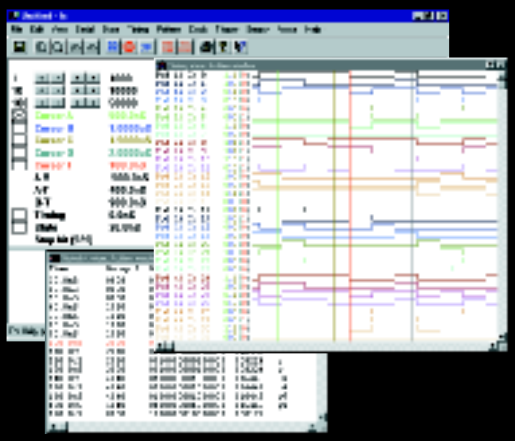
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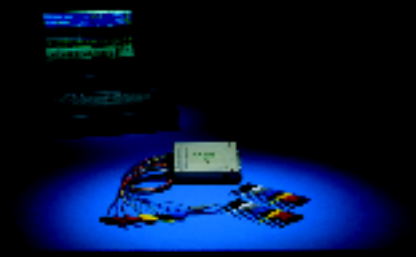


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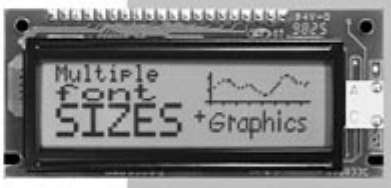
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TASK MANAGER

Engineering Pop Culture

Robotics experimentation used to be relegated to places like college campuses, R & D labs, and NASA. But today, amateurs, professionals, and enthusiasts from all walks of life are building robots for televised battles and entering contests that have cropped up all over the world.

The public's interest in robotics isn't new. If you look back over the past 40-plus years of movies and television, you'll notice plenty of plots involving robots. Some of the earlier ones were more for the sci-fi crowd—*The Colossus of New York* (1958) and *Gigantor* (1965)—but the trend caught on quickly with movies like *Star Wars* (1977) and *The Terminator* (1984).

The difference between then and now is that people don't just want to watch anymore, they want to be a part of the action. After cutting *Mystery Science Theater 3000* (picked up by the Sci Fi Channel), Comedy Central started airing *BattleBots*, which has definitely found its way into popular culture. Everyone wants to compete; the contestants range from teenagers to 50-year-olds, cashiers to professional engineers.

You won't find a ton of scholarly research about popular culture; scholars predominantly study high art instead. Many scholars view popular culture as simplistic and low brow, and thus undeserving of their attention. Popular culture is inherently for the masses, which, they argue, means it's dumbed down—stripped of the complexities that would make it difficult to be understood and accepted by the lowest common denominator.

I disagree with this position. For one thing, elements of pop culture aren't simplistic. (OK, some pop culture is completely stupid (*Joe Millionaire*) and aimed squarely at simpletons.) Take popular fiction, for example. Are the messages about society, gender, class, or race the same in novels by Stephen King, John Grisham, Mary Higgins Clark, and Zora Neale Hurston? Or, how about music: Britney Spears, The Rolling Stones, Elvis, Eminem, and the Dixie Chicks? The thing about pop culture is that there's something in it for everyone, which is what makes it successful, and what makes it representative of society. Elements of popular culture say something about who we are.

So, what does the growing interest in robotics say about society? You can usually approximate when something moved into the realm of popular culture. I guess for technology it was the day when 10-year-olds demonstrated a better working knowledge of the $1500 family computer than their parents. Somewhere along the way, understanding and applying technology rather than just using it became popular. People now seem to have a vested interest in being a part of the engineering. You can see it in the way advertisements have changed: manufacturers don't just market computers, they tout the processor power, memory size, and networking capability.

It might seem strange to put engineering and technology in a category with Dave Matthews Band, the GAP, SUVs, Coke, and *Friends*, but it fits. I think that says something decidedly positive about society.

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Cover photograph Chris Rakoczy—Rakoczy Photography
PRINTED IN THE UNITED STATES

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CIRCUIT CELLAR®, THE MAGAZINE FOR COMPUTER APPLICATIONS (ISSN 1528-0608) and Circuit Cellar Online are published monthly by Circuit Cellar Incorporated, 4 Park Street, Suite 20, Vernon, CT 06066 (860) 875-2751. Periodical rates paid at Vernon, CT and additional offices. **One-year (12 issues) subscription rate USA and possessions $21.95, Canada/Mexico $31.95, all other countries $49.95. Two-year (24 issues) subscription rate USA and possessions $39.95, Canada/Mexico $55, all other countries $85.** All subscription orders payable in U.S. funds only via VISA, MasterCard, international postal money order, or check drawn on U.S. bank.

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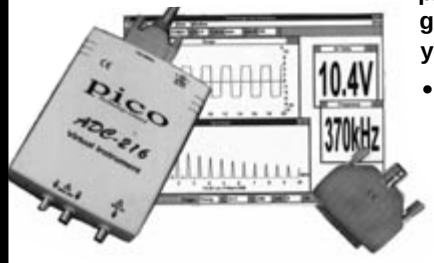
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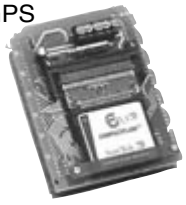
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ISSUE 153



FEATURES

12 **Autonomous Robot**
Mini-Sumo Meets IsoPod
Mike Keesling

20 **Electrical Engineering Robot**
Follow the Line
Peter Hiscocks & Jim Koch

30 **Muscle for High-Torque Robotics**
Lonne Mays

36 **Updating the Home Control System**
Part 2: FPGA Design Methodology
Robert Morrison

42 **Communications Protocol**
MIL-STD-1553B Data Bus
George Novacek

58 C **Portable MSP430 DMM**
Bruce M. Pride

76 **Get One-Chip Programmer Power**
Tom Napier

COLUMNS

52 **APPLIED PCs**
Test-Driving the Z8
Fred Eady

66 **ABOVE THE GROUND PLANE**
Balanced Mixing
Ed Nisley

70 **FROM THE BENCH**
Intro to Mindstorms
Jeff Bachiochi

78 **SILICON UPDATE**
E-Chips
Tom Cantrell

4 **Task Manager**
Jennifer Huber
Engineering Pop Culture

8 **New Product News**
edited by *John Gorsky*

11 **Test Your EQ**
edited by *Dave Tweed*

94 **Advertiser's Index**
May Preview

96 **Priority Interrupt**
Steve Ciarcia
What You Don't See Counts

C Contest-Related Article



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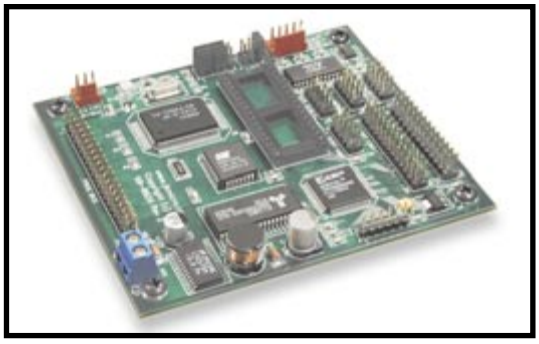
NEW PRODUCT NEWS

Edited by John Gorsky

DOS-BASED SBC

The **Flashlite 186** controller makes the convenience of a DOS-based embedded system more affordable than ever. Loaded with standard features, the Flashlite 186 is a fully programmable, compact, single-board computer that targets data acquisition, industrial control, and communications applications.

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NEW PRODUCT NEWS

FREE SOFT MODEM REFERENCE DESIGN

Based on the MCF5407, the **soft modem reference design** is engineered to enable systems designers to reduce development times and overall system costs in applications in which low-cost connectivity is key (e.g., remote utility management and data logging). By using a soft modem, companies may obtain and analyze information from anywhere in the world, simply by using a phone line to connect.

The third in a series of application-specific reference designs based on Motorola's ColdFire architecture, the soft modem reference design includes schematics, an application note, and source code that is free on the Motorola web site for registered users.

This newest design tool is ideally suited for applications with infrequent, small data transfers (i.e., less than a few hundred bytes) such as remote utility management, remote data logging, point-of-sale terminals, transaction terminals, home automation systems, security systems, and set-top box back channel operations.



In these applications, "less is more," with the soft modem connection quickly established and the transaction complete before a higher-speed modem would have finished negotiating the connection. Connecting via a modem and phone line is convenient because the system can be called at any time, from any place, to get an up-to-the-minute, comprehensive status report on all conditions being monitored. Statistics such as quality level, real-time pricing and power, voltage, time, and errors can be monitored.

The reference design is at www.motorola.com/coldfire.

Motorola, Inc.
www.motorola.com

SIP PRESSURE SENSORS

The **SM5415** and **SM5455** pressure sensors use an MEMS-based piezoresistive pressure sensor element in a new, small footprint SIP. These products are available in gauge, absolute, or differential configurations. They have barbed pressure ports for secure tubing attachment. Straight or bent pins are available.

These uncompensated pressure sensors have the same excellent performance characteristics of the popular SM5410 and SM5450 (DIP packages), including the unique 0.15-psi full-scale pressure for low-pressure measurement. Designers using their own signal-conditioning electronics can incorporate this uncompensated sensor.

The sensors work in a wide range of sensing applications including medical equipment, HVAC, level detection, barometric pressure monitoring, altimeters, and industrial control. The SM5415 is available for pressure ranges 0 to 5 psi up to 0 to 100 psi. The SM5455 is available for pressure ranges from 0 to 0.15 psi up to 0 to 3 psi.



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www.si-micro.com

LOW-COST OEM SBC

The **OEM2500 Coyote** single-board computer provides designers extremely low-cost embedded control for high-volume applications. The OEM2500 offers multiple options for custom orders to lower OEM product costs.

There are two standard models—one with Ethernet, one without. The Coyote can be customized to user-specified configurations when manufactured in volume orders (greater than 500). Various combinations of features are available for memory, 10BaseT or 10/100BaseT Ethernet, digital I/O, serial ports, LEDs, and an on-board back-up battery.

The Coyote features the Rabbit 3000 microprocessor at 29.4 MHz, 256 KB of flash memory and 128 KB of SRAM, five serial ports, 16 rugged I/O (plus one A/D input and two D/A outputs), four LEDs, and 10 timers. The Coyote is designed for control and data acquisition of a broad array of industrial applications such as OEM products, equipment, and robotic systems. All Coyotes come standard with industrial Molex-type connectors for rapid production in an assembly process.

The Ethernet interface is fully supported by a royalty-free TCP/IP stack to allow easy programming, data acquisition, and control of applications with LAN/WAN or from anywhere in the world via the Internet.

The OEM2500 starts at **$69** and **$99** (with Ethernet) in 500-unit quantities. A development kit is available for **$299**.



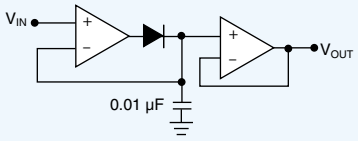
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CIRCUIT CELLAR

Test Your EQ

Edited by Dave Tweed

Problem 1—The circuit below is one way to build an op-amp peak detector. The first op-amp compensates for the forward voltage drop of the diode, and the second op-amp buffers the voltage on the capacitor, isolating it from the load current.



Even if the op-amps are an FET-input type, leakage current through the diode can create an unacceptable voltage drop. Show how the addition of one diode and one resistor can eliminate this problem.

Contributed by Dave Tweed

Problem 2—Name some of the methods used to overcome the "skin effect."

Contributed by M.K. Suvarnakumar

Problem 3—What is a good approximate formula for skin depth in a conductor such as copper or aluminum?

Contributed by M.K. Suvarnakumar

Problem 4—The power-handling capacity of a coaxial cable is limited by what?

Contributed by M.K. Suvarnakumar

Problem 5—Direct measurement of voltage and current is possible in a non-TEM (transverse electromagentic) transmission line. True or false?

Contributed by M.K. Suvarnakumar

What's your EQ?—The answers are posted at www.circuitcellar.com/eq.htm

You may contact the quizmasters at eq@circuitcellar.com

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FEATURE ARTICLE

Mike Keesling

Autonomous Robot

Mini-Sumo Meets IsoPod

Before putting your pride on the *Shikiri* line in a mini-sumo ring, you should make sure your warrior 'bot has the brains to match his brawn. In this article, Mike shows you how to build the perfect IsoPod-based brain for your autonomous robot warrior.

Two sturdy opponents are facing off in the *Dohyo*—the sumo ring. Standing patiently still behind the *Shikiri* lines, they're poised for attack. In a few seconds, they will do their best to push and shove each other from the ring. The successful combatant will achieve *Yuko* points. They will face each other three times, and have a total of 3 min. each time to attain victory. The first contestant to receive two *Yuko* points wins the match.

Are you envisioning a great sumo-wrestling match in Tokyo? You aren't far off, except this match might be happening in Seattle, Portland, Los Angeles, Dallas, Chicago, Vancouver, or Calgary. What's truly surprising is that these opponents are actually miniature robots, only 10 cm on a side (slightly less than 4" wide). Yet, like their human counterparts, they will start by themselves, find their adversary, employ strategies, implement swift movements, and hopefully shake and shove their unlucky opponent right off the edge of the ring. This is the relatively new and rapidly growing sport called mini-sumo.

There are actually several different flavors of robotic sumos. The Japanese-class sumo is 20 cm on a side, any height, and 3 kg (i.e., 7 7/8", 6.6 lbs). The lightweight-class sumo is 20 cm on a side, any height, and 1 kg (i.e., 7 7/8", 2.2 lbs). The mini-class sumo is 10 cm on a side, any height, and 500 g (i.e., 3 15/16", 1.1 lbs). All three of these classes have two divisions—autonomous and remote control.

The mini-sumo autonomous division is the most affordable and accessible to the average enthusiast. It also seems to be the fastest growing. Their limited size, as well as the restrictions against vacuum pumps, sticky tires, the deliberate jamming of sensors, and so on, keeps the competition simple enough for almost anyone to participate, yet not so small that special machining or assembly techniques are mandatory. The autonomous robots are by far the most fun to watch, and I always wonder how they manage to pull off their human-like tricks.

The *Dohyo* that the mini-sumo robots compete in is a 30" (77 cm) black disk with a *Tarawa*—a 1" (2.5 cm) white band—on its edge. Many of the mini-sumo robots have line sensors and can sense when impending doom is at hand. Certainly, while searching for their opponents, they will want to know if they are approaching the edge so they can try not to go any farther.

My interest in mini-sumo developed rather recently. I've built and experimented with a number of robots—both walkers and rollers. I have also assembled a team and begun construction on a BattleBot. But there is something magical about a mini-sumo. The level of competition is well within the range of one person operating on a hobbyist's budget, but it has all of the positive elements of competition without the wholesale destructive abuse inherent in some other forms of robotics competition. In addition, the autonomous aspect makes the mini-sumo combatants true robots, not glorified radio-controlled cars like the combat robots on television.

MY EXPERIENCE

I developed my motion control skills at work. I've been involved in the many engineering facets of the motion picture business for the last 20 years. I'm constantly interfacing this or that to the other, as it were, and always

searching for something better.

In the course of building controllers for cameras and lenses, I've tried many processors (e.g., 6502s and Z80s). When the Parallax Basic Stamp came out over a decade ago, it changed my way of doing things, to be sure. I used many of them at home and work. (This tiny controller is a common brain that's used in the mini-sumo-sized robots.) As engineers often do, I quickly discovered that tasks tend to outgrow the Stamp, and found myself accommodating the Stamp's limitations. A Stamp was fine for simple tasks in which only one thing at a time needed to be done; however, when programs took on too much complexity, I kept hitting walls.

As other companies made products that cloned the Basic Stamp, I switched over to newer models (e.g., BasicX-24 from NetMedia) hoping to gain faster operations or floating-point math. I also came across another microprocessor board supplier—New Micros, Inc. (NMI)—whose processors, language tools, and rapid development systems became a way of life for me. I've been using them on and off for more than 10 years. The NMI Forth-based products have been instrumental in my career.

Let me back up and explain. This is probably a good time to mention how I helped win an Emmy for my previous employer. This camera company was awarded an Emmy in 2001, and I was cited by the Academy as a major contributor because of my Image Shaker and Squishy Lens.

The Image Shaker, which is based on a Basic Stamp, was used for movies including *Jurassic Park III*, *Starship Troopers*, and *Saving Private Ryan*. Perhaps you remember the effects. You can see the Image Shaker at work when a shell explodes and the blast shakes the earth in *Saving Private Ryan*, or a stomping dinosaur or bug's legs shake in *Jurassic Park III*.

Internally, two high-quality optical glass wedge prisms with an optically pure silicone fluid trapped between them are moved. The elements are moved by tilting one on the x-axis and the other on the y-axis at variable angles. A Basic Stamp II, driving motion

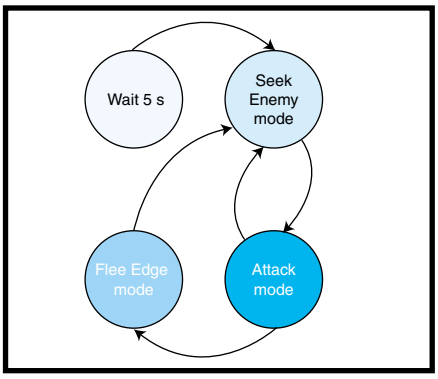


Figure 1—*After the quiet comes all of the action. As you can see, there is a nice range of possibilities, including seeking an enemy, attacking an enemy, and fleeing the edge of the ring.*

command impulses (via D/A-to-power amplifiers), and an ADC (for the input controls with an LCD) control it all. The initial programming took about two weeks, but it took another month or so to refine it to fit all of the functionality into the limited program space.

My Squishy Lens was used for movies such as *Minority Report*, *X-Men*, and *What Women Want*, in addition to several TV shows, including *Star Trek: The Next Generation*, *The Pretender*, *Malcolm in the Middle*, and *Nash Bridges*, to name a few. The Squishy Lens has three servomotors that compress a silicone lens element. When the lens is fully compressed, it appears transparent and has no effect on the image. When it's partially compressed, the edges are affected with a center spot size of varying diameter. You might have seen *Minority Report*, in which the "pre-cog" characters could see into the future. Their dream-like visions, which were clear in the center and distorted toward the edges, were shot with the Squishy Lens.

The Squishy Lens required a lot of math and fast update rates. It was too complicated for the smaller processor, so I used NMI's F68HC11 and LM629-based motor control boards.

The Squishy Lens is a remarkable tool. The silicone element took six months to develop, the mechanical design took four months, and the electronics and software took two months. Given the more complex interaction of the three axes of vastly more refined motion control, the electronics and programming was still the shortest portion of the project.

Finally, lest my current employer go upraised, I'm happy to tell you that I'm currently employed as a system engineer for the world's largest manufacturer of motion picture equipment. I'm still working with motion control hardware, as well as acting as the engineering glue between the optical, mechanical, and electronics engineering departments. Some of my current lens projects include working with lens-positioning systems, which are accurate to one one-thousandth of a degree and 0.2 µm.

My professional career has given me a lot to draw on, especially when it comes to building robots. Although the challenges are similar, mini-sumo has a unique set of obstacles. When I think of imbuing mini-sumo robots with intelligence, I'm first constrained by the size that's available. There are many small 8-bit solutions out there (e.g., processors from Microchip, Ubicom, Atmel, and even Intel, Phillips, and Motorola). In my opinion, though, the functionality of the mini-sumo robots has been greatly hindered by the lack of truly sophisticated microcontrollers. It's difficult to integrate motors, batteries, sensors, and support electronics into a space that small and still have room for a truly capable controller.

ENTER IsoPod/IsoMax

Until recently, nothing really new and exciting had hit the microcontroller market in six or seven years that had made me say, "Wow!" Last fall, however, when the president of NMI contacted me about a new product he was working on, I listened intently. Suddenly, after considering what I had heard, I realized that the "wow" was about to be back.

After he told me what he was working on, he asked for my opinion and requested some input concerning the evolving design. I was more than happy to offer my advice—I was honored. He was proposing a revolution in both the embedded hardware and the software that drives it. Now, over a year later, the new product—the IsoPod—is out, and you can see it for yourself in Photo 1.

On the hardware end, the IsoPod has a 16-bit digital signal processor—a motion control-specific chip that runs

at 80 MHz. The board features two channels of quadrature decoding with digital filters, 16 timers, 12 dedicated PWM channels, and a CAN bus. In addition, it has one RS-232 and one RS-422 serial channel, SPI, eight channels of 12-bit A/D converters, and 16 GPIO pins. These features are packed in a 1.2″ × 3″ carrier board, complete with voltage regulation, and three programmer-friendly programmable indicator LEDs. The hardware is extraordinary, particularly when you consider its small size, but the software is truly amazing.

The IsoMax language is the inspiration for the IsoPod board's name. IsoMax is a language unlike any other language that you've encountered in your embedded micro experience. In turn, the inspiration for the name of the language comes from the Greek root word *isos* 'equal,' or on the same level. The "Iso" portion of IsoMax means that the language is made so that multitasking is natural. Multitasking is achieved by putting all tasks on the same priority level.

In my opinion, IsoMax represents a natural evolution in programming languages. The language is actually a fusion, or maturing, of several different programming concepts: multitasking operating systems, structured programming, event-driven responses, and object-oriented actions. It borrows its machine structure from state-machine programming, and its input/output programming elements from object-oriented programming. The flexible, one-level Scan Loop was borrowed from the successful programmable logic controllers using relay ladder logic language. Its interactivity and extensibility was borrowed from Forth. This successfully creates a perfect blend of structure, utility, and flexibility—which is ideal for real-time control, robotics, and motion control in particular.

IsoMax is a multitasking language in the truest sense of the term; however, the tasks themselves are best described as little machines. The Isostructure is like allowing a score or more of virtual machines to all work in parallel. According to the IsoPod manual, "Virtually Parallel Machine Architecture (VPMA) is a new programming paradigm. VPMA allows small, independent machines to be constructed, and then added seamlessly to the system. All these installed machines run in a virtually parallel fashion." [1]

```
**************************************************************
The state elements can be codified in IsoMax.
**************************************************************
MACHINE MINI-SUMO
  ON-MACHINE MINI-SUMO
    APPEND-STATE WAIT-5-SECONDS
    APPEND-STATE SEEK-ENEMY
    APPEND-STATE ATTACK-MODE
    APPEND-STATE FLEE-EDGE

**************************************************************
The transition elements can be individually codified.
**************************************************************
IN-STATE
   <state name>
CONDITION
<Boolean condition>
CAUSES
<Procedural action
THEN-STATE
  <next state name>
TO-HAPPEN

**************************************************************
Here is the rightmost transition in the diagram.
**************************************************************
IN-STATE
  SEEK-ENEMY
CONDITION
  ENEMY-DETECTED
CAUSES
  CALCULATE-TRAJECTORY
THEN-STATE
  ATTACK-MODE
TO-HAPPEN
```

Figure 2—*Use IsoMax to codify the state elements depicted in Figure 1. Clearly, the transition elements are codified one at a time.*

In addition, IsoMax is fully interactive, allowing for complete access to all of the processes that take place. The language and operating system is actually resident and interactive in the chip. A terminal is all that's required to run and develop code. Everyone uses PCs in some form or another, so you would use your PC with a terminal emulator to talk to the board. Here's the important point, though: when you have an interactive session with the IsoPod, you're working with the processor itself. You aren't just running a big compiler on the PC, which, at best, blindly simulates the hardware on the IsoPod, and you don't need an expensive in-circuit emulator with a nasty wiring harness.

This means that you can develop software on your IsoPod, and, because the language is the IsoPod's multitasking O/S, you can run code in the background while developing in the foreground. You can build up your machines one small task at a time, and install and run them in the background. Then, you can add more machines, test and debug them, and add them to the background. All this time the first machine ran as if it were part of the built-in hardware. It became a virtually parallel machine. Each machine that you add is similar. You could have dozens of machines running in the background and not even notice the load on the processor in the foreground. Basically, there hasn't been anything quite like this before.

IsoMax on the IsoPod is a remarkable brain that's just the right size for a mini-sumo project. So, let's take a look at what it would be like to combine a mini-sumo and IsoPod.

MINI-SUMO CHASSIS

The easiest way to get involved with the mini-sumo sport is to use a kit for the mechanical system. The Portland Area Robotics Society's Mark III Mini-Sumo is an economical place to start your journey. The chassis kit includes a battery tray, plow for the front, main chassis piece, four standoff/servo mounts, Velcro, and associated hardware for mounting everything. The chassis kit, a set of wheels, and two RC Servo motors are all you need to get started.

Assembly is relatively straightforward so long as you follow the instructions on the web site (www.junun.org/MarkIII/). It's a simple matter of modifying the RC servos for continuous rotation, mounting the modified RC servos to the chassis with the four standoffs, and attaching the front blade to the chassis. Add wheels to the drive shafts of the servo, and you'll have a quick start on a little rolling robot. You can assemble the robot chassis to this point in less than four hours.

A PIC-based controller board, which you can program in BASIC, is also available on the web site. Obviously, I'm going to skip the existing electronics and opt for the much more powerful IsoPod instead. Mounting the electronics to the chassis is relatively easy if you use a Vector board (or some other perforated board). I built a small interface board that nestled in-between the mounting posts and a second board that sits on top of the mounting posts. The first board is used as an interface board, with which I regulate current to sensors and provide other interface functions. The top board gave me a

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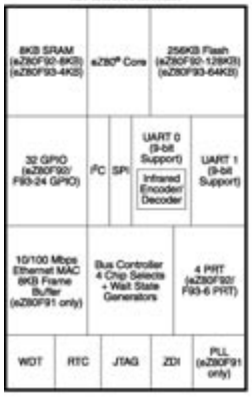
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eZ80F91 Block Diagram



	eZ80F91	eZ80F92	eZ80F93
Maximum Speed	50MHz	20 MHz	20MHz
External Address/Data Bus	24-bit/8-bit	24-bit/8-bit	24-bit/8-bit
Flash/SRAM Memory	256KB/16KB	128KB/8KB	64KB/4KB
Other On-Chip Memory	512B Configuration FLASH	256B Configuration FLASH	256B Configuration FLASH
Max. Addressable Space	16MB Linear	16MB Linear	16MB Linear
Chip-Selects and Wait-State Generators	4	4	4
10/100BaseT EMAC	Yes	No	No
UART with HW handshake	2	2	2
IrDA EnDec	Yes	Yes	Yes
SPI and I²C	Yes	Yes	Yes
Timers, Special Timer Features	4x 16-bit, Selectable timer clock inputs, 2x ECs, 2x Tout, 4x PWM, 4x ICs, 4x OCs	6x 16-bit, 2x Tin, 2x Tout	6x 16-bit, 2x Tin, 2x Tout
Real-Time Clock and WDT	Yes	Yes	Yes
GPIO	32	24	24
Full-featured PLL	Yes	No	No
JTAG and ZDI	Yes	Yes	Yes
Operating Voltage	3.0V - 3.6V	3.0V - 3.6V	3.0V - 3.6V
Package	144 LQFP	100 LQFP	100 LQFP
Development Kit Part #	eZ80F91020ZCO	eZ80F92020ZCO	eZ80F93020ZCO

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convenient place to mount the IsoPod and add ancillary components such as sensors. Be mindful of your 10 cm × 10 cm footprint.



Photo 1—*Note the generous number of connectors. You'd be hard-pressed to use all of these signal pins in a sumo robot.*

ACCESSORIES

The web site also sells accessories. I recommend purchasing a minimum of two Sharp GP2D12 distance sensors, three QRB1134 IR photoreflectors, and a Devantech SRF04 ultrasonic range finder. These are really useful products. I prefer the Futaba S3003 servo, but you can purchase some fine modified servos from the web site as well.

Please read on to learn more about other sensing technologies. I consider the aforementioned sensors to be the bread and butter of mini-sumo sensing, but the possibilities are limitless.

Although the Mark III Mini-Sumo provides a great starting point, there is a lot more to a true mini-sumo contender than wheels, motors, and a brain. Take some time to come up with a strategy, and think about which sensors will best help you realize this goal. The beauty of mini-sumo is its flexibility.

KNOW THE TERRAIN

Knowing your terrain is an important aspect of mini-sumo. With this in mind, remember that sensors are vital for navigation. Consider the following: quadrature sensors on the wheels; optical mouse ground tracking; Sharp GP2D120 distance sensors; QRB1134 photodetectors; an ADXL-202 accelerometer; and a Murata ENC-03J rate gyro.

The wheel-quadrature sensors will enable it to maintain perfect wheel velocity and odometry. The optical mouse sensor will tell you if you're in a slippage condition, and the accelerometer will be used to sense a tilt or unexpected acceleration. QRB1134 photodetectors can aid in determining if you're close to the edge. In addition, limited inertial guidance can be achieved with the accelerometer and rate gyro.

Because the IsoMax includes floating-point math and advanced trigonometry operations, you can implement highly sophisticated math. The IsoPod is nimble and adept at handling math functions, including those that are based on Taylor series expansion like log(x).

ENEMY DETECTION

Of course, knowledge of the terrain is of little value if you cannot apply your knowledge against your foe. In the sumo ring, you'll need to determine your enemy's location. You can achieve this in a variety of ways.



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There is an assortment of active (and even some passive) means by which you can search for your enemy: Sharp GP2D12 and GP2D120 distance sensors; an optical mouse motion sensor; a Devantech SRF04 ultrasonic ranger; and PNA4602M and I/R LEDs.

The GP2D12 and SRF04 are both employed in an active fashion to measure the distance to the enemy. By using multiple sensors, especially sensors that are able to scan via miniature servos, you can use floating-point math to gain a clearer picture of where you are in relationship to your enemy. By fusing the sensors' data with the knowledge of your terrain, you can even calculate the range and bearing of your enemies.

Another exciting technique involves replacing the lens of an optical mouse with a lens of a different focal length. Objects within the field of view and depth of focus can be tracked. A sensor of this type, looking downward at an angle, would see motion both toward and away, as well as side-to-side. The PNA4602M is an infrared remote controller detector that detects the presence of infrared radiation with a certain carrier frequency and a packet modulation. It can detect the IR light when reflected off a nearby object. Because there is a band-pass filter, slightly changing the frequency on your transmitting IR LED rolls off the sensitivity of the receiver. If you take advantage of this trick, you can deduce the distance to an object.

IsoMax OVERVIEW

Fusing all of this data can be an interesting task, to say the least. The sheer amount and variety of inputs and outputs on the IsoPod call for a powerful and unique language. IsoMax fits the bill perfectly. Written explicitly for real-time programming, it's efficiency and speed will impress you.

Because IsoMax is a new language, it deserves some coverage. As you now know, by fusing finite state machine (FSM) architecture with a highly object-oriented language, IsoMax achieves a multitasking environment without the inherent complexity of a multitasking language. You program by making virtual machines, which is almost like adding hardware to a circuit design, and then stringing the various pieces into an ever-intertwined final system.

I will look at the task and take a top-down view. Let's talk about the states a mini-sumo might operate in (see Figure 1). First, there is a mandatory quiet period of 5 s after being activated, so this is clearly a state in which the robot will find itself. Immediately following this, the robot will want to begin looking for the enemy. So, another state might be Seek Enemy mode. In this state, the machine can wheel in circles until it's pointing at the target. After an enemy is found, the robot can move into Attack mode. The robot can switch back and forth between these two modes until an edge detect has occurred. At that point, if the robot is about to drive off the edge of the arena, it can go into Flee Edge mode. After it's clear, it can return to Seek Enemy mode.

The state elements of the machine can be codified in IsoMax (see Figure 2). The transition elements can be codified individually, one at a time, in a struc-

ture that looks like the second section in Figure 2. So you can see the detail, the right-most transition in the diagram is shown in the third section of Figure 2. This code tells the processor that if you're in Seek Enemy mode and the Enemy Detected condition becomes true, then it should perform the Calculate Trajectory action and transition into Attack mode. Notice that program flow is inherently event driven.

Obviously, the words "Enemy Detected" and "Calculate Trajectory" are not known in the IsoMax language. These must also be user-written pieces of code. The procedural portions are written in a Forth-like structure of definitions built upon definitions. Usually, these sections are short, because the bulk of the programming magic is in the Isostructure of the state machines.

This is the basic structure of the state machines. These states and transitions are added to make each an individual virtual machine (VM). Such machines are chained together in sequence. The processor runs through the entire chain of VMs fast enough that they appear to become actual machines that were built from hardware.

Because of the IsoPod's extensive hardware interface capabilities, several sensors could be easily incorporated into a mini-sumo, while leaving a lot of capability untapped. For instance, five GP2D12 distance sensors can be connected to the analog inputs; two GP2D120 distance sensors can be connected to the analog inputs; two QRB1134 photodetectors to GPIO A; and four QRB1114 photodetectors can be connected to the Timer A0 to A3 for quadrature. For tilt sensing, the ADXL202 accelerometer can be connected to Timers B0 and B1. Ground tracking is facilitated with an ADNS-2051 mouse sensor connected to the SPI channel. In addition, one ENC-03J rate gyro can be connected to an analog input via an op-amp, and two S3003 servos can be connected to one of the PWM banks.

This leaves you a lot of functionality to play with. Uncommitted inputs and outputs include: one PWM port comprised of six PWM pins, which can run at any frequency; four PWM pins running at 50 Hz for R/C servos; eight GPIO B pins; six GPIO A pins; and one CAN bus port. Also add to this list one RS-232 channel, one RS-485 channel, and six unassigned timer pins.

Now that you know about the sensors that go into a mini-sumo, as well as the software that interfaces them, it's just a matter of deciding how you want your mini-sumo to behave. Think about the sensors and tactics you will use. With the sophistication afforded to you by the IsoPod's speed and flexibility, you won't be hindered by performance or interfacing issues.

In addition to the obvious notion of avoiding the edge at all costs, think about how you want to control the arena. Finding the center of the arena is highly desirable. After you have control of the center, it's simply a matter of driving your foe to the edge and giving him a good push.

You should also consider the evolution of your robot. Eventually, you'll find yourself looking toward faster, stronger motors and perhaps a custom chassis. Many people take advantage of the lack of a height restriction by building mini-sumo robots that tip down after the beginning of the match. This enables them to build large wheels and long ramps for bodies.

The possibilities for your mini-sumo configuration are endless. What's guaranteed is that you'll be hard-pressed to overload the IsoPod's interface options. The IsoPod/IsoMax combination offers a unique and highly flexible assortment of integrated hardware interface modules. This unique microcontroller solution should serve me well, both professionally and recreationally, for many years to come.

Mike Keesling is a self-trained systems engineer. Well versed in optomechanical, mechanical, electrical, and software engineering, he currently works for a company that manufacturers motion picture equipment. Mike's hobbies include holography, photography, kinetic sculpture, and robotics. You may reach him at bigbug@bio-bot.com.

PROJECT FILES

To download the code, go to ftp.circuitcellar.com/pub/Circuit_Cellar/2003/153/.

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[1] New Micros, Inc., *IsoPod User's Manual*, www.isopod.net

RESOURCES

D. Clark and M. Owings, *Building Robot Drive Trains*, McGraw-Hill, New York, NY, 2002.

G. McComb, *Robot Builder's Sourcebook*, McGraw-Hill, New York, NY, 2002.

Fugisoft ABC, Inc., Sumo robot overview, www.fsi.co.jp/sumo-e/out/outa0000.html.

SOURCES

ADNS-2051 Mouse sensor
Agilent Technologies, Inc.
(650) 752-5000
www.agilent.com

ADXL-202 Accelerometer
Analog Devices, Inc.
(800) 262-5643
www.analog.com

Ultrasonic Ranger SRF04
Devantech Ltd.
+44 (0) 1379 640450
www.robot-electronics.co.uk

QRB1134 IR photoreflector
Fairchild Semiconductor Corp.
(207) 775-8100
www.fairchildsemi.com

S2003 Servo
Futaba
www.futaba-rc.com

ENC-03J Rate gyro
Murata Electronics, Inc.
(770) 436-1300
www.murata.com

IsoMax, IsoPod
New Micros, Inc.
www.newmicros.com

PNA4601 Photodetector
Panasonic
www.panasonic.com

Mark III Robot Kit
Portland Area Robotics Society
www.junun.org

GP2D12 Analog distance sensor
Sharp Electronics Corp.
(800) 237-4277
www.sharp-usa.com

FEATURE ARTICLE

Peter Hiscocks & Jim Koch

Electrical Engineering Robot

Follow the Line

Interested in steering their students toward successful electrical engineering careers, Peter and Jim built a line-following robot. Serving primarily as a lab aid, the eebot is a ready-built starting point for students enrolled in software and system programming courses.

For Ryerson University undergraduates taking our Electrical Engineering course, learning microprocessor technology is a real challenge. They start by learning the programming model and instruction set with its addressing modes. Then, they have to master the mechanics of writing, testing, and debugging a program. After that is in hand, they must learn the peripheral hardware and methods of interfacing to external devices. In addition, we hope that our students will develop some of the skills needed to organize and structure a computer program.

We can convey the course's objective in one sentence: At the end of the course, the student will be able to design and build a substantial program in assembly language for a microprocessor system, using the hardware features of a typical modern microprocessor.

MICRO LAB

The Ryerson microprocessor programming lab is central to this educational process. Over the years, the lab has evolved from a cardboard computer simulator (the "Cardiac"), to the 6800, then the 6809, and most recently to the 68HC11. The lab had kept pace with changing technology, but in the summer of 2001, it was time to revise it again.

The previous labs had consisted of small programming exercises concerning various subjects. Students found them to be relatively easy to complete; however, the exercises did not deal with module interactions, which is where many problems occur. Furthermore, documentation isn't needed to comprehend a small program. Writing a series of small programs is not the same as writing one large program, which is both quantitatively and qualitatively different.

On the other hand, a project is large enough to highlight several important issues in software design and motivate students to learn about them. Such a project addresses the following: top-down design and bottom-up coding; organizing the program into a main loop and subroutines; protecting variables, possibly using a stack; designing and implementing data structures; mastering procedural complexity with a state machine; and debugging in a systematic manner.

This project is large enough to be dangerous. It highlights the difference between small and large programs, which is an important learning experience for students. Most importantly, they learn that hacking without a plan is ineffective: the program must be engineered. Because most students don't believe this until the complexity monster bites them, we wanted them to have that experience.

Conversely, even though there were several good reasons to make life more challenging for the students, we felt that we should encourage student involvement by making the project more visual and interactive. Many programs don't do much—they write clock digits to a display, for example. But, if the project involves building a robot and your robot steering algorithm is incorrect, it will crash into things. The software design becomes an obvious and engaging problem.

It's a big reward when the program works and the robot finally does something interesting. From our standpoint as lab supervisors, it's much more interesting to watch a robot go through its paces than look at another clock display.

HARDWARE CHOICES

Should we require students to construct a robot from scratch (possibly providing a kit with parts) or should we provide a ready-built robot? Both approaches are used in microprocessor labs at other universities. But, because of our focus on software and system programming, as well as the 13-week timeframe for the course, we decided to provide hardware in the form of a ready-built robot—the electrical engineering robot, or eebot. (The project director's main responsibility was choosing a catchy name for the project. All the rest was mere detail, right? Well, not quite.)

DESIGNING A MOBILE ROBOT

Form should follow function, so we needed to identify a specific task for the robot. For the lab's final project, we decided to focus on line following.

A line follower can be used for a variety of tasks (e.g., tracking around a simple oval, navigating a serpentine track at high speed, or solving and retracing a maze). The front end of the robot would have an array of light sensors that could track a line and detect branches. Bumpers would detect obstacles, and motor control circuitry would support maneuvering.

Some design decisions were obvious. For instance, we wanted to use readily available parts. Also, we wanted the design to be maintainable and robust, because the undergraduate lab is a hostile environment for electronics and mechanics. Additionally, we decided that a modest cost and small physical size would allow us to have lots of them.

Because we wanted a lot of debugging aids, we chose to use LEDs to display all of the major signals (e.g., there would be LEDs on each wheel rotation counter and an alive indicator to show that the program was still running). We chose to use an LCD for status displays such as the battery voltage. For simplicity in recharging, the robot would run off of one battery for the microprocessor and motors.

MICROPROCESSOR

The 68HC11 wasn't the most compact or inexpensive option available, but, it was an obvious choice because of the tools we had on hand. Ryerson Professor Ken Clowes had developed a simulator, we had HC11 systems on the benches, and we had developed our own in-house system board.

Most importantly, the HC11 has features that make it relatively easy for students to learn. There are free software assemblers for DOS and Unix, so students can carry out development work on their own. In addition, the HC11 has a simple memory model without register banks or memory pages. With a monitor program in external EPROM, a student can download a test program from the host workstation into the on-board RAM and then debug it with breakpoints and memory dumps.

The HC11 has several features that are particularly useful for a mobile robot: an SCI port that's used for downloading code and uploading monitor displays; A/D converters used for a line follower, monitoring the battery, and reading the bumper; hardware timers for delays and duty cycle modulation of motor voltage for speed control; and vectored interrupts, which are used for wheel counters and delays.

The in-house HC11 system board—the MPP Board—is shown in Photo 1. It was originally used in a fourth-year instrumentation course (and fourth-year thesis projects), where students would assemble the computer from a kit. Because it's entirely self-contained with a built-in monitor program and the I/O devices needed for the project, the MPP board became the top layer in the Dagwood sandwich that makes up the robot. You may download the schematics for the MPP board's CPU and memory sections from the *Circuit Cellar* ftp site.

The CPU section of the MPP board is conventional: it has an RS-232 translator (U4, MAX232), so communications are possible from any host with a serial port. A low-voltage interrupt (U10, MC34064P-5) resets the processor

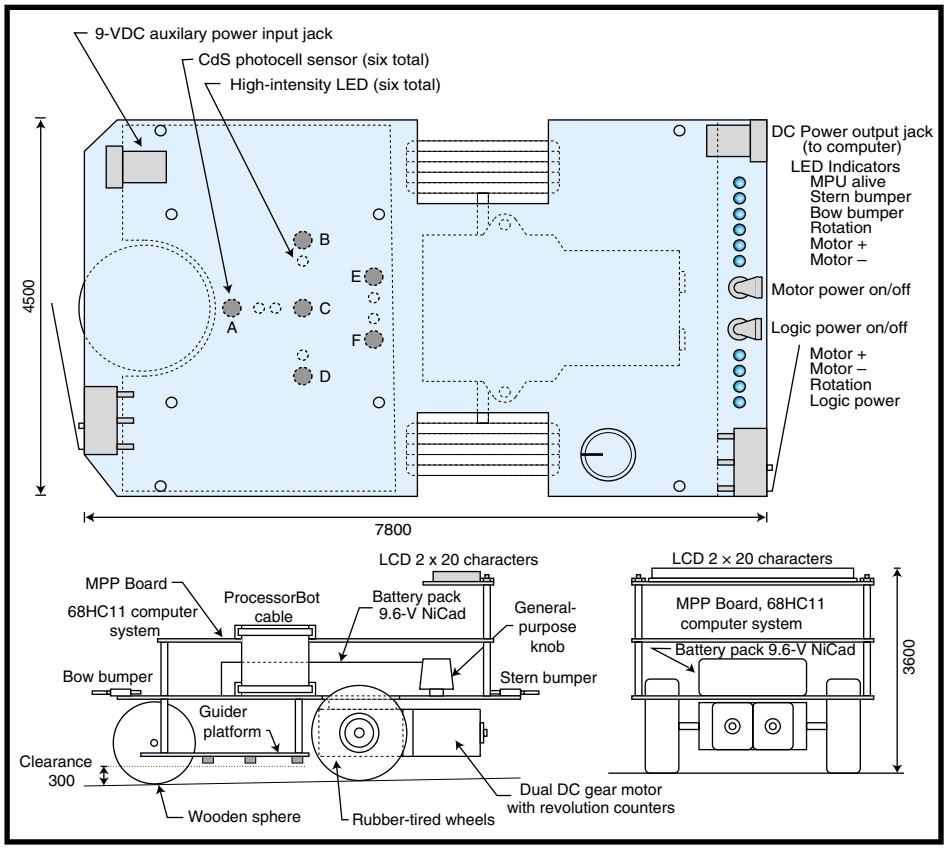


Figure 1—*Weight distribution was planned so that most of the weight is over the two driving wheels. Even so, enough is forward of the wheels to keep the front roller on the ground. A combination of threaded and plain standoffs—with some long bolts—make the sandwich relatively easy to dismantle. The controls, LED readouts, and LCD are positioned so they can be viewed from the rear of the robot.*

if the supply voltage drops out of spec. The memory map is decoded by a GAL device (U9, 16V8), which can be reprogrammed if there is a requirement to modify the map. An octal flip-flop (U1, 74HC373) demultiplexes the address-data information into separate busses.

The memory section provides jumpers so that various sizes of RAM and EPROM can be used. The `Buffalo Monitor` and `Floating Point` routines are normally burned into the upper region of this memory, so the board has some built-in intelligence. The program under development is normally loaded into RAM and exercised there. If the program must be protected through power cycles, you can use battery-backed RAM devices (e.g., Maxim's DS1213B SmartSocket 16k/64k) in the RAM socket. A general-purpose 8-bit output port (U6, 74HC273), input port (U5, 74HC244), and LCD module (i.e., 2 × 20 Sanyo DM2023) are mapped into the address space by the decoder GAL.

COMPLETED EEBOT

The complete robot is shown in Photo 2. Take a look at Figure 1 for a three-view diagram. The underside of the robot is shown in Photo 3. From top to bottom, the layers consist of the LCD, MPP board 68HC11 computer, main robot platform with drive circuits, and the guider board.

Spacers and bolts of various lengths hold the robot together. The wheel configuration is the usual differential drive where each of the two drive wheels has its own DC motor. After considering various surplus motors, and for reasons of supply continuity, we decided to use a Tamiya dual-gear motor kit (i.e., the 70097) with model aircraft wheels.

The front wheel was a lucky find at a craft store; it's a 1" wooden ball that can rotate or skid sideways. (We tried a ping-pong ball, but it couldn't survive the student environment.) The position of the drive wheels puts most of the weight over the drive wheels, but enough to ensure that the front ball stays on the ground. The motors can be switched off independent of the processor power.

The controls and indicators are mounted on the rear deck. A small adaptor PCB on the MPP board acts as a junction box for the various connecting ribbon cables.

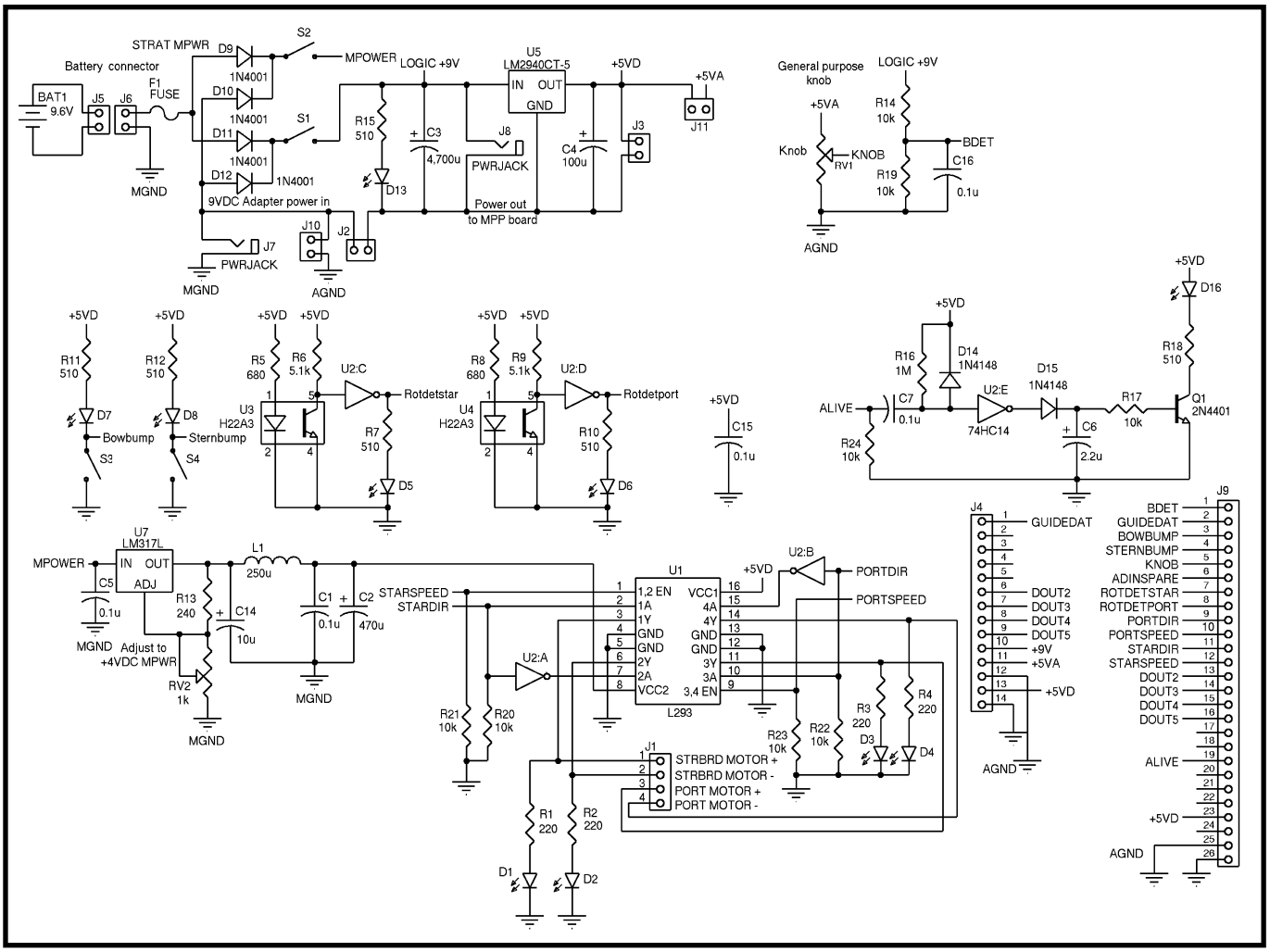


Figure 2—*To allow the robot logic to use the same power source as the motor, a three-terminal regulator and an inductor-capacitor filter isolate the motor power. Lots of LED indicators make problems easier to diagnose. The Alive indicator is a discrete-component monostable that triggers on a negative edge from the microprocessor. The program toggles a microprocessor output line to keep the LED continuously illuminated. Another small PCB (not shown here) adapts all of these signal lines to the various microprocessor connectors on the MPP board.*


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MAIN BOARD SCHEMATIC

The main board is depicted in Figure 2. We used a 9.6-V RC NiCad rechargeable battery. Fast chargers from Radio Shack were used to recharge the battery between classes. Diodes D9 through D12 logically OR the battery and AC adaptor power inputs so that the robot uses the largest of these two voltage sources.

The bow and stern bumper switches, S3 and S4, drive the A/D inputs of the 68HC11. When the voltage is high, the switch is open; when it's low, the switch is closed. We could have used digital inputs on the MPP board, but it was more convenient to wire this way.

Optointerrupters U3 and U4 are mounted on the underside of the main board. By sheer luck, the prongs of the photo-interrupter fit in the motor gearbox and can straddle one of the gears. We drilled four holes in that particular gear so it interrupts the light beam in the photo-interrupter as it rotates, generating a pulse waveform that can be counted by the computer. The gear rotates 13 times for each rotation of the gearbox output shaft, so the optoisolator generates 52 pulses per revolution (4 × 13) of a drive wheel. If you look carefully at Photo 3, you can see one of these holes in a motor gear.



Photo 1—*The microprocessor project platform has a 2 × 20 LCD. The 68HC11E1FN is the 52-pin PLCC. To its right are the memory map decoder GAL and serial port connection. To its left are the EPROM, RAM, and the various I/O ports. The large holes in the prototype area at the bottom of the board mount a small PC board that adapts the robot cables to the MPP board configuration.*

The 9.6-V battery supply is reduced to 4 V for the L293D motor controller, U1, by an LM317T linear voltage regulator, U7. A switching regulator would have been much more efficient, but we opted for the simplicity of a linear regulator. The regulator U7, inductor L1, and filter capacitors C1 and C2 all help to minimize the transmission of motor noise to the logic circuitry. As a consequence, the single 9.6-V battery can reliably operate the entire circuit.

The motors require a maximum of about 3 V for operation. They're controlled from an L293D H-Bridge controller, U1. Two lines from the microprocessor—`stardir` and `portdir`—control the direction of the motors. Two additional lines—`starspeed` and `portspeed`—enable and disable the L293D outputs. They're driven by timer outputs from the microprocessor and can be duty-cycle modulated to control motor speed. Our students rapidly discover that when controlling the robot, the objective is not to make it go as fast as possible, but as slow as possible. They use this feature extensively.



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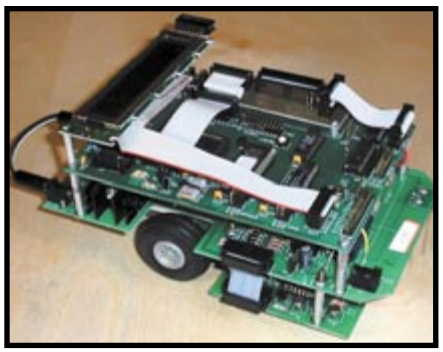


Photo 2—*Looking from top to bottom, you can see the LCD, MPP board computer, robot mainframe, and guider board. The large heatsink for the motor power regulator is at the rear of the mainframe layer. You can replace the guider board with a board that has different sensors that would plug into the mainframe in the same manner.*

To minimize electrical noise from the motors leaking into other circuits, it's important to keep the various power supply lines and ground lines separate. When laying out the PCB, it was necessary to force the PCB autorouter to do this by giving the nets different names and providing jumpers in the various lines at the desired connection point. When the board was built, wire links were soldered through the jumper holes. These jumpers are J2, J10, and J11 in Figure 2.

Figure 2 also contains the general-purpose knob (some people call it the frob knob) and a battery-monitor voltage divider. These drive A/D inputs on the microprocessor.

The "alive" circuitry illuminates an LED as long as the Alive signal from the microprocessor is toggling up and down. Somewhere in the main loop of the program, there are instructions to flip a microprocessor output line, which generates the Alive signal. If this output stops in either state, the LED extinguishes to indicate that the program has crashed.

GUIDER

Many line followers use an infrared emitter-detector pair; however, because it's difficult to see infrared illumination or it's reflection, infrared can be difficult to debug. To make it easier for the students to identify problems, we decided to use visible light emitters and detectors.

The spectral responses of a cadmium sulphide (CdS) cell and a high-intensity red (gallium arsenide) LED are shown in Figure 3. Ideally, these curves should coincide so that the response of the detector is coincident with the response of the emitter. However, with a 2300-mcd light output, the LED emitter is powerful enough to make up for the mismatch. (It would be interesting to try high-intensity blue or white LEDs, which are a better spectral match to the CdS cell. These weren't available when the guider was designed and are still a bit pricey.)

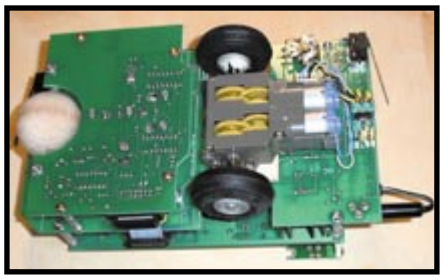


Photo 3—*Check out the belly of the beast. Notice the LEDs poking through holes in the sensor board and the corresponding CdS photoresistor sensors. In the Tamiya dual-motor gearbox, there are four holes that trigger a photointerrupter for counting wheel rotation. The model aircraft wheels are hot-glued to collars that are screwed to the motor shafts.*





The CdS cell responds relatively slowly to changes in the light level. It takes a few milliseconds to respond to light and about 50 ms to return to the dark state. This limits the guider scan rate to about seven times per second, which then limits the maximum forward speed of the robot. If high-speed line tracking were one of your requirements, you'd have to use a different type of detector.

Four pattern-detector/LED-detector pairs were used to detect the line and its branches. There was also a differential pair intended for fine control when steering down a line.

Each photoresistor has its own LED illuminator. In our original design, all of the LEDs were on at one time, and we scanned the photosensors' outputs. However, crosstalk proved to be a major problem. Reflections and light emitted out the side of the LEDs affected several photosensors at one time, and the contrast between light and dark targets was marginal. Dark tape on a light background wasn't properly detected, because the light areas created too much stray illumination. The guider track had to be red tape on a black background.

In a revised design, we put the sensor circuit board closer to the floor with the LEDs on the top of the board aiming down through the holes. The microprocessor individually enables each LED while reading the corresponding photosensor. This produces a much better contrast. Now, you can use black electrical tape placed on a light background for tracking. As a bonus, selectively illuminating the LEDs cuts down on power consumption. When all of the LEDs are off, the sensors can read the ambient background illumination level.

PATTERN DETECTORS

You may download the bottom view of the four pattern detector sensors (i.e., A, B, C, and D), each with its LED illuminator, from the *Circuit Cellar* ftp site. For a simple steering algorithm, cells B and D can be used to detect the line and correct the direction of the robot. Or, sensor A can be swept from side to side over the line as the robot progresses. An intersection is detected, for example, when the robot is on track and both A and B or C and B detect the line.

SENSOR CIRCUIT

The usual circuit for a CdS photoresistor detector is a simple voltage divider with a fixed resistor for the upper resistor and the CdS cell as the lower resistor. You may download a diagram of the photosensor circuit from the *Circuit Cellar* ftp site.

The change in cell resistance causes a change in output voltage; however, the change in cell resistance is somewhat diluted by the effect of the upper resistance. To see this effect, suppose the resistance, R_c, of the cell increases. This decreases the voltage across the fixed resistor, R, which reduces the current down the divider network. The decrease in current partially reduces the original increase of voltage across the cell.

On the other hand, if the upper resistor is a current source, then the current through the cell is fixed and any change in resistance results in a proportional increase of voltage across the cell. For instance, when you have a 5-V power supply, a fixed resistance of 3600 Ω in the upper part of the divider and a cell that changes between 1700 and 3600 Ω (light to dark), the output voltage change is 0.9 V. If you have a 0.8-mA current source in the upper part of the divider and the same cell change, the output voltage change is 1.44 V. With the constant current source, the photocell detector has a much larger change in output voltage for a given change in illumination.

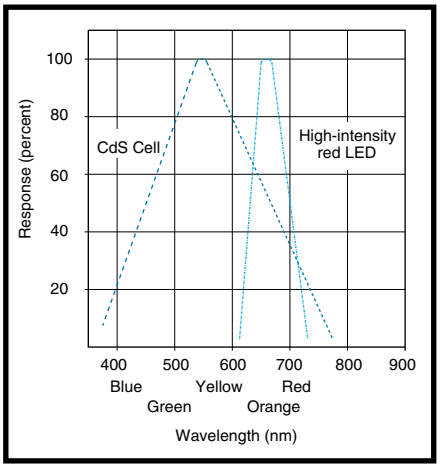


Figure 3—*The CdS cell spectral response covers most of the visual spectrum, which is why they're popular for film camera metering. The overlap involving the high-intensity red LED shows that they're a reasonable match as an emitter-detector pair.*

DIFFERENTIAL DETECTOR

The differential detector is shown as the E-F pair in the configuration diagram on the *Circuit Cellar* ftp site and the complete guider schematic (see Figure 4). It's wired as a voltage divider with a photoresistor in both the upper and lower positions. As a result, the output voltage is sensitive to the difference in illumination at the two sensors but largely independent of the absolute level of illumination.

The two detectors are exactly 0.75″ apart (the width of electrical tape). When the vehicle is centered over a line made with electrical tape, each sensor is half illuminated by the light from the tape and the background, and the output voltage is around 2.5 V. If the vehicle moves to one side or the other, the output voltage will increase or decrease depending on the direction of movement.

The differential sensor is sensitive and ignores ambient light; however, the differential detector is only useful when the vehicle is close enough to the line that at least one sensor is over the line. Beyond that point, the differential sensor information isn't useful.

GUIDER CIRCUITRY

The guider's circuitry is shown in Figure 4. CdS cells PR103 through PR106 are the pattern detectors A through D. A constant current is created through each one by its respective op-amp and PNP transistor driver. The preset potentiometers adjust the cell current so that the output voltage doesn't saturate the PNP transistor when the cell is at its maximum resistance.

Cells PR101 and PR102 form the differential line detector. All of the sensor voltages are selected by the analog mux, U101, which directs the selected output to an A/D input on the microprocessor.

Each sensor has its own LED illuminator, D101 through D106. These are selected in synchronism with the selection of the sensor by the 1:8 decoder, U103, so that a sensor is illuminated by its LED only when the computer is

reading its voltage. Disabling U103 disables all of the LEDs. This allows the computer to make a reading of background illumination.

PROGRAMMING MODEL

You may download a programmer's view of the robot signals from the *Circuit Cellar* ftp site. Five of the eight possible A/D inputs are used for various sensor inputs. Input captures IC2 and IC3 are usually programmed to trigger interrupt routines that keep track of the wheel rotation counts. Output-compare lines OC4 and OC5 are used control motor speed by duty cycle modulating the motor voltage. The output OC5 is traditionally used by the Buffalo monitor program to single step a computer program, so we left that one alone.

Six of the eight general-purpose outputs are used to control the direction of the two motors and select the guider sensor. Note that the diagram shows neither the eight general-purpose digital inputs, which are available but currently not used, nor the liquid crystal display, which is mapped to two locations in memory.

PROGRAMMING EXERCISES

When all of this technology finally gets in the hands of students, what can they do with it? We created a series of lab exercises for them to work on.

The first exercise is an introduction to the monitor program and assembly language programming. Next, the students learn about programming the LCD. In the third exercise, they cover battery and bumper displays. The fourth lab deals with motor control and the hardware timer, and the fifth gives the students a feel for the robot-roaming program (simple bump-and-turn behavior).

The sixth and seventh exercises focus on wheel counter interrupts and the eebot guider, respectively. Finally, the last two labs deal with motor speed control and "The Robot Guidance Project" (i.e., solving a maze).

The guider and motor speed control modules are given to the students to use. The project is a major undertaking that's allocated five of the 13 weeks. All of this material is available on the 'Net (www.eelabinstruments.com).

Most students become quite engaged with this material and put in a considerable mount of effort. After two years of experience with the new lab curriculum, it appears to have enhanced the competence of students in assembly language programming. And, yes, it's a lot more fun to watch than yet another clock display.

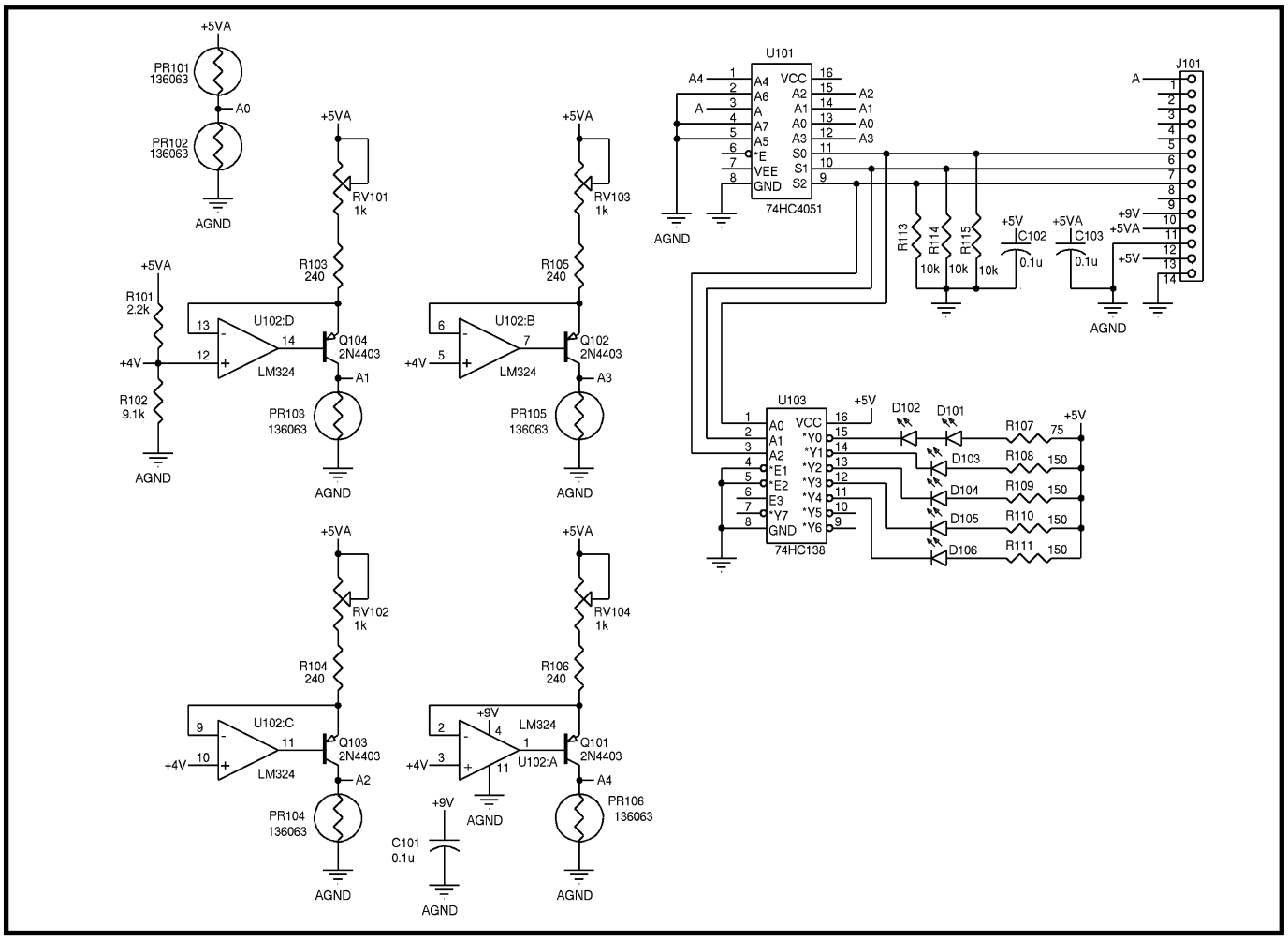


Figure 4—*CdS cells E and F form the differential line sensor for fine control during guiding. The other cells, A through D, form the pattern detector. Each is driven by an op-amp current source to enhance the sensitivity. Each detector has its own illuminating LED, which is selected at the same time the sensor output is selected. Detectors are scanned by the 8:1 mux; the 1:8 decoder enables the LEDs.*

Authors' note: We'd like to thank to Ryerson University's tech staff—including Tu Phan, Vince Luong, and Nripendra Malhotra—for helping with the construction and management of the robots.

Peter Hiscocks is a professor of Electrical Engineering at Toronto-based Ryerson University. Peter teaches courses in digital and analog circuit design. In his spare time he enjoys astronomy and technical writing. You may reach Peter at phiscock@ee.ryerson.ca.

Jim Koch earned a BTech degree from Ryerson University and is currently lead technologist for engineering support at the university. His interests include microprocessor circuits and railroad modeling. You may reach Jim at jkoch@ee.ryerson.ca.

PROJECT FILES

To download the code and additional files, go to ftp.circuitcellar.com/pub/Circuit_Cellar/2003/153/.

RESOURCES

CdS light sensor information, www.plazaearth.com/usr/gasperi/cds.htm.

CdS photoconductive cell information, www.xinld.com/photoresistor.htm.

CdS photoresistor data, www.pree.com.cn/product1.htm.

Red solid-state lamps, Lite-On Technology Corp., www.liteon.com.tw/databook/main.htm.

K. Clowes, "SIM11—A Simulator for the 68HC11 Microprocessor," 2002, www.ee.ryerson.ca/~kclowes/sim11/index.html.

J. Crisman, "System Design Via Small Mobile Robots," *IEEE Transactions on Education*, vol. 39, no. 2, May 1996.

R. Uribe, L. Hakem, and M. Loui, "A Design Laboratory in Electrical and Computer Engineering for Freshman," *IEEE Transactions on Education*, vol. 37, no. 2, May 1994.

SOURCES

MPP Board, 68HC11 microprocessor system kit
Syscomp Eltronic Design, Ltd.
(416) 465-0325
www.eelabinstruments.com

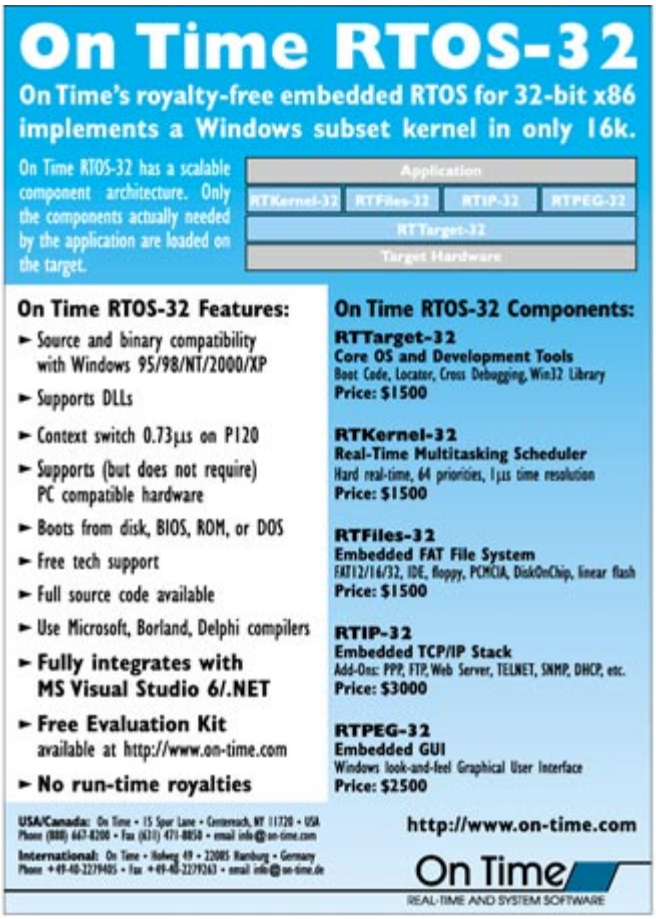
68HC11 Microprocessor
Motorola, Inc.
(847) 576-5000
www.motorola.com

LM317T Linear voltage regulator
National Semiconductor Corp.
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70097 Twin-motor gearbox
Tamiya America, Inc.
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FEATURE ARTICLE

Lonne Mays

Muscle for High-Torque Robotics

Is your favorite robot getting to be a bit too atrophied for your taste? Does it lack vim and vigor? If so, don't worry. What you need is high torque and speed. With the MC33887D integrated H-Bridge and a little direction from Lonne, you can bulk up your robot in no time.

Analog servomotor control ICs—such as the venerable MC33030—have facilitated my motion control tasks for many years. Integrated circuits of this genre contain the op-amps to process the information (i.e., voltage) from analog position sensors, the comparators to process position-command voltages (i.e., reference voltages), and the mixed-signal circuitry to close the control loop while taking care of drive functions like window detection, drive direction, braking, and stall detection. The drive capability of these ICs, however, is generally limited to tiny low-voltage motors (e.g., less than 12 V at less than 500-mA steady-state).

TORQUE VS. SPEED

When you're limited to such wimpy motors, the issue of obtaining high torque involves a trade-off between the actuator speed and the required torque or force. This is because a high-ratio gear train is required to achieve a torque multiplication factor. As a consequence, the speed of the mechanical actuator is reduced (divided) by the same factor. In essence, it becomes a choice between torque and speed. For many applications, a high-ratio gear train is ill suited, because the mechanical delay imposed between commanding a new position and that new position being achieved can become greater than what the system requirements will tolerate.

TORQUE + SPEED

To have both high torque and speed requires you to employ a more potent motor. Such motors don't have to be large, but they do require a heftier V × A product delivered to their terminals. Of course, the output of the servo IC can be boosted via a handful of discrete PNP and NPN bipolar junction power transistors, but the biasing of this external array of parts is a nontrivial task.

Care must be taken to provide bias tracking stability over temperature, given the PN junction's notorious negative temperature coefficient. Additionally, there is the undesirable inherent inefficiency of the multiple V_{CE}(sat) voltage drops in series with the load, as well as the power wasted in the emitter ballast resistors. Creating an external H-Bridge with discrete MOSFETS is also problematic, because this approach requires different drive circuits for the high-side and low-side FETS and the use of charge pumps.

Using a monolithic power H-Bridge ASIC like the MC33887DH is by far an easier means for boosting the output of a servo controller (whether analog or digital). Because this IC incorporates not only the low RDS(on) H-Bridge but also the gate drive, charge pump, and input logic circuitry, it's a simple yet robust solution for boosting the output of a servo controller IC. The MC33887DH allows you to select motors requiring up to 6 A steady state at up to 30 V. This means motors up to 180 W may be utilized, thus providing both high torque and speed via low-ratio gear trains.

SOFTWARE VS. HARDWARE

The latest generation of microcontrollers makes closed-loop servo control an easy task, especially when the micro's brains are teamed with the nerves and muscle of power ASIC's (e.g., the MC33887, MC33886, MC33486, MC33186, and MC33880).

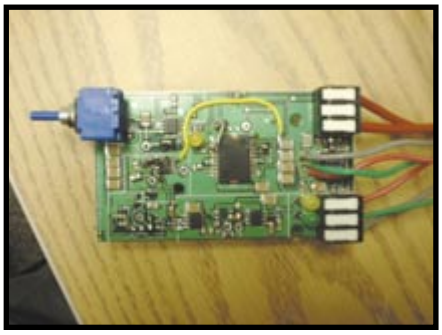


Photo 1—*The entire module has the same dimensions as a standard business card, yet it's capable of controlling 5-A, 12-V motors without additional heatsinking. Surface-mount technology was used for the majority of the components.*

Using the MCU's A/D inputs to read the position sensors and its PWM or parallel/serial output to communicate with the power ASIC makes servo control more of a programming exercise than a hardware design exercise.

THE ROBOT WARRIOR

Toward the end of keeping this a totally hardware-oriented article, this design example takes a sans-micro approach to tackle the task of converting a standard radio control (RC) pulse-width-coded signal into a high-speed, high-torque servo response. Referring to the schematic in Figure 1, note that there are five functional areas to the design. From this point on, I'll focus on the function and operation of each area delineated in the schematic, beginning with the servo amp.

SERVO AMP

The upper right-hand area of the schematic—labeled "servo amp"—represents the control and power functions that I've already described. Note that it contains only two ICs: the MC33030 servo IC is the brain, and the MC33887DH acts as the nerves and muscle. The MC33887DH is the large IC in the center of the PCB shown in Photo 1.

As you can see in Figure 1, the MC33030's two outputs, which would ordinarily go to a small motor, are interfaced to the two inputs of the MC33887 via two small diodes. Any small signal diodes will do in this case, because their only function is to prevent the MC33030 outputs from overdriving the MC33887's inputs. (Note that the MC33887 has CMOS/TTL-compatible 5-V logic inputs with internal 80-µA current source pull-ups.)

Utilizing the current feedback output of the MC33887 has preserved the stall-detect and over-current shutdown feature of the MC33030. The MC33887 uses the loss-less technique of current mirroring to sense the motor load current. This technique provides a ratioed sample of the load current (1/375 in this case), which is easily converted into any desired voltage via a single resistor. Applying this resistor to the CDLY input of the MC33030 enables the IC to detect a motor stall or over-current condition and shut off the drive signals. The drive signals will remain off until a direction reversal is commanded via the error amp or reference input.

The particular stall current threshold is set by the value of the feedback resistor (i.e., R10 in Figure 1). Capacitor C8 is added to filter out current spikes, which may be present because of capacitance in the load. (Don't forget that it's often necessary to place small capacitors across the motor brushes to reduce EMI/RFI.)

PW-V CONVERTER

The upper left-hand area of the schematic shows the circuit that I've dubbed a pulse width-to-voltage converter, or PW-V converter. The input to this circuit is the servo pulse supplied from an RC receiver. The width of this pulse corresponds to the servo position commanded from the RC transmitter. For instance, a pulse width of 1.5 ms corresponds to a requested servo position of "center"; a pulse width of 2 ms corresponds to a requested servo position of "fully clockwise"; and a pulse width of 1 ms corresponds to a requested servo position of "fully counterclockwise" (or vice versa, depending on the side of the servo shaft you're standing on).

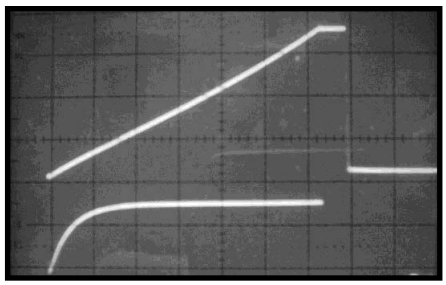


Photo 2—*Take a look at the ramp generator output versus the input pulse width. As the pulse varies in length, so does the length and final height of the ramp. The slope of the ramp is fixed.*

The output of this circuit is a linear voltage ramp that peaks at a voltage corresponding to the requested servo position. This voltage will be sampled, held, buffered, and applied to the servo IC as the reference voltage. (You'll learn more about this shortly.) An MC33078 op-amp is used to buffer the input pulse, which is then inverted by an MC74HC1G04. Q1, C3, and the associated resistors form a linear ramp circuit, which produces a ramp proportional to the width of the input pulse. The slope of the ramp can be varied by adjusting the ratio of R2 to R7, or by the "Ramp slope set" potentiometer. Use only one or the other in the physical circuit, not both. Photo 2 shows the input pulse and the resulting ramp.

SAMPLE AND HOLD TIMERS

As you can see in the lower-left portion of Figure 1, I used MC1455 timer ICs in this portion of the circuitry. Timer1 is triggered by the falling edge of the input pulse—courtesy of the differentiator comprised by C29 and R19.

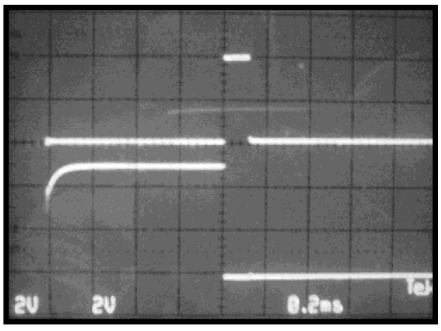


Photo 3—*There's nothing too complicated here. The Sample and Hold command is generated at the termination of the RC code pulse.*

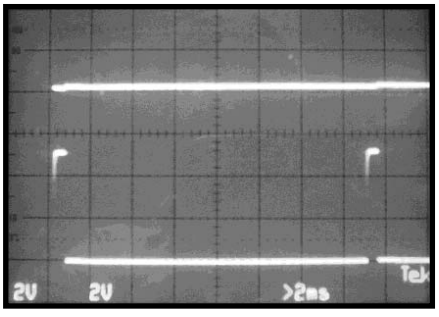


Photo 4—*The radio control servo control pulse has an ~15-ms repetition interval. Note that it's the width of the pulse (0.5 to 1.5 ms) that's critical, not the pulse repetition interval.*

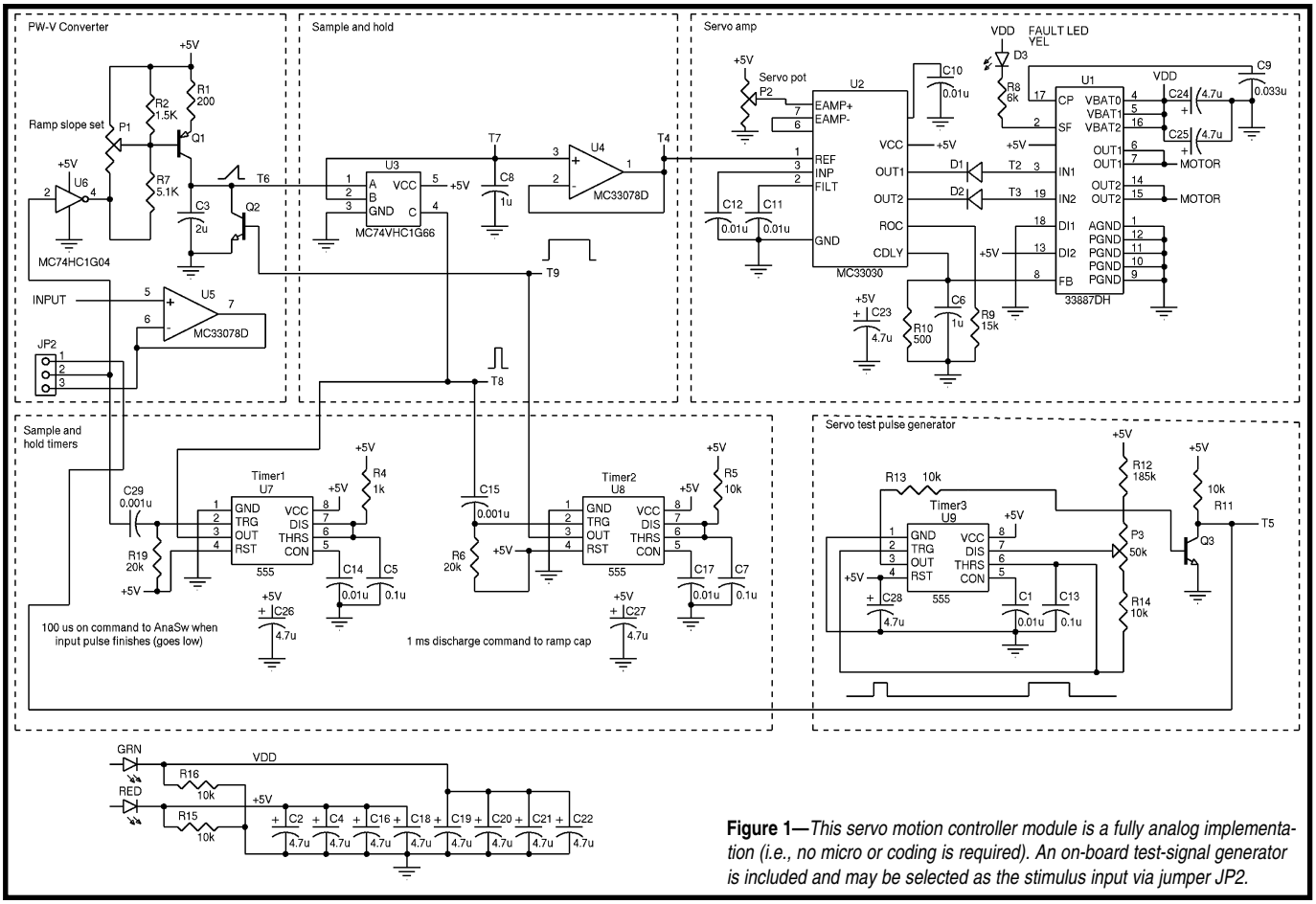


Figure 1—*This servo motion controller module is a fully analog implementation (i.e., no micro or coding is required). An on-board test-signal generator is included and may be selected as the stimulus input via jumper JP2.*

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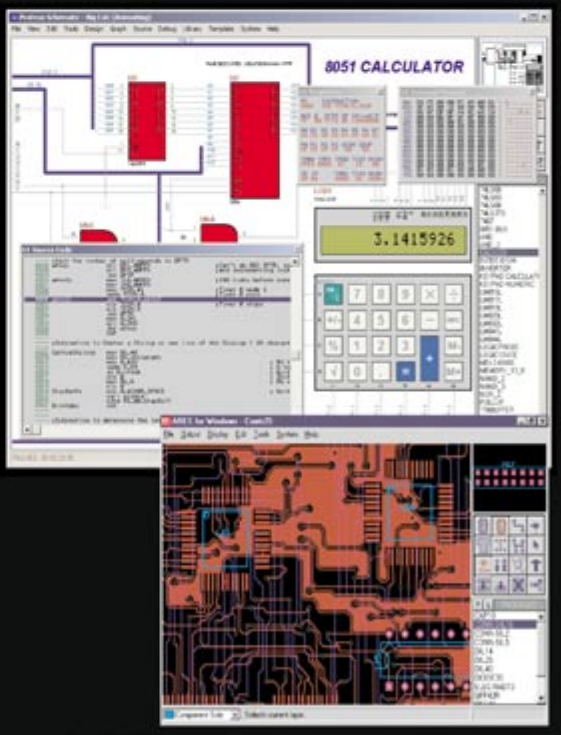
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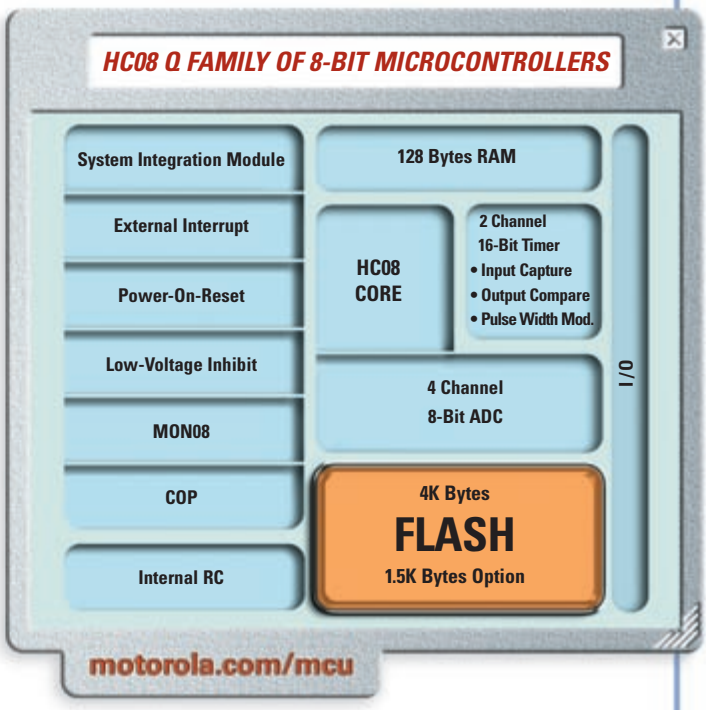
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This timer generates a 100-µs command to the sample and hold circuit.

Photo 3 shows the input pulse and timer pulse. Note that the 100-µs timer pulse begins on the falling edge of the input pulse. The falling edge of Timer1's pulse is fed through a differentiator (i.e., C15, R6) to trigger Timer2. Timer2 provides roughly a 1-ms pulse to the base of Q2, causing it to saturate fully and rapidly discharge the ramp capacitor, C3. Keep in mind that this 1-ms pulse begins at the falling edge of Timer1's 100-µs pulse.

ANALOG SWITCH

The heart of this little circuit is the MC74VHC1G66 analog switch. After receiving the pulse from Timer1, the analog switch transfers the voltage on C3 (i.e., the PW-V converter) to C8. Recall that Timer1's pulse occurs at the falling edge of the input pulse; thus the voltage on C3 will be ramped up to a peak corresponding to the width of the input pulse.

Recall also that Timer2, which generates its pulse after the completion of the sample and hold activation pulse, discharges C3. Photo 4 shows the output of the sample and hold circuit versus the input pulse. (Note that the input pulse repeats in 15-ms intervals. The pulse repetition interval isn't critical and doesn't contain any information. It varies from 10 to 30 ms, depending on the brand of RC transmitter.) The voltage stored, or held, on C8 is buffered by another MC33078 op-amp—the other half of this dual op-amp chip—and applied to the position reference input of the MC33030.

TEST-PULSE GENERATOR

This servo test-pulse generator is simply a test-pulse generator that's added to the board so that it can be tested without an RC transmitter and receiver. Jumper JP2 is provided so that the PW-V converter can receive a pulse from an external receiver or the on-board test-pulse generator.

WATCH YOUR FINGERS

I used a simple, single-reduction motor and gear assembly for testing the circuitry. A worm gear was mounted to the shaft of a 5-A motor, and the position feedback potentiometer was mounted to the mating worm wheel. The potentiometer provided 320° of rotation.

Testing showed that the system responded to position commands with the high speed associated with a single-reduction gear and the high torque associated with the 5-A motor. In fact, the speed and torque were of a magnitude that merited physical precaution for my fingers!

Several alternatives would be practical for the gearing and potentiometer assembly. For instance, if a multi-turn potentiometer (e.g., 10 turn) were used in place of the single-turn device, a winch servo would be created without sacrificing positional accuracy. Likewise, a pure linear-force mechanical arrangement could be accomplished via an ACME lead screw and follower nut, which would be attached to a linear potentiometer.

With deference to my MCU-focused colleagues, I acknowledge that this entire exercise could have been done with one HC08 microcontroller, one MC33887DH, and about 2 KB of code. But wasn't sticking strictly to a hardware solution more fun?

Lonne Mays is a systems and applications engineer for Motorola's Analog Products Division. Lonne has been with Motorola for 25 years, and working with electronics circuitry for over 35 years. He has a Master's degree from Arizona State University, as well as a B.S. degree. In his spare time, Lonne likes to work at home in his machine shop and electronics lab. You may reach him at lonne.mays@motorola.com.

SOURCES

MC33887DH Integrated H-Bridge
Motorola, Inc.
(800) 521-6274
(847) 576-5000
www.motorola.com

MC1455 Timer, MC30330 servo IC, MC33078 op-amp, MC74HC1G04 single inverter, MC74VHC1G66 analog switch
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FEATURE ARTICLE

Robert Morrison

Updating the Home Control System

Part 2: FPGA Design Methodology

Ethernet support, audio, and video—these are what HCS dreams are made of. Last month, Robert awakened you to the possibility of bringing such technology to the table. Now he's back with the FPGA design methodology and source code to get you started.

Last month, I described an exciting new architecture path for the *Circuit Cellar* Home Control System II. By adding an FPGA with a variety of new features, I substantially extended the HCS II's capabilities and positioned it to ultimately connect to Ethernet (and, of course, the Internet!). This month, I'll help you start building your upgrade by describing the FPGA design methodology and the HCS II FPGA source code (i.e., the hardware language description of the circuitry that's programmed into the FPGA).

FPGA BLOCK DIAGRAM

The FPGA source code consists of 14 files, starting with a top-level file, hcs_fpga.v, which has no circuitry in it but instantiates the remaining modules (see Figure 1). Using this hierarchical circuitry description makes it trivial for adding or removing modules. (Removal is done to get the design to fit in a smaller FPGA; adding is performed when additional functions—such as RS-485 network modules—are needed.) There is a control interface (hcs_to_fpga_if.v) that takes the HCS II processor board signals and synchronizes them safely into the FPGA clock domain. A command decoder takes these synchronized signals and interprets accesses to the FPGA. There's also a collection of specific function modules such as UARTs. You may download the code from the *Circuit Cellar* ftp site.

I wrote all of this in Verilog, but you can easily convert the files to VHDL if it's your favorite language. Verilog is more like C, whereas VHDL is for those of you who like strong-typed languages. It's a religious issue whether or not one is better than the other. I prefer Verilog because you don't have to fight the language to get something done. But, on the other hand, Verilog can get you in trouble if you don't know what you are doing (e.g., with mismatched bus connections). Despite the differences, most tools will accept either language, so you can take your pick.

First, let's cover a few global FPGA issues. Generally speaking, it is best to asynchronously assert and synchronously release reset. I use asynchronous resets for both assertions and releases, but I run the risk of releasing reset within the clock setup and hold of a flip-flop, thus risking a metastable event when coming out of reset. However, I make the assumption that none of the modules are active right out of reset, so I should be safe, but it's easy to overlook something here.

My design doesn't have latches (bad news for a variety of reasons, including testability issues, time-constraint problems, etc.) and negative clocked flip-flops (bad news for similar reasons). I do have two clock domains, so I must be careful with cross-clocked signals. I believe my design should safely handle the clock domain issue. The best way to handle this is to never have more than one clock go into a module unless the module's only function is to synchronize between domains, which should be the case here.

Let's start with the HCS II control interface. It must accept the read and write strobes, the 0x0E000 strobe that used to enable the IND54 extended I/O buffer board (I appropriated that address range for the FPGA), data, and the lower eight address bits. This address range, combined with the 0x0E000

enable signal, allows me to specify 256 registers within the FPGA. These signals are synchronous to the HCS II clock, which must be converted to the FPGA clock domain before it's used.

I made some assumptions to simplify this interface, but still require one full clock cycle (about 54 ns) to resolve possible metastable events. I synchronized the read and write strobes along with the 0x0E000 signal and made two assumptions: the HCS II strobe is always going to be longer than one FPGA clock cycle, and the strobe accesses will never be closer than one strobe every two clocks.

These two assumptions allow me to do a simple pulse extraction from the synchronized read or write pulses that then go to the command decoder. Note that writes are always synchronous and reads are asynchronous to provide the correct timing of status information back to the HCS II clock domain. Additionally, the write data is synchronized. You might think this is unnecessary because it's stable during the write strobe to the FPGA; however, because I synchronize the write strobe, it actually performs the write later, so I must clock the data to make sure it is valid during the synchronized write access.

Some read accesses also perform synchronous operations (e.g., a read of a UART will clear the UART receive interrupt), so I have a separate synchronized read pulse generator to do these operations. All of these functions are inside the hcs_to_fpga.v module.

Now that I've completed the slightly messy business of synchronizing different clock domains, it's time to have fun! The command decoder has three parts: a synchronous write case statement to interpret writes to the FPGA; an asynchronous read case statement for reading back registers or status; and a synchronous read case statement in case the read must cause an event in the FPGA clock domain (e.g., clearing an interrupt).

The command decoder will typically hold simple functions, such as holding the LED output register, but it usually sends control and data information out to modules that hold more complex functions such as UARTs. Many modules need 16 bits of data, but the HCS II works on eight bit bytes, so I created a low-byte holding register that's used when the upper byte is written to a 16-bit register such as the Voice SPI 16-bit interface.

The clock and pulse generator is a sequence of counters designed to synchronously generate pulses at various time intervals. Single clock pulses at 1-s intervals, for example, trigger an (maskable) interrupt that can be used by the HCS II to time events. Other clock pulses provide configurable timing for the UARTs or other FPGA functions.

The watchdog timer is simple: after it's written, a watchdog counter counts down to zero every second. If the counter isn't reloaded before it reaches zero, the HCS II reset input will be driven. Unfortunately, the reset on the daughtercard connectors is an output from the processor board reset circuit, so I had to provide a short cable from the custom board to the reset jumper (J3 on the processor board). I drove this reset with an open-collector driver on the upgrade board. (The FPGA could have driven it in open-collector mode; however, because I had this buffer on the board anyway, I used it instead.)

The interrupt vector module is a nice way of simplifying the work that the processor has to do when responding to the FPGA interrupt. There are a lot of interrupt sources on the FPGA, so making the processor read FPGA status registers to try to figure out which interrupt service routine to jump to can result in long interrupt latency response times. I took advantage of available SRAMs in the FPGA to store an interrupt vector for each interrupt source. In addition, I put a simple interrupt arbiter on the FPGA to decide which interrupt vector to use. Now, when the FPGA pulls on the INT0 signal, the HCS II processor just reads the interrupt vector register and jumps to it, resulting in fast interrupt response times.

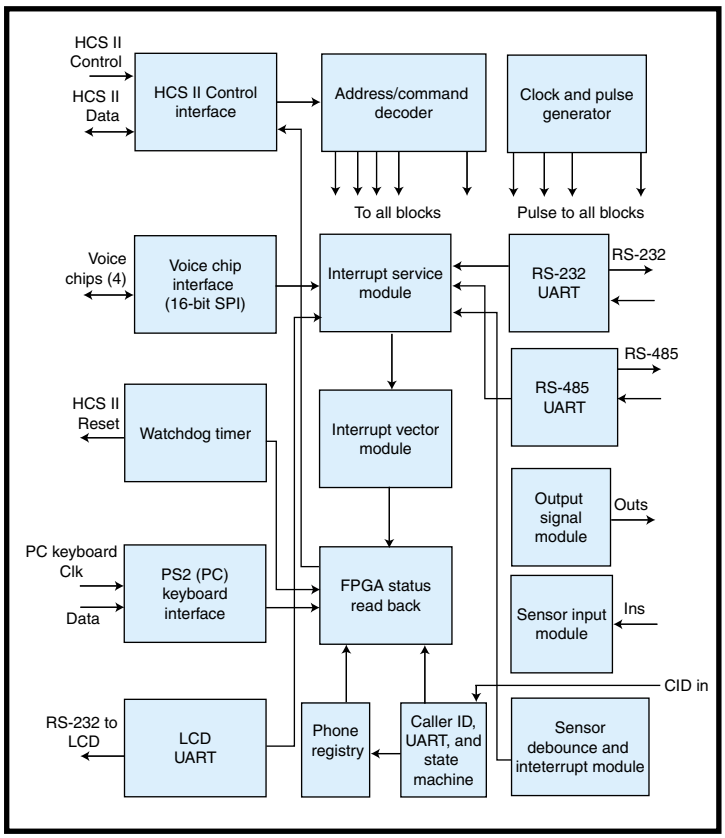


Figure 1—*The FPGA block diagram shows the functional modules programmed into the FPGA. The circuitry for the FPGA is programmed at power-up by the FPGA; it automatically loads information stored in the configuration EPROMs external to the FPGA at power-up, and then goes into Operational mode.*

The remaining modules are relatively straightforward. The sensor inputs and outputs are handled directly in the command decoder, because these are simple register and status accesses that aren't worth bringing out to a separate module. Debouncers and individually masked interrupts for each sensor input are provided. The outputs are just registers. The FPGA has much more current drive than the old HCS 8255 chip, so for local external devices such as LEDs, the FPGA outputs can drive them directly. But be careful to externally buffer and pro-

tect any signals that go off the upgrade board. You don't want ESD to zap your FPGA! I have an external sensor array board that goes into RC and diode protection before driving 74LS244 buffers that then drive the FPGA.

All of the rest of the circuitry are UARTs of one form or another—six of them. Several more are planned, because I intend to add an additional RS-485 network and a diagnostic logging port (which will output actions taken by the ROM code for debugging purposes). I may eventually add another Ethernet connection to the FPGA, but for now, there are UARTs for the PS2 keyboard module, LCD, caller ID module, voice chip module interface (this is a synchronous UART method known as 16-bit SPI), RS-485 network interface, and RS-232 interface.

I wrote a generic transmitter and receiver UART module that seems to be extremely robust. The receiver is clocked at eight times the data rate, thus sampling the serial input using a noise-reduction scheme. The transmitter is a fairly generic triple-buffered shift circuit. Both have proven to be reliable.

I picked up the PS2 keyboard interface on the 'Net from www.opencores.com. This module took a little work to get going correctly (I made several modifications so it would not use as much logic, and there was a bit-timing problem that I fixed), but it seems to work well now. Note that I got pretty lazy and only read the keyboard. The PS2 interface allows writing out to the keyboard to configure it or turn on its LEDs, but I didn't need that. I just read the scan codes as they come in and use an SRAM in the FPGA to convert to ASCII characters. The PS2 keyboard sends a key code on assertion and release of a key. Therefore, I used the ROM interrupt service routine to throw away the second occurrence.

I also put the phone caller ID support in the FPGA. The circuitry automatically takes the CID UART characters and buffers them so the HCS II firmware can search for the phone number. Then, it compares that phone number with numbers stored in the firmware phone registry memory. It's really cool to have the processor detect two rings and read the phone code from the registry to see what message to output on the intercom (who is calling). There are also several status and diagnostic registers that are useful in getting the upgrade board working, and I have numerous plans for future expansion.

HOW TO BUILD IT

So, you've decided to take this step too! I'll show you what you need to get and what you need to do. You may download a lot of this information (i.e., code, schematics, parts list, etc.) from my web site, www.zetaengineering.com. The site contains all of the source files necessary to build the project, as well as up-to-date details on how to proceed.

To upgrade to the HCS-FPGA (the unofficial name for the FPGA-upgraded HCS II), you first need to realize that this effort is a moving target. It's unlikely that my project will ever stand still long enough to be called finished. However, I'm always trying to ensure that I don't do anything that will break existing users. Note that the project is in versions, so you can always decide when you want to step in and upgrade.

In addition, I am trying to be sensitive to designers who have other directions in mind. The HCS community will decide what path we will take. This is a spin-off investigation to show you what you can do by adding an FPGA (and eventually the Rabbit 3000 module, which will follow the HCS-FPGA and is called HCS-R).

The process of migrating to the HCS-FPGA has two parts: synthesizing and adding the FPGA, and adding the supporting circuitry and connections. You're likely find that the *Circuit Cellar* HCS II web site contains newer information pertaining to upgrading the main processor and network modules, but the subject of this article—adding the FPGA to an existing HCS II—is just the first step.

At this point, if you want to immediately add an FPGA, you will have to get a prototyping board and install an FPGA on it. There aren't any PC boards available, but you can check in with the local.cci.hcs2 newsgroup on the bbs.circuitcellar.com site. A lot of discussion is going on right now that will likely result in the development of a standard board that has an FPGA, a Rabbit RCM3010, and other parts on it that will plug into the HCS II stack. Still, that's months away, so if you want to add an FPGA now, a prototyping board is your only solution.

I've tried to design this project so it will work for anyone with a sufficiently large FPGA (i.e., around 50,000 to 80,000 FPGA gates). The source files should be FPGA-independent with a couple of exceptions that you'll find easy to modify. The Xilinx part that I use specifies the pads on the top level of the source (hcs_fpga.v). You'll likely want to change or remove these assertions, which are comments with a special keyword that look like this:

```
output [1:0] talk_relays;  /*
  synthesis xc_loc="AD7,AL27"
  */.
```

I also instantiated some synchronous SRAMs. Both Xilinx and Altera provide 2-Kb SRAMs in a variety of formats. If you use a different FPGA, you may have to do a little work to instantiate the SRAMs.

Other than that, the code should compile for any FPGA. Currently, it will fit in a relatively inexpensive Xilinx Spartan-II part called the XCS2-100. (This is Xilinix's promotion part, "100,000 gates for $10," but that price is for 250,000.) It will also fit in the Altera 20K100 device. Because these parts are inexpensive, I suspect Xilinx or Altera might offer samples. Or, you can check with the local.cci.hcs2 newsgroup; we may try to do a group buy to get the cost down. Even so, the part in small quantities shouldn't be too bad.

As I've indicated, the current design will fit in these devices using about 50% of the FPGA resources. If you're really strapped for funds, the design will also fit in the next smaller device, the XCS2-50, using 78% of its resources. I strongly recommend going with the largest possible device, because the design is likely to grow. It's easy to remove modules in the design that you don't need. I tried to write the FPGA code in hierarchical fashion so that the top level has no logic—it just instantiates modules. That way, you can easily remove modules you don't need or, conversely, add new modules (e.g., additional UARTs) that you do need that aren't in the current design.

As you know, adding the FPGA requires that you add a board to the stack, because the FPGA communicates with the processor via the two daughtercard stack connectors. The FPGA resides at address 0xE000 and uses the INT0 interrupt, so neither of these HCS II resources can be used by other cards. This means you cannot select INT0 on the voice or phone interface cards (current versions of the ROM don't support that anyway), and you cannot use the second buffer card (i.e., IND54).

After you have the FPGA connected (next month I'll show you how I did it), you must pick up the new Xpress compiler version 5.02 and HCS-ROM version 5.02. (The versions may be updated by the time you read this.) Note that the compiler version must match the ROM version, because the HCS II checks that they are the same.

THE FINAL INSTALLMENT

Now you know what's needed to create the FPGA that's used in the FPGA upgrade. Next month, I'll explain how to get the code from the web site, tell you which parts to get, and show you how to put together the HCS II FPGA board and write Xpress code to talk to the FPGA upgrade. In addition, I'll provide a portion of the Xpress program that I use that shows how to control the phone interface, the new voice chips, and some other basic capabilities.

After absorbing the forthcoming information, you'll be ready to give your HCS II system new life! Not only that, this upgrade will be compatible with the next big step, the migration to the Rabbit 3000 processor board with faster processing capability, more memory, and Ethernet connectivity!

Robert Morrison has been an ASIC designer at Hewlett-Packard for 23 years. In his free time he studies and teaches classical piano, and enjoys discussing physics and astronomy. You may reach Robert at zeta@zetaengineering.com.

PROJECT FILES

To download the code, go to ftp.circuitcellar.com/pub/Circuit_Cellar/2003/153/.

SOURCES

PS2 Keyboard interface source code module
www.opencores.com

Rabbit 3000 module (RCM3010)
Rabbit Semiconductor
(530) 757-8400
www.rabbitsemiconductor.com

LCD
Scott Edwards Electronics, Inc.
(520) 459-4802
www.seetron.com

Synplify Pro
Synplicity, Inc.
(408) 215-6000
www.synplicity.com

ISD4003-8 Voice chip
Winbond Electronics Corp.
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ISE WebPACK, Spartan-II, Virtex-E (XV2000E)
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(408) 559-7778
www.xilinx.com

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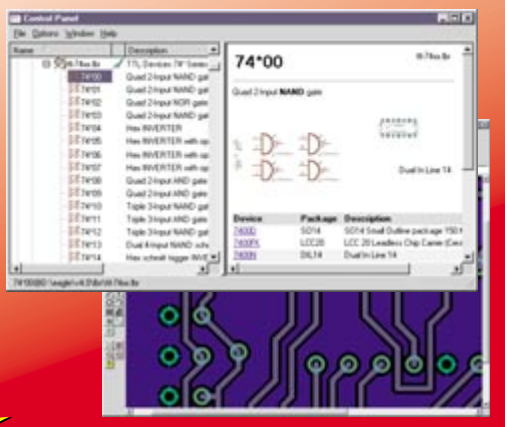
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* IRQ10-IRQ15 requires 16 bit connector option

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FEATURE ARTICLE

George Novacek

Communications Protocol

MIL-STD-1553B Data Bus

In the early 1970s, the MIL-STD-1533 communications protocol—grandfather to many of today's protocols—was created to enhance military and aerospace applications. In this article, George maps the MIL-STD-1533's history and explains its effect on new technology.

Thirty years ago, most aircraft electronic systems—such as navigation, communications, embedded closed-loop control, and weapon systems—comprised numerous stand-alone devices that were interconnected by point-to-point wiring. Those were mostly analog systems with their system interfaces carrying analog signals. The limited need for digital data communications was easily covered by slow, unsophisticated but reliable serial protocols such as ARINC 429 (G. Novacek, "Communications Protocol in Aeronautics," *Circuit Cellar Online*, May 2001).

It didn't take long, especially for the military with its sophisticated weapons systems, to develop a need for additional data exchange. New sensors and their associated processors used up space, energy, and added weight—all of which have always been at a premium. The need for sharing data among different systems resulted in unwieldy rats' nests of heavy copper wire. Clearly, what was needed was a fast, reliable communications link that would facilitate the efficient sharing of sensors' data by many subsystems, reduce the weight of equipment, simplify wiring, and allow for the transfer of data at a rate and volume nearly impractical to achieve by point-to-point wiring.

By 1973, the MIL-STD-1553 communications protocol was born. In this article, I'll take a closer look at this protocol and show you how it works. It's likely that many of you have never heard of it, primarily because it has been limited to military and aerospace applications. Yet, its development was an important engineering milestone, and many of its underlying principles have found their way into today's local area networks.

The protocol's 1-Mbps data rate, which was revolutionary at the time, is slow by present-day standards. Today, there are newer, faster protocols claiming to be just as reliable as the old MIL-STD-1553B. But when data communications reliability is paramount and the customer isn't willing to take any chances, the MIL-STD-1553B still remains the best choice for many engineers.

Over the past 30 years, this communications protocol has gone through several modifications and tweaks; but for the past 25 years it has been at revision B with Notice 1 and then Notice 2 added. It was also introduced as MIL-STD-1773, which is a fiber optics-based version. So, why bother with a communications standard that's so old? Because it is one of the grandfathers of modern network communications, which, when it comes to data reliability, still gives many modern protocols a run for their money. Understanding it and its underlying principles will



Photo 1—*Take a look at the MIL-STD-1553B remote terminal using the C-MAC chipset. The two black squares to the right of the IC are the coupling transformers, which are a dead giveaway that this is a dual-redundant system.*

give you a better understanding of and appreciation for what you can find today even in the common PC.

DEVELOPMENT AND HISTORY

In 1968 the Society of Automotive Engineers (SAE) set up a committee with the goal of defining a new communications protocol that would satisfy the growing data communications requirements of the military avionics community. [1] Designated A2-K, the committee produced the first draft of the protocol in 1970, but it took another three years of reviews, testing, and changes before the first official version of MIL-STD-1553(USAF) was released in August 1973. The first beneficiary of the new system was the F16.

As the system entered field service, changes and improvements were made that resulted in the 1975 release of the updated MIL-STD-1553A. The primary user remained the Air Force's F16, but other aircraft, such as the AH-64A Apache attack helicopter, adopted the protocol. Continuing field experience identified additional features that were badly needed in real life. Three years later in 1978, MIL-STD-1553B saw the light of day. At that point, the design was frozen. Not that it was perfect, but the freeze was needed to facilitate development of fairly complicated hardware (by that day's standard) and to gain additional field experience.

Since then, the protocol has remained at revision B, although Notice 1 and then Notice 2 (in 1986) were introduced to tweak the standard. Notice 2 also removed references to airborne applications, thus opening the door to wide industry use. Notice 3 and Notice 4 were issued in January 1993 and January 1996, respectively. Both of these notices merely confirm the continued validity of the standard, but do not introduce changes.

Although military aircraft remain the main users of the system, the protocol has found its way into many aerospace applications, including satellites, space shuttle payloads, tanks, ships, missiles, and weapon systems. The last version of the ubiquitous Hercules transport aircraft (C130J) uses the MIL-STD-1553B data bus to interface most of its avionic systems, bringing significant savings in wiring weight and labor. The protocol was accepted and implemented by NATO and some governments such as the United Kingdom.

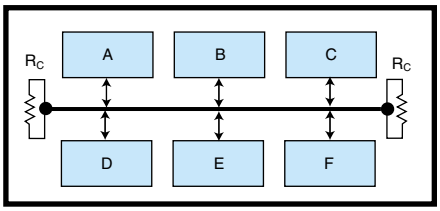


Figure 1—*The architecture of an MIL-STD-1553B system is a simple bus. Up to 31 terminals are connected to it through stubs designed in such a way that a failure of a terminal cannot bring down the entire bus.*

So, why isn't such a marvelous protocol found in just about every piece of electronic equipment around us? In my opinion, there are several reasons, but, mainly, the protocol was ahead of its time. Since its introduction, it has been difficult for nonmilitary equipment designers to justify its high cost of implementation when not all of the features were needed or could be achieved more economically in a different way.

The most common implementation is by a dedicated IC (see Photo 1). Its manufacturers, however, have never felt the need to entice the commercial industry to its use by lowering the price, which, in turn, has kept the volume low and the price high. Even today, the OEM price of the chip with its coupling transformers is well over $1000. And, frankly, even if the price were to drop, it's too late. The retail prices of complete network cards reliable enough for most commercial applications seldom exceed $50, and data communications protocols suitable for safety-critical applications with some data rates exceeding 100 Mbps are just around the corner.

Protocols such as the ANS from Boeing/Rockwell-Collins and from TTTech, just to name a few, are poised to take over. Because of their focus on not only military but also automotive, railway, and commercial aircraft applications, it could be expected that the significant volume will drive the chipset price low, making it even more likely to be used in new designs.

HARDWARE

MIL-STD-1553B is formally known as the digital time division command/response multiplex data bus—a name that quickly betrays its military/design committee parentage. The important indicator in the name is the "time division multiplexing" portion, which is defined as "the transmission of information from several signal sources through one communications system with different signals samples staggered in time to form a composite pulse train." [1] This, albeit a mouthful, is a good description of what goes on in the protocol.

By definition, MIL-STD-1553B is a bidirectional, half-duplex deterministic communications protocol with central control, where each member (i.e., remote terminal) can receive or transmit data. A 1553B network consists of four major components: transmission media, remote terminals, a bus controller, and a bus monitor. The transmission media is a twisted, shielded wire pair with direct or transformer coupling. The data rate is 1 Mbps of Manchester-encoded, biphase datastream. Up to 32 words can comprise a single message in which each word is 20 bits long. One system can accommodate up to 31 remote terminals, a bus controller, and a bus monitor.

The interface hardware for the network members is generally designed around a standard chipset, regardless of whether or not the ultimate use is a remote terminal, bus controller, or bus monitor. Circuits with all the important interfaces and encoding/decoding functions integrated in them are available

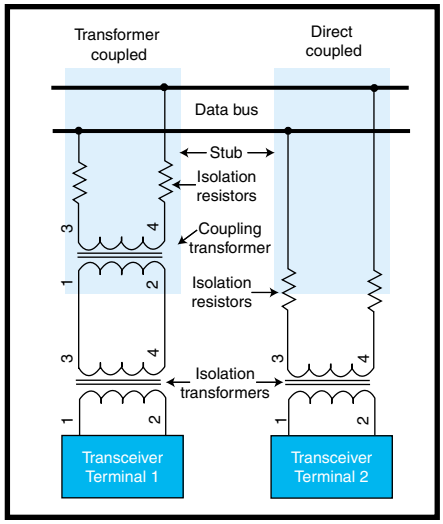


Figure 2—*Coupling to the data bus is through direct or transformer stubs. The direct-coupled stub's maximum length is 1′; the transformer-coupled stub can be as long as 20′.*

on the market, although, as I've already mentioned, they are quite expensive.

TRANSMISSION MEDIA

The transmission media is a shielded, twisted wire pair that's terminated at each end by the cable's characteristic impedance ±2% (see Figure 1). The wire pair has at least four twists per foot with a maximum 30-pF capacitance between the wires. Consequently, the bus characteristics are those of an infinite transmission line with impedance of 70 to 85 Ω and attenuation of no more than 1.5 dB per 100′ of length at 1 MHz.

The individual terminals are connected through stubs, as shown in Figure 2. Unfortunately, the stubs create an impedance mismatch, which is responsible for electrical reflections degrading the bus performance. To control this degradation, the length of the directly coupled stubs is limited to 1′, and the transformer-coupled stubs can be up to 20′ long. There is no maximum bus length, although careful design, stub placement, and modeling are needed to achieve reliable performance at several hundred meters of length, especially when direct coupling is used.

Fault tolerance is a paramount consideration in safety-critical systems. Although the isolation resistors prevent the bus failure in case of a terminal's short circuit, transformer coupling is a more reliable method, providing better performance overall, albeit at a greater cost. Coupling transformers with several secondary windings have been developed to alleviate this cost. Those transformers are often toroid transformers with the bus wire simply passing through its core. Thus, no metallic connection to the bus is needed and its integrity remains intact.

REMOTE TERMINALS

All network members other than the bus controller and monitor are referred to as remote terminals. The purpose of the terminal is to provide a communications interface between the bus and a subsystem, just like a network card or modem. The block diagram of a typical remote terminal and its associated subsystems is shown in Figure 3. Most often the remote terminal is an embedded part of a subsystem, just like a network card in a PC. This can be seen in Photo 2.

LINE CODING

To transmit digital information over a digital communications system, you need to convert the binary data sequence into a corresponding digital signal. The selection of a coding technique you can use depends on several factors. In systems where bandwidth is at a premium, your major concern will be to maximize the data rate. In systems such as local area networks (LANs), other concerns may be more important, such as the ease with which the bit timing can be recovered from the arriving digital signal. Additional concerns, such as the immunity to interference or inherent error detection, may be at the top of your list. And, as always, you cannot ignore the cost and complexity of the implementation.

Figure s1 illustrates several popular coding techniques. [1] The drawing shows line-signal representations produced by the different line-encoding techniques for a binary sequence 101011100.

The most rudimentary encoding technique is the unipolar, nonreturn-to-zero (NRZ) method, which is shown on the top line. Here, a binary 1 is represented by an amplitude +A; binary 0 is represented by the absence of a signal. Assuming that the probability of occurrence of ones and zeros is 50%—which means the same number of ones and zeros over a time—the average transmitted power will be as follows:

$$P = \frac{1}{2} \times A^2 + \frac{1}{2} \times 0^2 = \frac{A^2}{2}$$

Polar NRZ encoding improves the energy efficiency of the code by mapping the logic 1s to +A/2 and logic 0s to –A/2; therefore, the average transmitted power will be one-half of the unipolar NRZ code, as expressed in the following equation:

$$P = \frac{1}{2} \times \left(\frac{+A}{2}\right)^2 + \frac{1}{2} \times \left(\frac{-A}{2}\right)^2 = \frac{A^2}{4}$$

Now let's look at the frequency spectrum resulting from the line encoding. This is shown in Figure s2 and is again based on the assumption of the same number of ones and zeros over a time. The unipolar and bipolar encoding methods produce the same spectrum. The immediately obvious problem is that the spectrum extends well into low frequencies and potentially DC. What it means is that such encoding is not suitable for systems—such as MIL-STD-1553B—in which AC coupling by transformers is used.

Bipolar encoding fixes this low-frequency spectrum problem by mapping logic 1s alternatively to +A and –A. Logic 0s remain at zero level. For a datastream with period *T*, the frequency spectrum of the bipolar line code is centered on 1/2T.

Recovery of timing is another important attribute of a line-coding scheme. This is usually done by the receiver monitoring data transitions at the edge of the bit intervals. The problem arises when there is a long string of zeros or ones, which results in the absence of transitions. Under such conditions the receiver may lose its synchronization. This problem is somewhat alleviated in bipolar encoding, where ones are represented by alternating voltage, but a long string of zeros still poses the problem. In some telephone transmission protocols, this is resolved by placing a limit on the maximum number of consecutive zeros that may be transmitted. If a number of zeros exceeds the limit, it's encoded in a special sequence containing ones and zeros identified by a flag that is an invalid bipolar code. Two ones that don't alternate polarity is an invalid code.

Another problem with polar coding is that a system error could cause all zeros to be detected as ones and all ones as zeros. This can be avoided by mapping the binary

information into transitions at the beginning of each interval. This is depicted as differential NRZ encoding in Figure s1. Ones are encoded so that the signal transits; zeros are represented by no transition. The frequency spectrum extending to low frequencies will continue to limit the system application, and errors will tend to occur in pairs, because an error in one bit will provide a wrong reference for the following bit.

Bipolar encoding has been used in long-distance transmissions lines, because it has good bandwidth efficiency. In LANs, where the distances are relatively short, the bandwidth efficiency is less important than the cost of equipment. Therefore, Manchester encoding has been used in Ethernet and token-ring LAN standards. It's a synchronous clock encoding technique, where the binary data are not sent as a sequence of ones and zeros—such as in the NRZ encoding—but the bits are translated into a more advantageous format.

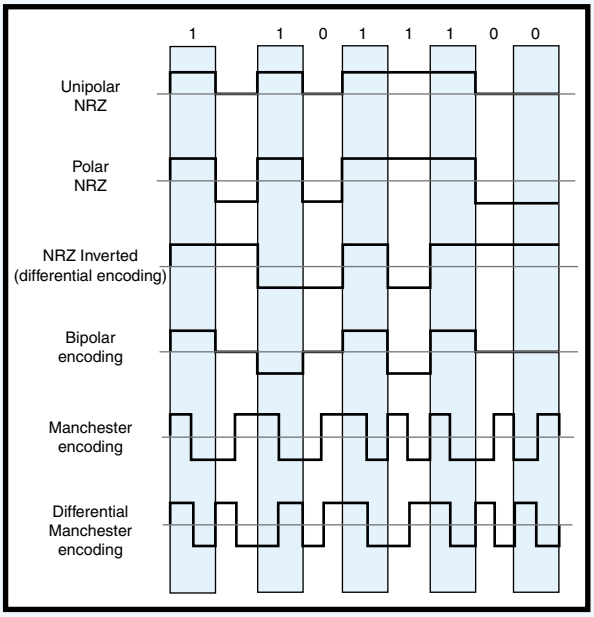


Figure s1—*There are several popular encoding techniques. The drawing shows different representations of binary sequence 101011100.*

In Manchester encoding, a logic 1 causes a negative voltage transition in the middle of the bit interval, and a logic 0 causes a positive transition (also in the middle of the bit interval). To ensure that rule for multiple ones or zeros, the voltage may have to transit back at the beginning of the next bit interval to be ready for the appropriate transition in the middle. Thus, the fundamental Manchester code weakness (i.e., the double pulse rate as compared to polar encoding). As you can see in Figure s2, its frequency spectrum is twice as high as that of the other techniques because each binary bit requires two pulses. Because this could be viewed as a transition at 90° phase, Manchester code is sometimes referred to as a biphase code. You can imagine that, in reality, "01" represents a binary 0 and a "10" sequence a binary 1.

Differential Manchester code is used in token-ring networks (see Figure s1). It retains the transitions in the middle of every bit interval, but the binary data is mapped into the presence or absence of a transition in the beginning of the bit interval. Binary 0 is shown as a transition in the beginning of the interval; binary 1 is marked by the absence of a transition.

If the bandwidth is not at premium, Manchester code provides excellent reliability and purely AC interface with no DC component to worry about. Because of its frequent transitions, it's easy to extract the clock using a phase-locked loop (PLL) receiver.

Remembering that in Manchester code two transmitted pulses represent a single data bit, a binary pattern of 0111001 encodes as 01 10 10 10 10 01 01 10. An interesting situation occurs when the binary data pattern is 101010 (and so on). This encodes as 10 01 10 01 10 (and so on). This preamble sequence encodes in a 10BaseT Ethernet network to a 5-MHz square wave, which is extremely distinct and excellent for receiver clock synchronization.

Ethernet LAN, which uses the 10BaseT physical layer, operates at 10 Mbps. It uses Manchester encoding and, therefore, a bit rate of 20 million pulses per second. The transmission cable length is limited to 100 m (about 330'). To put this in perspective, the signal travels along a coaxial cable at approximately 0.77 times the speed of light (300,000 km/s); therefore, a bit occupies 23 m of cable, and the smallest frame would be 13.3 km. The propagation speed along a twisted pair is lower—approximately 0.59 times the speed of light. Increasing the bit rate (e.g., using 10BaseT) decreases the time available to send each bit into the wire, but doesn't affect the propagation speed.

The 10BaseT Ethernet is a different story. As you know, Manchester encoding is inefficient with its use of bandwidth. For 10BaseT running at 100 Mbps, it would require a rate of 200 million pulses per second, notwithstanding the accompanying problem with higher electromagnetic interference (EMI). Therefore, other more sophisticated line-encoding schemes were developed for the fast Ethernet.

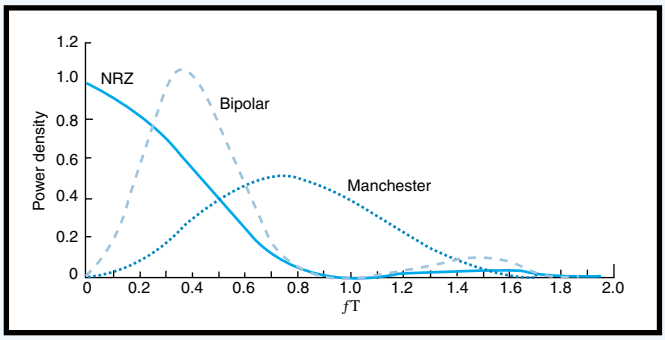


Figure s2—*Manchester encoding has a great effect on the frequency spectrum of the signal. The spectrum shown here assumes the same number of ones and zeros over time.*

REFERENCE

[1] A. Leon-Garcia and I. Widjaja, *Communication Networks: Fundamental Concepts and Key Architectures*, McGraw-Hill, New York, NY, 2000.

Looking at Figure 3, you can immediately see one feature that sets MIL-STD-1553B apart from most others: it's dual redundant. Although this is not always a specific requirement, most of the systems in critical applications are dual redundant. Remember its military pedigree. You just can't afford to have a single bullet sever a single wire and bring down a multimillion-dollar F16. So, two wire pairs connected through two stubs to two monolithic transceivers (XCVR) in the remote terminal chip. But you must remember that the dual redundancy of the data bus doesn't mean the system itself is dual redundant. When dual, triple, or more redundant systems are used, each one has the dual-redundant 1553B interface. Thus, a dual-redundant system has four wire pairs (buses) to communicate.

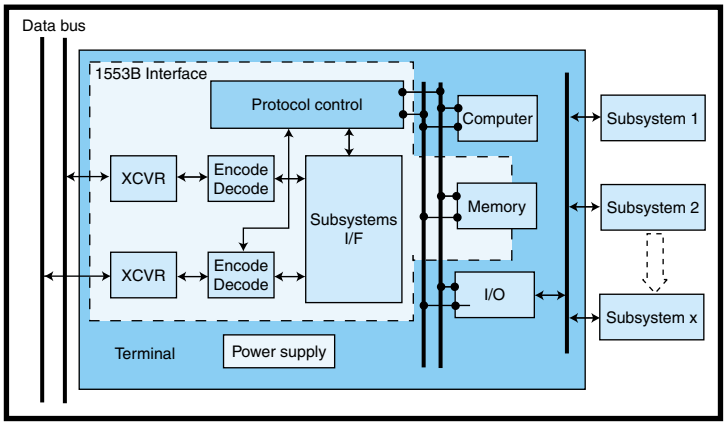


Figure 3—*A typical remote terminal includes the 1553B bus interface, microprocessor, and a number of subsystems. The bus interface is generally purchased in the form of a dedicated IC (as you can see in Photo 1).*

The chip looks after the resource-intensive encoding and decoding in addition to the bus's electrical interfaces (i.e., receivers and drivers). The remote terminal is responsible for buffering the messages and validating them; usually, it's memory mapped to an external microcomputer bus while sharing its memory. It unloads the microprocessor of all communications chores, merely accepting from and placing on the internal data bus the communicated data. It strictly follows the bus controller commands (i.e., speaks only when spoken to, and acknowledges the receipt of valid data within a predetermined time window).

The subsystems in Figure 3 can be literally anything you want them to be—any device that needs to communicate with other devices and share data in a large system (e.g., sensors, actuators, indicators, command interfaces, you name it). Typically, a number of "black boxes"—one of them might be a landing gear control unit, another a fuel management system—would be on the network run by the mission computer. Each one of those units might have several subsystems (e.g., braking, nose wheel steering, etc.).

BUS CONTROLLER

The bus controller is in charge of all of the traffic on the bus. It can be an integral part of the mission computer, fire-control computer, and so on. The fundamental part of the hardware is no different from the remote terminal, because the bus controller must send and receive data from the bus just as the remote terminals. The bus controller functionality is performed by software (firmware), which is usually external to the interface chip. Obviously, only one controller can exist on the bus.

Today, several bus controller architectures exist. The simplest and oldest one—the word controller—transfers one word at a time. It's primitive, and you would be hard pressed to find one still in operation, but it should be mentioned for completeness.

Message and frame controllers are prevalent today. Message controllers put out one complete message at a time, and are capable of performing many error-correction and fault-recovery activities internally while passing on more complicated functions to the computer. Frame controllers can process several messages at a time; they essentially unload the external computer from all communications activities. The bus controller's architecture is not defined by the standard, only its activities, so it's left up to the equipment designer to find the most effective approach. The details of the message and/or frame structure and sequencing that must be performed by the bus controller are beyond the scope of this article; however, they're well defined in the documentation that I've listed in the resources section of this article.

BUS MONITOR

The purpose of the bus monitor is to listen to the chatter on the bus. The only difference between the bus monitor and a remote terminal is that

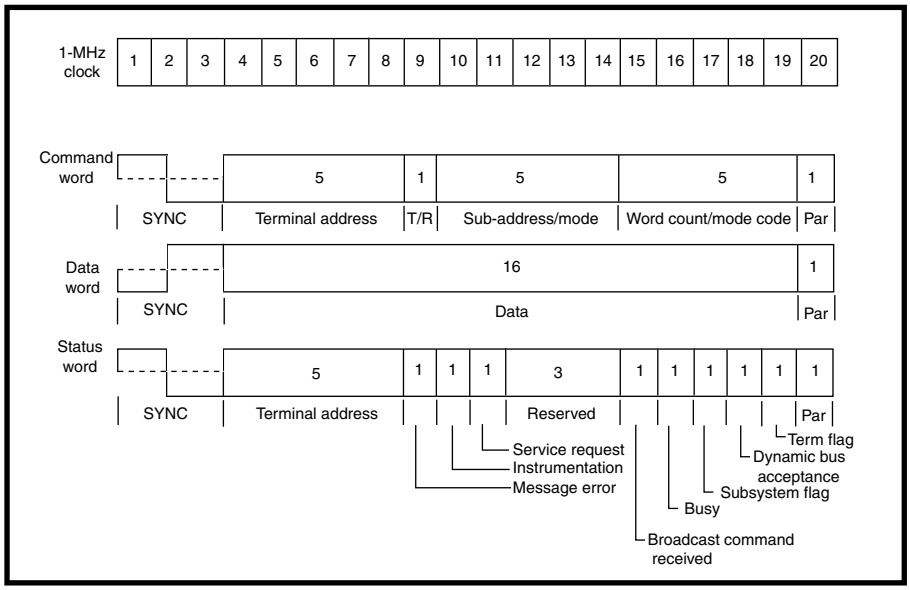


Figure 4—*Three distinct 20-bit words are exchanged on the 1553B data bus: command, data, and status. Command, data, and status have individual bit assignments.*

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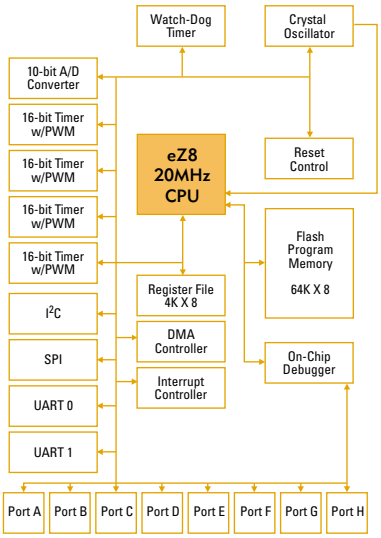
Hardware
- Evaluation Board
- Target Interface Module Board
- Serial Cable
- Universal Power Supply

Software
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- Sample Code
- Device Drivers
- Documentation CD

THE Facts

Z8 Encore!™ will be available in all standard flash memory configurations from 4K to 64K. Incorporated into new designs or upgrading from existing 8-bit (including Z8®) architectures, this next-generation MCU has features and performance that leaves the competition in the dust.

The New Z8 Encore!™ MCU Block Diagram



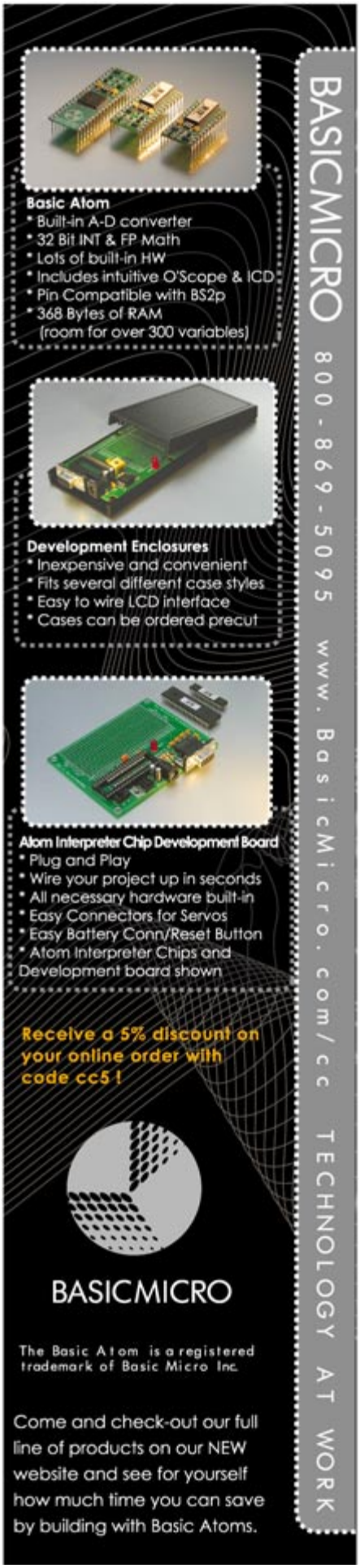
FEATURE	ZILOG Z8F6403	MOTOROLA MC68HC908AS60A	ZILOG Z8F3202	MOTOROLA MC68HC908GP32
Actual CPU Speed	20MHz	8MHz	20MHz	8MHz
On board DMA	Yes	No	Yes	No
High Speed Flash	64K	60K	32K	32K
SRAM	4K Bytes	2K Bytes	2K Bytes	512 Bytes
A/D Converter	10-bit	8-bit	10-bit	8-bit
SPI & I²C	Both	No I²C	Both	No I²C
UARTs	2 (9-bit)	1 (8-bit)	2 (9-bit)	1 (8-bit)
16-bit Timers	4 Multi-mode Independent Timers	2 Multi-channel Synchronous Timers	4 Multi-mode Independent Timers	2 Multi-channel Synchronous Timers

This comparison is valid as of 9/27/2002.

Z8 Encore!™ Flash Microcontrollers

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the former of the two does not transmit. For this reason it cannot be used for active participation in the system, because it violates the protocol by not being able to respond to valid data. So, it's found supplying data to flight recorders and back-up receivers, providing feedback to the bus controller, testing, and so on.

Often, the bus monitor hardware is identical to a remote terminal, functioning as a remote terminal on data specifically addressed to it as it records all of the other data. It can also be found as a back-up bus controller or a critical remote terminal, monitoring the bus traffic until it needs to reconfigure itself and become an active participant in the system.

PROTOCOL

The bus traffic carries three types of words: command words, data words, and status words. Let's take a closer look at their structure, which you can see in Figure 4. All words, regardless of their designation, start with a 3-bit synchronization sequence and are 20-bits long. The last bit is always a parity bit. Its odd parity is based on the single word.

The 3-bit sync field is an invalid Manchester code waveform with the transition occurring in the middle of the second bit. It allows the decoder clock, usually a phase-locked loop (PLL), to resynchronize with the transmitter. Notice that two distinct patterns are used (see Figure 4). The command and the status word sync sequences start with the positive level and the data word sequence is inverted.

The command word, which starts every message, defines the functions expected from the remote terminal. Following its synchronization preamble is a 5-bit terminal address (TA) for routing the message. Terminal addresses 00000 through 11110 are valid, and 11111 is reserved as a broadcast address. Neither the bus controller nor the bus monitor requires an address; therefore, 31 remote terminals can be in a network. The standard requires that the remote terminal address is externally programmable. In practice it means that the five bits are accessible on a connector and

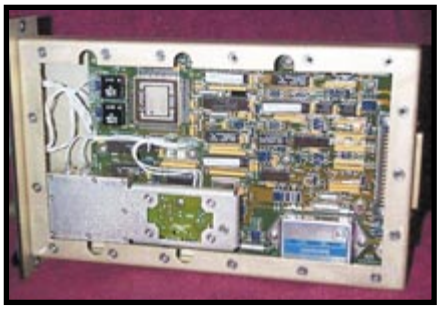


Photo 2—*The remote terminal is an embedded part of a control subsystem.*

externally strapped to ground for "0." Open circuit is decoded as "1." The remote terminal is required to verify the address by odd parity, because of field experience where high vibration levels—such as those encountered during the firing of a missile—resulted in address corruption.

The T/R bit defines the direction of the information flow from the point of view of the remote terminal. A logic 1 signifies that the remote terminal is about to transmit. Five subaddress (SA) or mode command bits follow the T/R bit. 00000 and 11111 signify that the following command is a mode code command. All other addresses route the data to different subsystems and functions within the system, as shown in Figure 3. For example, 0001 may be position command, 00002 position feedback, and so on.

The next five bits define the number of words in the message (up to 32) or—in case the previous five bits having value 00000 or 11111 indicated the mode code command—indicate the mode code to be performed. And, as I've already explained, the last bit is an odd parity bit.

The data word also starts with the sync preamble, albeit inverted, starting at the negative level. It's followed by 16 bits of data, the actual information I want to be transferred by the message, with the first transmitted most significant bit (MSB). The word is again finished with an odd parity bit. Although a lot of freedom is given to the utilization of the message bits, there are guidelines for use in military systems. Use the resources at the end of this article to learn more about these guidelines.

The status word confirms to the bus controller that a valid message has arrived, and it substantiates the remote

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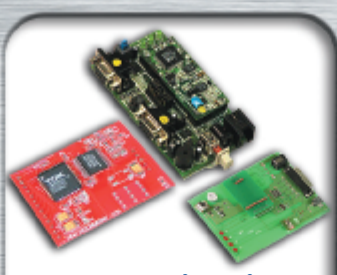
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terminal's status; therefore, the bus controller never transmits it. As the command and data words, it also starts with the synchronization pattern. Generally, the status word is reset and reassembled after receiving a valid command in order to indicate the updated status. Here again, refer to the documents listed in the resources section of this article for additional details. The sync sequence is followed by the 5-bit terminal address to identify the source.

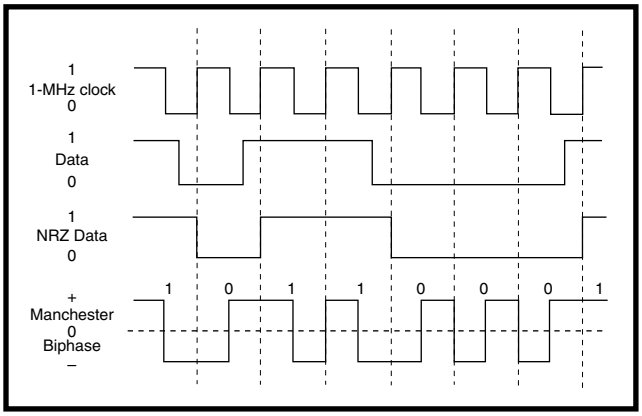


Figure 5—*This timing diagram explains the Manchester biphase encoding used by the MIL-STD-1553B protocol.*

The message error bit's purpose is self-explanatory. The bit is set to indicate error. Because both the command word and status word have identical synchronization patterns, the instrumentation bit is used together with the two possible mode identifiers (00000 and 11111) in the command word by the receiver to distinguish between the command and status words. This still presents a problem with bus monitors. Because the instrumentation bit is the MSB of the command word subaddress, half of the possible subaddresses are lost.

In new systems, monitors are smart enough to determine whether the word is command or status by merely following the bus traffic. In systems where the bus controller polls the network subscribers, the service request bit (when set) informs the controller that it needs to talk. The reserved bits are for future growth and must be set to zero. If any of these bits are set, the bus controller indicates error.

The purpose of the broadcast command received bit is self-explanatory. The busy bit was needed in the early days when terminals were unable to process data at the speed it arrived, but it's seldom required today. The subsystem flag is the terminal's health indicator, and the dynamic bus control acceptance bit confirms that the dynamic bus control mode code has arrived on the bus and has been accepted by the terminal. Generally, the remote terminal will set the bit as a result of passing some diagnostics and then become a new bus controller. The incumbent bus controller, having received the status word with the bit set, ceases to function as the controller and may, for instance, revert to a remote terminal.

The terminal flag set to one indicates an internal terminal fault to the bus controller. And finally, the last bit is again an odd parity bit of the status word.

SIGNAL CHARACTERISTICS

During transmission, direct-coupled drivers output a waveform 6 to 9 V_{PP}. Transformer coupling requires the electronics to output 18 to 27 V_{PP}. The signal is allowed no more than 5% distortion with 100- to 300-ns rise and fall times. Conversely, the receiver will work well with input levels of 1.2 to 20 V_{PP} for direct coupling and 0.86 to 14.0 V for transformer coupling. The input impedance of the receiver needs to be about 1000 Ω for direct and 2000 Ω for transformer coupling with the input circuitry common mode rejection (CMR) of ±10 V peak at frequencies from DC to 2 MHz.

Transmitted bits are encoded in biphase, Manchester II format, as is depicted in Figure 5. The major advantage of the waveform generated in this format is that it is self-clocking, and the bit sequence is independent. What's more, the positive and negative excursions of the signal are balanced, so there's no remaining DC-level component and the signal can be efficiently coupled through transformers.

Looking at Figure 5, you can see that the signal transitions always occur in the middle of the bit time. In this format, logic level 0 is encoded as the negative-to-positive transition of the waveform; logic 1 is a positive-to-negative transition. (See the Line Coding sidebar for additional information.)

A FINAL WORD

With this article I've tried to introduce you to the fundamentals of the MIL-STD-1553B communications protocol. This is the precursor to many of the protocols used today. And yet, despite its age, it's still used whenever reliable data communications under severe environmental and EMI conditions are absolutely necessary.

This article is far from exhaustive, but dwelling on the operational details would've made its size unmanageable and obscured the engineering concepts you'll need to understand in order to appreciate the new protocols that are currently being introduced into service. If you're interested in the details, take a look at the resources that I've provided.

George Novacek has 30 years of experience in circuit design and embedded controllers. He is currently the general manager of Hispano-Suiza Canada, a division of Snecma Group of Companies, the world's leader in manufacturing propulsion and landing-gear systems. You may reach him at gnovacek@nexicom.net.

REFERENCE

[1] Ponsor Corp., "MIL-STD-1553B Tutorial," Version 3.10, Ponsor Corp., San Diego, CA, 1992.

RESOURCES

U.S. Department of Defense, MIL-HDBK-1553A, *Multiplex Applications Handbook*, November 1988.

———, MIL-STD-1553B, *Aircraft Internal Time Division Command/Response Multiplex Data Bus*, Notice 1 and Notice 2, September 1978.

MIL protocols, www.dsp.dla.mil.

APPLIED PCs

Fred Eady

Test-Driving the Z8

Do you remember your first experience with the Z80 microcontroller? Some things sure have changed over the years. Follow Fred as he looks to the past and future while test-driving the easy-to-use, inexpensive Z8 Encore! development kit from Zilog.

It wasn't too long ago when we were all praising the king (the Z80) in his court (the Tandy computer center). Radio Shack and Tandy had suddenly taken the market with the introduction of their TRS-80 PC line. Running at just below its 2.5-MHz clock limit (2.03 MHz), the TRS-80 Model 3—equipped with a Z80, 16 KB of RAM, a version of BASIC in 14 KB of ROM, a monochrome video display, and a floppy drive—cost you about $1000. You could walk into just about any Radio Shack and walk out with one in hand.

I remember the "computer specialist" at my store once said, "Man, the new 4-MHz models are coming out soon. I don't know if our software can keep up." He drove a Cadillac; and yes, I was one of those sales-floor guys at Radio Shack. I was known as "The Wizard" in those days. It's amazing what knowing the resistor color codes can do for your career. One time, when the boss saw that I could operate the store demo, he put the TRS-80 in the window in an attempt to attract the attention of passersby by having me play games during my downtime. And, for you guys and gals working today's computerized Radio Shacks, we would write all of our tickets by hand, including the big ones for TRS-80 Model 3s.

For those of us (employee or customer) who couldn't afford a shiny steel-gray TRS-80 Model 3, there were the Z80 micro, 2716 ultraviolet-erasable EPROM, 74LS04-driven clock generator, 2-KB chunk of relatively expensive static RAM, 74LS138 address decoder, and 74LS244 and 74LS373 for I/O and Z80 assembler code. Back then about the only thing that a homemade Z80 embedded system had in common with Radio Shack was the perf board it was built on.

I can recall purchasing a Z80 cross assembler for my PC for $450. (Yeah, I really wanted it bad, didn't I?) The idea was to be able to write the Z80 source code on my PC and assemble it with the PC so that I could load the resulting Z80 object file directly into my EPROM programmer, which was also attached to my PC via a proprietary plug-in card. Using this configuration, I could actually write the Z80 mnemonics and have the PC do the compiling and linking work instead of hand-assembling hexadecimal Z80 machine instructions. Boy, I had arrived! At that time, my Z80A projects were sometimes running with a clock that was as fast as my PC's clock.

Today, for as little as $49 (at the time of this writing), you can purchase a Z8 Encore! development kit containing a 20-MHz, Z80-like device (i.e., Z8F6403) running at 18.432 MHz with 64 KB of embedded flash memory to replace the EPROM and the ultraviolet EPROM eraser, 4 KB of native SRAM (which eliminates that external SRAM IC and address decoder), and most of the goodies found on the original Z80 (e.g., DMA, timers, and so on). In fact, the Z8 Encore! microcontrollers sport their own set of on-chip UARTs and A/D converters; however, the dynamic RAM refresh feature of the original is nowhere to be found on the new models.

THE Z8 KIT

The Z8 Encore! development kit is more useful for learning about the basic Z8 hardware and experiment-

ing with the code than anything else. There is no breadboard area with the exception of a couple of spare SMT pads. The only way to get the Z8F6403 out of the house is by way of a couple of dual-row expansion headers.

My Z8F6403-based development kit, shown in Photo 1, came standard without the optional Conexant SocketModem. The second Z8F6403 UART is pinned to the Conexant modem socket. Because the modem is an option and I don't have one of the SocketModems in the Florida Room, I won't be dialing up anything using a Z8F6403 and Coexant SocketModem this go around.

To augment the dual-row expansion headers, a Philips PCA8550 is incorporated on the development board. The PCA8550 is designed to allow PC chipsets to perform "jumperless" configuration operations on motherboards. Basically, the PCA8550 is 4 bits of input and 4 bits of output multiplexed between an I^2C input and 4-bit bus input. The PCA8550's other features include a fifth non-muxed latched output bit and a write-protect line for the I^2C interface.

On the development board, the PCA8550 4-bit input bus isn't connected, and three of the four output bits are terminated on one of the dual-row expansion headers. This allows you to use the Z8F6403's on-chip I^2C engine to twiddle the 3 bits on the expansion header (i.e., ID_0, ID_1, and ID_2) using the services of the PCA8550.

The console connection (wired DCE) is under control of the first Z8F6403 UART and shares the communications lines with the on-board Zilog ZHX1810 IrDA encoder/decoder (Endec). The IrDA interface is designed to allow you to optically tie the development board to a PDA or similar device that's capable of short-range (1 m or less) infrared communications.

The services of both UARTs also can be used to establish a couple of RS-485 links if you so desire. In addition, the second UART is wired as a DTE for direct connection to an external modem via a male nine-pin shell connector. The multiple interfaces attached to each UART are mutually exclusive with respect to the UART the shared interfaces are attached to.

A special six-pin debugger port on the development board mates with the Target Interface Module Board you see in Photo 2. The Target Interface Module Board is simply a MAX3232 RS-232 interface IC and a single buffer Philips 74LVC1G125. The tri-state-capable 74LVC1G125 can handle both 3.3- and 5-V inputs. The combination of the MAX3232 and 74LVC1G125 transforms the PC's two-wire (i.e., TX and RX) serial interface into a one-wire serial interface at the Z8F6403's debug (DBG) pin.

The on-chip debugger (OCD) is yet another feature of the new-generation Z8F6403. The OCD interface is configured as a single-pin, bidirectional, open-drain, half-duplex transceiver. To keep it as simple as possible, the OCD uses a standard start-stop asynchronous data format; it's designed to connect to a PC's serial port using a minimal amount of interface hardware. All you really need is a pull-up resistor and a blocking diode (or tri-state buffer like the 74LVC1G125) to use the OCD. The whole scheme works on pulling one side of the 10-kΩ pull-up resistor to ground for zeros and leaving it alone for the ones. Also, it doesn't allow the transmit and receive signals to influence each other in the process.

The Z8F6403 can speak to other computers or micros using one-wire and two-wire dialects. It should be no surprise that the flash memory generation of Z80s can also speak four-wire-ese. The on-chip four-wire SPI interface is directly connected to a Dallas/MAXIM DS1722 digital thermometer. Although the DS1722 will work in both standard three-wire and SPI modes, the Z8F6403 only does SPI. With a little programming, you could enable a separate three-wire interface.

Another feature not found on legacy Z80 parts is the 10-bit, analog-to-digital converter. The Z8F6403 multiplexes 12 analog inputs with general-purpose I/O pins. The reference voltage for the ADC block is either generated internally by the Z8F6430 or applied via an external voltage fed through a MAX6160 adjustable voltage reference. A direct memory access (DMA) channel can be activated to automatically take an analog reading and transfer it to the Z8F6430's register file. There are two more DMA channels that support moving data to and from on-chip peripherals such as the UARTs.

The standard pieces of microcontroller equipment (e.g., an interrupt controller subsystem, multiple timers with PWM and capture options, and a programmable watchdog timer) are all part of the Z8F6403 architecture. The Z8F6403 is a 3.3-V part with 5-V tolerant I/O. The development board includes both 3.3- and 5-V power supply circuitry to provide power to the various development board subcircuits and the Z8F6403 microcontroller. Another Dallas/Maxim part, the DS1233A, makes sure the Z8F6403 is reset properly by providing a clean 350-ms reset pulse on power-up or reset switch closure.

What is any development board without push buttons and some sort of display? Well, the development board does the standard thing with the three user-programmable push buttons and offers the unusual in the display category. Instead of using a standard LCD or multisegment LED display, this board comes equipped with four Lite-On LTP-757G 5 × 7 dot matrix displays. Individual dots on each display are illuminated using 74HCT374s to drive the rows and columns of the dot matrix displays. The LTP-753G dots are arranged as a common anode row and common cathode column. So, to light up a dot, the programmer latches in a logical low (zero) to the dot's column and a logical high (one) to the dot's row. Here's where the fun begins!

BRINGING UP THE SOFTWARE

The Z8 Encore! device that comes with the development kit is a general-purpose microcontroller with a bevy of on-chip goodies. The good news is that it's really nice to have all of those hardware gadgets to play with. The bad news is that I haven't written in

Z80 code in years, and I don't want to learn the new Z8F6403 assembler mnemonics just to be able to blink a dot on one of the Lite-On display bricks. Besides, although the kit is loaded, it's still lacking one essential ingredient, Ethernet.

Zilog offers a ready-to-roll web server with a 10BaseT Ethernet interface for approximately $800. If you don't need all of the bells and whistles on the $800 model, I'll show you how to get on the 'Net for less than $100 with the $49 Z8 Encore! development kit.

After carefully studying the physical attributes of the development board, I explored the CD-ROM that accompanied the hardware. There was just as much to learn about the example code as there was about the jillions of parts on the Z8F6403-based development board. I came into this project knowing that the development kit included a C compiler and an IDE. So, I decided to start by going after the samples to load and compile correctly.

My first brush with the Z8 Encore! IDE (ZDS II) smelled a bit like Rabbit and tasted like 8051. Like Rabbit Semiconductor's ICs, the Z8F6403 is heavily register and sub-register-based when it comes to accessing the I/O ports and its internal peripherals. That makes sense because the Rabbit micro is based on Z80 principles. I was surprised yet pleased that the look and feel of ZDS II was almost identical to the Keil C51 µVision IDE. That meant that I could concentrate on getting up to speed with the Z8F6403's lingo without having to fight the IDE.

I love debugger mechanisms; however, in my opinion, the best debugger tool when you're on the ropes is a working serial port. If you can get the C language `printf` statement to put your characters in a HyperTerminal window, then you have a means of communicating with yourself via the program code. Take a peek at previous example code that I've written for *Circuit Cellar* articles, and you'll see that I like to put debug `printf` in lines like "I made it to here" as progress markers.

So, the first thing I did was make sure I could pass data through the development board console port to a HyperTerminal session on a separate PC. Instead of reinventing the stone cylinder, I used (and modified) the `uartcode` example code to test my understanding of the Z8F6403's UARTs. The `uartcode` contains statements that initialize both UARTs, read and write to program flash memory, and exercise the `printf` function. When you run the `uartcode` code from your own Z8 Encore! development kit, you'll see something similar to Photo 3.

As I was exploring the serial I/O code and hardware, I was pleasantly surprised to find that the OCD and ZDS II debugger components worked as advertised; and just like the Keil C compiler, I had a great view of the registers, processor internals, and various segments of code and data memory. I could even open multiple memory windows to look at different parts of the flash memory or register set at the same time.

ZDS II allows you to either simulate the code or download it to the development board in IEEE-695 format through the Target Interface Module Board. Source code for a flash memory loader is included with the development kit firmware for those of you who will need to load the Z8F6403 flash memory without the help of the Target Interface Module Board.

With initial success in my back pocket, I proceeded to load and run all of the sample code on the kit's CD-ROM. A couple of the programs used the Lite-On displays to scroll messages. One message read "WELCOME TO Z8 ENCORE!" Another message started with a group of smiley face images and then displayed "XTOOLS RULES!!!" followed by the room temperature as reported by the DS1722. I found it hard to believe that the Florida Room was a perfect "25 DEGREES C," so I put my finger on the DS1722 to see if the temperature reading had actually changed. It had.

It got better and better as I went. So far, I've seen plenty of working example code. ZDS II has proven to be an effective development tool and any software developer who decides to scroll "XTOOLS RULES!!!" on his company's demo board can code with me any day.

When I thought I was really ready to break out on my own and write some code, I decided to run the main driver's demo program. As it turned out, it was probably already loaded, and I decided to do my own thing and erase it when I was experimenting with the serial code. Now I had a serial connection established to an alternate PC. When I fired up the program, not only did I get the scrolling "WELCOME" message on the Lite-Ons, I got the screen full of what you see in Photo 4. Everything that I've talked about is in the menu. Now, not only can I play, I also have the source code for enabling and using the SPI and I²C subsystem ICs. In addition, I use this program to do some manual debugging of flash memory, SRAM, and the I/O ports if necessary.

OK, I'm potty trained. Let's write some real Z8F6403 code and add Ethernet capability to the Z8 Encore! development board.

THE Z8 GOES 10/100 Mbps

After thinking things over, I decided to write the Z8F6403 code for the ASIX 10/100-Mbps Ethernet IC. By doing so, I would automatically have the basis for porting the code to the RTL8019AS because both the ASIX and Realtek parts are NE2000 compatible. Using the ASIX IC also makes the initial hardware integration process a bit easier, because I can connect the Z8F6403 development board to the ASIX development board using ribbon cable and simple IDC connectors. The Z8 Encore! development board is designed to carry a daughter expansion board; therefore, it's not as tidy as other development boards as far as the expansion header layout. So, it looks like I'll be making some special interface cables for this job.

I started the serious coding by taking from the excellent examples that come with the kit. As I was plodding through, I realized that the scent of AVR was starting to flow from my ZDS II project window. I use ImageCraft ICCAVR for my Atmel



Photo 1—*What you don't see in this picture is the serial cable and universal wall wart that also come with the development kit. (I'm using those right now.) There's a CD-ROM full of goodies inside the Development Tools case on the left along with a quick-start guide.*

projects, and like the Z8 Encore! C compiler, the ImageCraft AVR C Compiler is a true ANSI implementation. After inhaling the Atmel aroma for a few minutes, it hit me as to why I had sensed the AVR in my coding. Get this—it all rotates around another C compiler that I use for my PIC projects, CCS's PICC.

The CCS compiler is ANSI-based as well, but it's heavily flavored with specialized functions for the PIC microcontroller family. As a result, the PIC's I/O ports and internal registers are directly bit addressable by function. With the ImageCraft and Z8 Encore! C compilers, these bits are still directly manipulated, but not with microcontroller-specific built-in functions.

For instance, if I wanted to set the MSB on output PORTB of the Z8F6403, the C source would be `PBOUT |= 0x80;`. Conversely, to clear the same bit, I would use `PBOUT &= ~0x80;`. Using CCS's PICC, the PIC source would read `output_high(PIN_B7);` to set the MSB of PORTB and `output_low(PIN_B7);` to clear it.

All of these differing C statements look different but do the same things. Instead of PBOUT, which is a Z8F6403 definition, PORTB is the common corresponding definition found in an AVR include file. Substitute PBOUT from the Z8F6403 include file for PORTB and you have just ported the AVR code to a Z8 Encore! microcontroller. There's absolutely nothing wrong with the PICC implementation. If you put your mind to it, you can port PIC code to the Z86403 just as easily as you can the AVR code. You just have to do a bit more typing to get your results.

My coding afterburners are on. I can now reuse a great deal of the packet code I have created for the AVR and PIC microcontrollers to get the Z86403 on the LAN. If you stop and think about it, handling an ARP reply or sending bytes using UDP and TCP doesn't differ in concept from microcontroller to microcontroller. Sure, you have to watch your byte ordering, but if you want to talk on a LAN using Ethernet, or use the services of the Internet, an Ethernet packet had better look like the other guy's Ethernet packet. If you plan to travel on the Internet, your UDP/TCP/IP headers and checksums must adhere to today's published standards.

Fortunately, I have a field-tested packet transmission/reception data structure that I can use to build the Z8 Encore! Internet code. After I write the code to allow the Z8F6403 I/O mechanisms to put the data in and get it out of the existing packet data structure, it's a piece of cake between the I and the O. Because the packet data will reside in predetermined locations within the packet data structure, I can theoretically use my existing algorithms to do the processing. That works out perfectly.

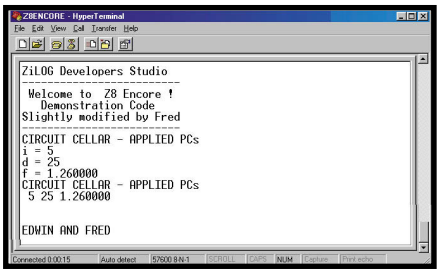


Photo 3—*This is a HyperTerminal shot showing the results of a modified demo program I used to get familiar with the Z8F6403 coding scheme and architecture. The numbers are examples of `printf` options (i.e., string, integer, decimal, and float). EDWIN was written in ASCII in a nondescript place in memory. I decided to join EDWIN in his hideout.*

GET ONE

I didn't think I would enjoy working with the Z8 Encore! development kit, because the old Z80 was a parts magnet when it came to putting a useful Z80 system together. In any case, the

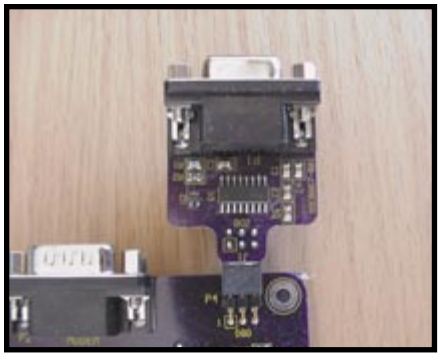


Photo 2—*Take a look at that clever little two-to-one module. It has a large rubber foot underneath it to keep it level and reduce the possibility of straining the DBG port pins.*

Z80 was an excellent microprocessor in its day. If you do some wave riding on the Internet, you'll find that there are still some guys out there riding Z80 surf boards.

I found the new Z8F6403 capable and easy to work with. During the research period for this article, I called the Zilog folks to talk about this development kit and found them to be extremely supportive and responsive to my needs. Based on what I experienced on the phone, I can say without a doubt that you won't have any trouble getting technical support from Zilog.

If you're remotely interested in the Z8 Encore! series, get yourself one of these development kits while they're still $49. There's no way you could build your own from scratch at that price. The C compiler and IDE are worth the price of the development kit without the hardware. And, the abundance of example source code is priceless.

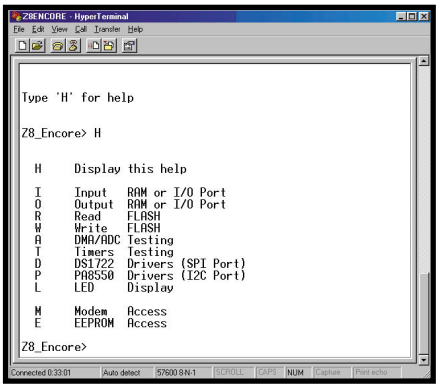


Photo 4—*You can test-drive the Z8F6403 from this console display. Choosing the LED menu item allows you to enter characters that are then automatically scrolled across the four Lite-On dot bricks.*

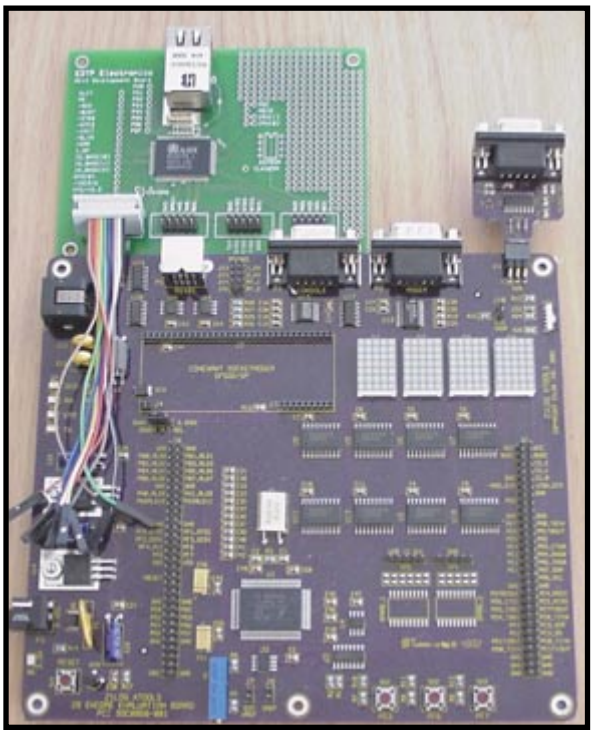


Photo 5—*As you can see, I still have a couple of special headers to assemble. After I'm finished, I'll be able to plug the 10/100-Mbps ASIX Ethernet development board into the Z8F6403 I/O subsystem and participate on the Florida Room LAN. You will get the final hookups and ported code in the download package.*

You don't have full schematics, because I just didn't have room to print them. The same goes for my source code and Zilog's. But fret not, because I'm going to leave you with the last shot of my final efforts (see Photo 5).

You may download my Z86403 Ethernet code from the *Circuit Cellar* ftp site. I'll provide an ASIX development board to those of you who want to put your newly acquired Zilog wonder on a LAN or the 'Net and prove once again that it doesn't have to be expensive or complicated to be embedded.

Fred Eady has more than 20 years of experience as a systems engineer. He has worked with computers and communication systems large and small, simple and complex. His forte is embedded-systems design and communications. Fred may be reached at fred@edtp.com.

PROJECT FILES

To download the code, go to ftp.circuitcellar.com/pub/Circuit_Cellar/2003/153/.

SOURCES

ASIX Ethernet development board
EDTP Electronics
(800) 499-3387
www.edtp.com

RTL8019AS
Realtek Semiconductor Corp.
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www.realtek.com.tw

Z8 Encore! development kit
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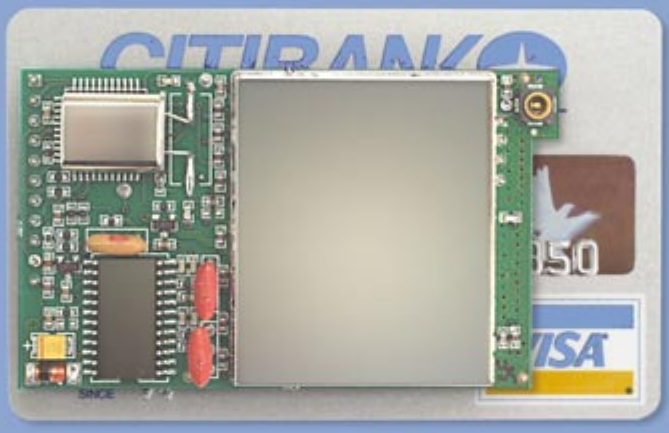
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FEATURE ARTICLE

Bruce M. Pride

Portable MSP430 DMM

To develop and debug electronic control-based systems, Bruce designed a portable DMM. By combining multimeter functions and a power supply in a single device, he has logic-level detection and point-to-point continuity capabilities, and can power breadboard circuits.

Participating in a *Circuit Cellar* competition like the MSP430 design contest allows you to try out the latest and greatest devices and their supporting development environments. This has been the case for all of the contests that I've entered (i.e., Z183, FPSLIC, and MSP430), and the Gadget-o-Rama contest was no exception. By using new devices and tools that you wouldn't normally use at work, you become more flexible and aware of what's available on the market. By the end of the project, you've learned enough about the device and toolset to know if you'd ever consider it for your future endeavors. This comes in handy if you're the lucky one who gets to pick the microcontroller for your next project! If you work on embedded systems for a living, you can never have enough in your bag of tricks, that's for sure.

Deciding what to design is usually the hardest part. My number-one requirement for a project is that it should be able to provide some sort of use later on. This was definitely the case for my PDA²-430 project (i.e., Programmable Digital-to-Analog Assistant with MSP430). I had always wanted to build a device that combined useful power supply and multimeter functions in one unit. The PDA²-430's power supply allows me to power breadboard circuits, and its multimeter functions give me basic point-to-point continuity and logic-level detection capabilities. Oh yeah, I also wanted it to be smaller than a typical portable DMM. Sound like an interesting device? Good, then let's take a look how the design works.

THE SYSTEM

The PDA²-430 is a hand-held, battery-powered (or DC input) DMM (see Photo 1). Useful power supply and multimeter functions are combined in one unit. I selected functions that would be the most useful for developing and debugging electronic control-based systems.

The user interface and LCD provide an easy-to-use, menu-driven interface for controlling the power supply and DMM functions. The power supply is digitally programmable from 0 to 30 V in 0.5-V increments. This range satisfies the voltage requirements of many devices (e.g., breadboard circuits, circuit board assemblies, and sensors).

The DMM functions consist of a continuity tester and logic probe. The former provides basic point-to-point testing for verifying device nets such as PCB board traces and cable/harness assemblies. In contrast, the logic probe verifies voltage levels greater than or



Photo 1—*The PDA²-430 design fits nicely inside an off-the-shelf DMM enclosure. This allows the device to be handled and used like a typical DMM. Also, notice the LCD and keypad, which make up the intuitive user interface. This makes navigating through the PDA²-430 menu structure a breeze.*

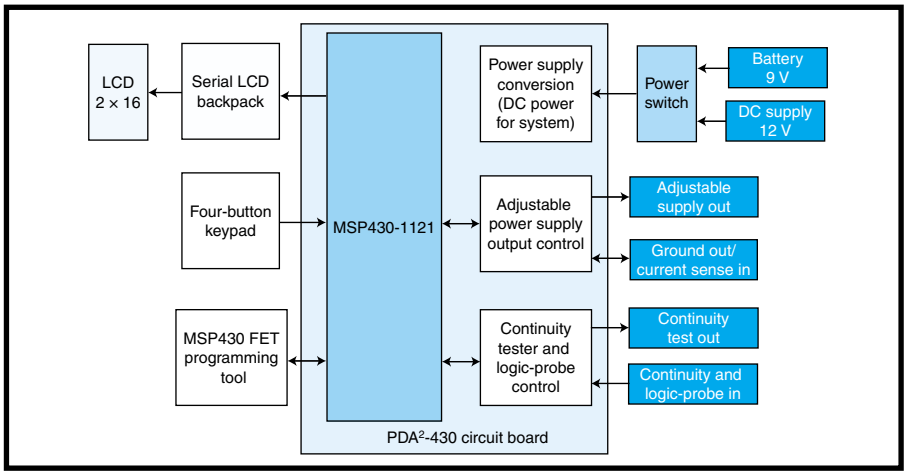


Figure 1—*This block diagram shows just how much work the MSP430 does—nearly all of it! The MSP430 has a little help from a serial LCD backpack, because of the limited I/O on the 20-pin part that was used. Besides that, the MSP430 took care of the rest.*

equal to logic levels, and it can even detect switching at lower frequencies.

So, given the PDA²-430's capabilities, how can you use it in system development? Because the PDA²-430 combines power supply and DMM functions, it can replace bulky lab power supplies and basic multimeters. By having one device, lab space is saved, and a cost-effective solution is obtained for technicians and engineers.

Most of the time during system development, power supplies and DMMs are required to both power and measure devices (e.g., sensors) and circuits that are undergoing evaluation. In my experience, these devices usually are low power (i.e., less than 3 W) and don't require a high-wattage power supply. Also, only basic DMM functions are needed to test these devices. This is where the PDA²-430 comes in handy: it can power and test these devices at the same time, making it a valuable multitasking test instrument.

SYSTEM BLOCKS

As you can see in Figure 1, the PDA²-430 is made up of a control board, an LCD with serial backpack, a keypad, a battery or DC supply, and the system-test inputs and outputs. The LCD and keypad make up the user interface. The LCD shows the menu options and test screens, and the keypad allows you to navigate through the LCD menus and modify values with the keys. Note that the LCD connects to a Scott Edwards Electronics LCD serial backpack, which mounts directly behind the LCD. It accepts asynchronous, 9600-bps serial data input from the MSP430, converts it to parallel data, and then outputs it to the LCD. This removed the immediate need for controlling the LCD from the MSP430 processor, which saved time during development.

To power the PDA²-430, an off-the-shelf 9-V battery is located in its battery compartment. This battery allows the PDA²-430 to be powered without an external power supply. The battery provides power for the DMM functions but not the adjustable power supply function. For the DMM functions, the battery is a good solution that will last for quite some time, especially because the MSP430 is truly a low-power micro.

To power the PDA²-430's adjustable supply, a 12-V DC power supply is needed (i.e., a wall wart type). It can also power the rest of the PDA²-430 functions, even if the 9-V battery is left in place. This also improves battery life if the PDA²-430 is being used for long periods of time. The PDA²-430's boost power supply circuit needs more than a 9-V input to operate; therefore, adding this 12-V line powered DC supply is required.

You're provided with four outputs from the PDA²-430 (see Figure 1). Two are for the adjustable power supply, and two for the continuity tester and logic probe. The benefit of this is that you can use the power supply and DMM test functions at the same time.

The final piece in the block diagram is the MSP430 flash emulation tool (FET) connection. This allows for in-system programmability and debugging from the integrated development environment. Code updates and changes are made easily by plugging into the on-board JTAG connector.

THE MICRO

The Texas Instruments MSP430 is the 16-bit flash memory microcontroller that provides the processing brains behind the design (see Figure 2). The MSP430 and its peripherals provide the control for the power supply, DMM functions, and user interface. In addition, the micro provides 4 KB of flash memory and 256 bytes of RAM, which is more than enough for the PDA²-430.

One of the MSP430's nicer features is that it doesn't require an external crystal, because it has a built-in, digitally controlled oscillator. I used this and programmed it to a speed of 1.3 MHz. The MSP430 is definitely a versatile and well-rounded micro.

DMM AND LCD CIRCUITRY

Currently, the LCD circuitry is an interface to an LCD serial backpack (see Figure 2). There are three lines connected to this backpack: a 5-V line, a GND, and an asynchronous, 9600-bps serial line from the MSP430. The backpack itself takes care of the required interfacing for the 2 × 16 LCD. The MSP430 simply sends serial data to the backpack without caring about the LCD timing. This is perfect for initial product design, but it isn't cost-effective. I added a second MSP430 device and a connector to the board, which will take the place of this backpack in the future.

The DMM test output signal from the MSP430 is used for the DMM continuity test. A pulse is sent out through this circuit, goes through a net (e.g., wire or PCB trace), and is then read back through the DMM test input. The diodes and series resistor are used to protect the MSP430 from accidental shorts to plus or minus voltages.

The DMM test input signal from the MSP430 is used for the DMM continuity test and logic probe test. For the continuity test, a pulse is or isn't received from the DMM test output line to determine if a short or open condition exists. For the logic probe test, the MSP430 looks for a high-

level signal to determine if the input is high or low. The diodes and resistors provide protection for the MSP430, but they also allow the logic probe to input voltages much higher than logic levels because the higher voltage would be clamped.

POWER SUPPLY CIRCUITRY

The MSP430 controls the adjustable power supply using its Timer A-1 PWM capability, which is set to a 2-kHz frequency. As you adjust the voltage value via the user interface, the PWM duty cycle increases or decreases. This PWM frequency is sent through an RC network to convert the PWM frequency into a DC voltage before going to the positive input of the LM358 op-amp (see Figure 2).

The LM358 op-amp amplifies the MSP430 PWM signal, now converted to a stable DC voltage, by a gain of approximately 10. The feedback is provided by a 100-kΩ potentiometer that's set to approximately 90 kΩ:

$$A_V = \frac{R_F}{R_I} + 1 = \frac{90\,k\Omega}{10\,k\Omega} + 1 = 10$$

The LM358 op-amp is powered by the 33-V switching supply. This allows the op-amp's gain of 10 to convert the PWM voltage from the MSP430 up to the maximum required voltage of 30 V:

$$V_{OUT} = V \text{ from PWM} \times 10$$
$$V_{OUT} = 3\ V \times 10 = 30\ V$$

The output current capability of the LM358 is not enough to drive the loads required by the PDA^2-430 (e.g., 5 V at 1 A); therefore, an emitter follower transistor stage was added after the op-amp. Note that the op-amp drives the transistor, which is connected to the 33-V supply, as well. A comparator circuit was added to monitor the current draw from the adjustable power supply. The 0.22-Ω shunt resistor has a certain voltage drop given the current drawn from the adjustable power supply. The voltage drop is sent through a divider and then compared to another PWM voltage, MSP430 Timer A-2. Then, the output of the comparator is brought to an input pin of the MSP430. This feature has not been implemented in the software. I'll describe it shortly.

BOOST-SWITCHING SUPPLY

The boost-switching power supply is based on the LM2577 switching regulator. Feedback is provided via the voltage divider, which includes a potentiometer for simple adjustments (see Figure 2).

The boost-switching supply converts 12 V to 33 V. The LM2577 receives the

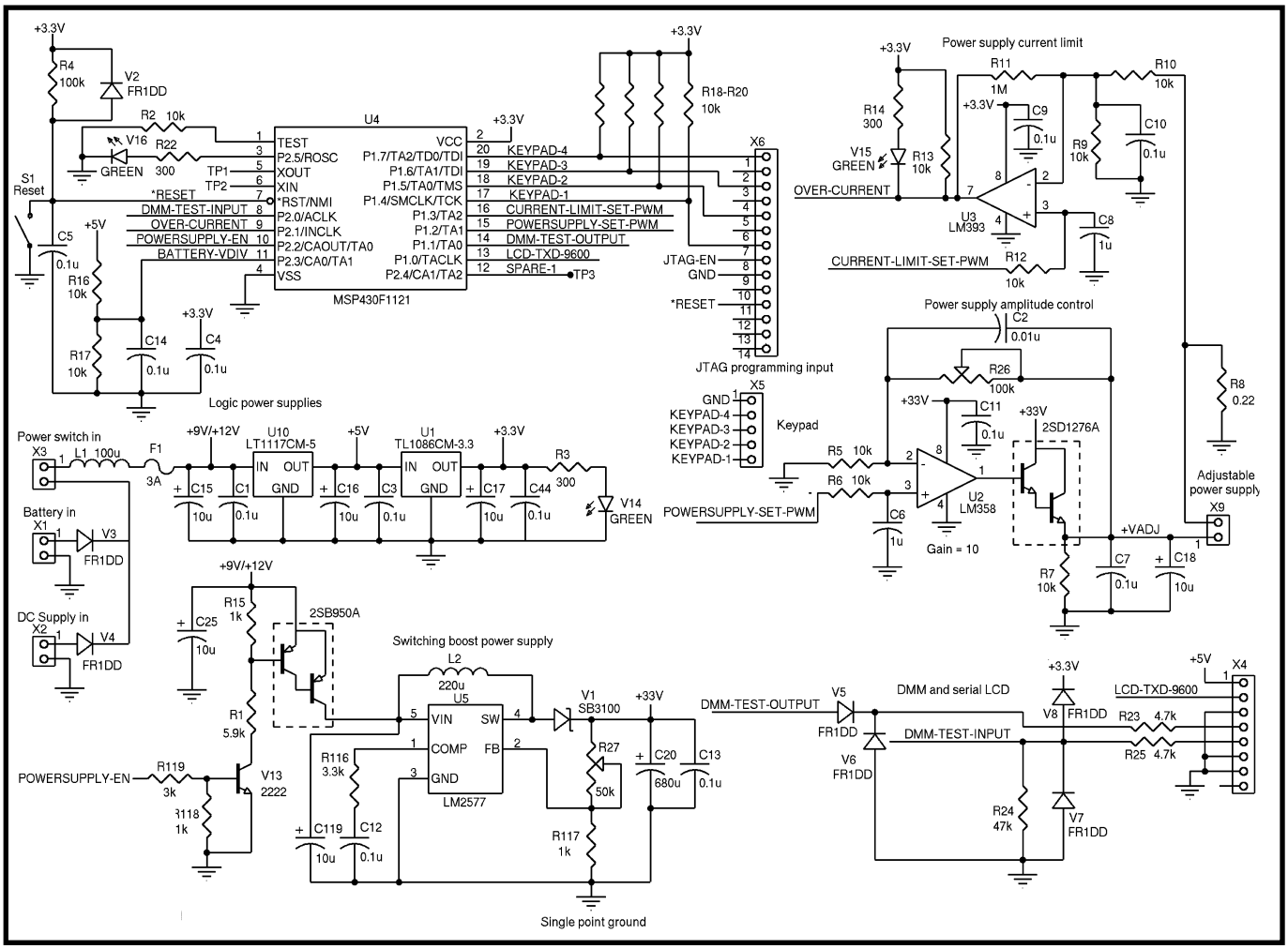


Figure 2—*The schematic reemphasizes just how much the MSP430 must control in the system. By putting more of a burden on the MSP430 and software, the hardware design was that much simpler.*

12-V input voltage from a PNP Darlington transistor, which is turned on via an NPN transistor that's controlled by the MSP430. Because you can control the switching supply via the MSP430, it can be left off when the DMM functions are the only ones in use. This cuts down on the total system current draw, because the LM2577 quiescent current is no longer a factor.

After the voltage is boosted, the 33 V is then supplied to the adjustable voltage control circuitry. Because the PDA^2-430's maximum required voltage is 30 V and the Darlington transistor stage drops 1.2 V from the collector to the emitter (V_{CE}), I had to use a voltage higher than 30 V. This is why the supply output is set to 33 V. I paid special attention to the grounding of this circuit because single-point grounding was required by the switching regulator.

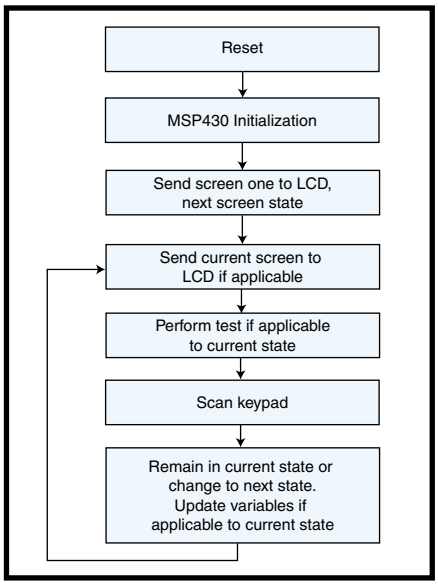


Figure 3—*Given the many menus and various functions of the PDA^2-430, it made sense to implement the software as one big state machine. By making each menu screen an individual state, the required functions are easily grouped together and kept track of. This made the software flow easy to understand and update, especially when adding or deleting menu items.*

THE PCB

Now that you know a little about the PDA^2-430's major circuits, let's talk about the PCB itself (see Photo 2). Because I was dealing with a switching supply that needed single-point grounding, I knew I should go right to a PCB design.

The PCB ended up being a double-sided, mixed-technology (i.e., surface mount and through hole) circuit board. It was developed using the ExpressPCB software package. This PCB package allows only the board to be hand routed, but the software is easy to use and, best of all, free.

DEVELOPMENT ENVIRONMENT

The PDA^2-430 software was developed using the IAR Systems Embedded Workbench for MSP430 Kickstart IDE. I needed a C compiler because I was avoiding the MSP430's native assembly language to save time and using the C programming language to implement the PDA^2-430. This IDE has a built-in compiler. Even though the Kickstart version of Embedded Workbench limits you to 2 KB of compiled code, this was ample space for the PDA^2-430 program. If your application requires additional code space, you'll need to get the full-blown version; however, you may want to look into other IDEs given the approximate $2000 price tag on this



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one. I believe ImageCraft sells an inexpensive IDE for the MSP430; it may be worth a look.

Because I used the Embedded Workbench IDE, it's worth mentioning some of its features that helped me develop and debug code on the MSP430. The device-programming feature is extremely useful. By connecting the MSP430 flash emulation tool (FET) to the target processor's JTAG port, you can download a new program in less than 10 s. This made code updates quick.

Single-step debugging gave me the ability to step through (or over) each line of code, which was useful for troubleshooting the program. The memory watch window was used to monitor various variables in certain C functions. This worked well when stepping over a function. The function could run in real time, and then the result of the function could be displayed.

Finally, breakpoints proved useful in conjunction with the memory watch window. When a certain piece of code was being debugged, I could easily break on it, and then look at the memory watch window for updates.

FIRMWARE DESIGN

The PDA^2-430 firmware performs several functions. In addition to having to set up the MSP430 and its peripherals, it must send menus and data to the LCD. Also, it must scan the keypad, control the adjustable power supply, and perform continuity and logic probe tests.

Given the aforementioned requirements, I came up with a program flow diagram of how the code should function (see Figure 3). Starting at the top of the flow diagram, the MSP430 boots up and is initialized. Then, the PDA^2-430 application code can begin. Because of my experience with generating state machines in other micros and FPGAs, I decided the firmware structure should be state machine-based. The current LCD screen determines which state the software is in, as well as which PDA^2-430 tasks will occur. Currently, there are six states to this state machine; however, because the structure of the program is based on screen states, it's easy to add or subtract states from the program as needed. This makes the firmware design understandable and flexible, which is useful for future revisions and applications.

As you know, I wrote the program with the C language. This was preferred to the native assembly language, but required extra care because it was a high-level language that required compiling. Developing the firmware produced around 20 C functions. This was the first embedded project that I implemented with C. Previously, I would first learn the native assembly language, and then figure out enough to get the system up and running. This time, however, I decided to try out a higher-level language. As a result, I have some reusable C functions that can be easily ported to my next project.

As an example, Listing 1 is the function that's called to perform the continuity test. This brute-force code is fairly simple and straightforward—it's easier to understand than assembly language. There's no doubt that I'll design my next complex micro project with C. You may download the rest of the source code from the *Circuit Cellar* ftp site.

FUTURE ENHANCEMENTS

I've already mentioned that the circuit board contains functions that are not yet implemented in software. The first function involves monitoring the battery voltage level via the MSP430 comparator input. The second provides current limiting via the scanning of an external comparators output through an MSP430 input pin. The comparator would compare this current to a PWM output from the MSP430. In addition, it will protect the PDA^2-430 from shorted outputs and loads that require too much current, because it will be able to shut off the power supply. Finally, the third function involves replacing the LCD serial backpack with a second

Listing 1—*Take a look at the C function that performs the continuity test and outputs the result to the LCD. The code deals with two MSP430 I/O bits, which are connected to the two continuity tester probes. It simply sends a signal out one probe and tries to read it on the other. If the probes are shorted together, the signals will match and a "short" will be found. If the signals don't match, it's an "open."*

```
void ContinuityTest(void)
  {
  unsigned char ContinuityPinValue;

    P2OUT |= ContinuityTestOut;       //Continuity test output high
      Delay20mS();                    //Wait 20 ms
      ContinuityPinValue = P1IN & 0x02;
      //Mask Port 1 for Continuity test in
  if (ContinuityPinValue == 0x02)     //Is it high?
    {                                 //Yes
    P2OUT &= ~ContinuityTestOut;      //Continuity test output low
    Delay20mS();                      //Wait 20 ms
    ContinuityPinValue = P1IN & 0x02;
      //Mask Port 1 for Continuity test in
    if (ContinuityPinValue == 0x00)   //Now is it low?
      {                               //Yes
      LcdCommand(199);                //Set LCD location
      SendData('S');                  //Send "Short" to LCD
      SendData('h');
      SendData('o');
      SendData('r');
      SendData('t');
      return;                         //Return from function
      }
    }
                                      //No short found
  LcdCommand(199);                    //Set LCD location
  SendData('O');                      //Send "Open" to LCD
  SendData('p');
  SendData('e');
  SendData('n');
  SendData(' ');
  }                                   //Function complete
```

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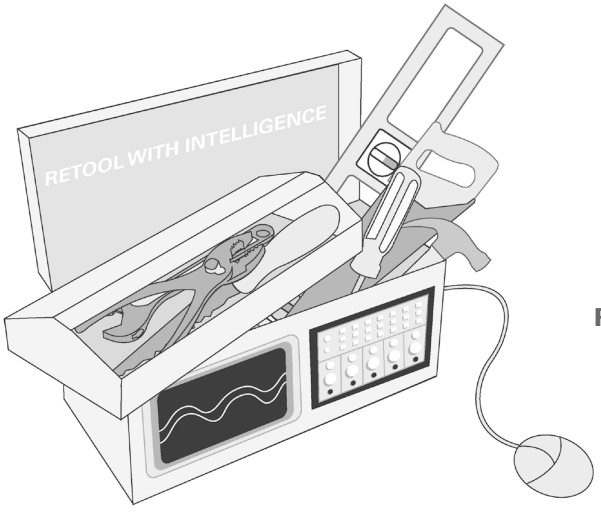
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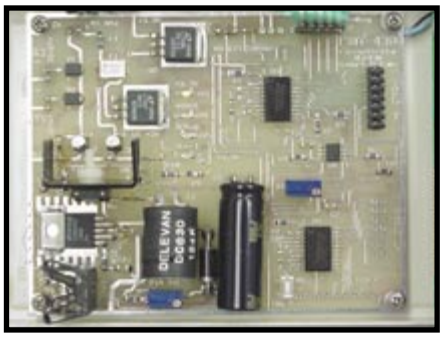


Photo 2—*The PDA²-430 circuit board had to be compact in order to fit inside the DMM enclosure. This resulted in the use of surface-mount parts in as many circuits as possible with many being on the backside of the PCB. The left-hand side of the board contains all the power circuitry, and the right hand all the MSP430 and signal conditioning circuitry.*

MSP430-1121 processor. To replace the serial backpack, a second MSP430 micro and a separate connector were hooked on to the current board. This micro would need to mimic the LCD backpack by receiving the serial data from the first MSP430 and then updating the LCD accordingly. Note that this will save system cost and provide more room inside the enclosure.

WRAPPING IT UP

This project was my attempt to make a DMM that combined useful power supply and multimeter functions into one compact, portable unit. These functions have proved themselves valuable for the development and debugging of electronic control-based systems.

To my knowledge, there isn't a multimeter currently available on the market that provides all of these functions inside one hand-held unit. This truly makes the PDA²-430 a unique and useful piece of test equipment.

Bruce M. Pride is an electrical engineer with a B.S. in Electronics. He enjoys designing embedded system hardware and software, including designs with 32-bit microprocessors, FPGAs, and various microcontrollers. You may reach him at bpride@monad.net.

PROJECT FILES

To download the code, go to ftp.circuitcellar.com/pub/Circuit_Cellar/2003/153/.

RESOURCE

Texas Instruments, Inc., "MSP43011x Mixed Signal Microcontroller," SLAS256B, June 2000.

SOURCES

ExpressPCB design tool
Engineering Express
www.expresspcb.com

Embedded Workbench
IAR Systems Software, Inc.
www.iar.com

LM2577, LM358, LM393
National Semiconductor Corp.
www.national.com

DMM Enclosure
OKW Enclosures, Inc.
www.okwenclosures.com

DMC16207N LCD
Optrex America, Inc.
www.optrex.com

LCD serial backpack
Scott Edwards Electronics, Inc.
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MSP430 Microcontroller
Texas Instruments, Inc.
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Ed Nisley

Balanced Mixing

Ed knows how important carefully controlled mixing is to radio design. This month, he'll show you how to bring some practicality and efficiency to your next radio project. So, get ready to learn what a switched-diode, double-balanced mixer can do for you.

Although RF signals can cause all manner of trouble when they mix in a corroded bolt near a receiver, radio design depends on carefully controlled mixing. The trick is to build a mixer that produces only the signals you want, when and where you want them.

In radio parlance, mixers have three ports: the local oscillator input (LO), which is pronounced "ell-oh"; the radio frequency input (RF), which is pronounced "are-eff"; and the intermediate frequency output (IF), which is pronounced "eye-eff." Mixers that are in circuits, and have nothing to do with radio, still label their ports LO, RF, and IF.

The names come from the earliest use of mixers. Those mixers shifted the radio's incoming RF signal frequency to a much lower (or sometimes much higher) IF frequency for further processing. Many radios use several mixers that produce first, second, and third (and so on) IF signals. Each intermediate frequency is chosen to optimize a specific function (e.g., filtering, amplification, demodulation, or whatever).

Remember that a nonlinear mixer modifies one input by a function of another to produce the output, and the exact function determines the output's characteristics. Often, however, the choice of function comes from what's practical rather than what's ideal.

The switched-diode double-balanced mixer (DBM) ranks rather highly in terms of both practicality and usefulness. Let's take a look at a DBM in action.

STRIKING THE BALANCE

Figure 1 shows the classic double-balanced mixer circuit. Two center-tapped transformers isolate the LO and RF inputs, while the IF output appears between the two center taps. All three signals generally will be ground-referenced as shown, but the mixer's operation does not require that.

Look again at the four diodes: they're connected in an anode-to-cathode ring, not the familiar bridge rectifier arrangement. At first glance it appears as though this can't possibly work, but the ring acts as an analog switch that's controlled by the LO input.

Suppose that pin 2 of TR1, the LO transformer, is positive with respect to the center tap on pin 3, which means that pin 4 will be negative. That voltage biases the left pair of diodes off and the right pair on. As long as the RF signal is small with respect to the LO signal, it will not affect the diode bias, so it sees both right-side diodes as relatively low-resistance elements. The opposite LO signal polarity turns the left diodes on and the right diodes off.

Half of the RF input signal appears across each half of the center-tapped secondary winding of TR2. When a positive LO signal biases the right pair of diodes on, they connect TR2 pin 2 to the center tap of TR1, which is grounded. TR2 pin 4 is effectively disconnected from the rest of the circuit because it terminates in the two biased-off

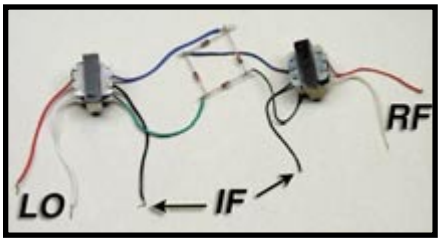


Photo 1—*A pair of output transformers and four diodes builds a serviceable balanced mixer for audio frequencies.*

diodes. Half of the RF input signal thus appears between TR2's center tap and ground.

When the LO input becomes negative, it reverses the bias applied to the diode ring, which disconnects TR2 pin 2 from ground and connects pin 4. This reverses the polarity of the RF signal, because pins 2 and 4 always have opposite polarities.

By switching the RF phase 180°, the LO input multiplies the RF amplitude by 1 or –1 on successive half-cycles of the LO. Although this may not seem like much of an achievement, it's a nonlinear effect that can produce the same frequency mixing effects you read about in my February column ("Nonlinear Mixing," *Circuit Cellar* 151).

Now things get tricky! Because the LO turns on both the upper and lower diode of each side, the RF signal appears equally at the top and bottom of the LO transformer. Therefore, TR1 cannot couple any RF to the LO port through its balanced windings. Similarly, the RF port doesn't see any of the LO signal, because the only connection to TR2 comes from the balanced halves of TR1.

The circuit also isolates the IF port from the LO. Trace the connections for both LO polarities, and verify that the IF port is connected to both halves of TR1 in such a way that the net voltage is always zero.

Surprisingly, the IF port doesn't see the raw RF either, because the RF phase flips with each LO half-cycle, and that causes precisely the frequency shift we're looking for. The only signals at IF are the mixing products of the RF and LO frequencies!

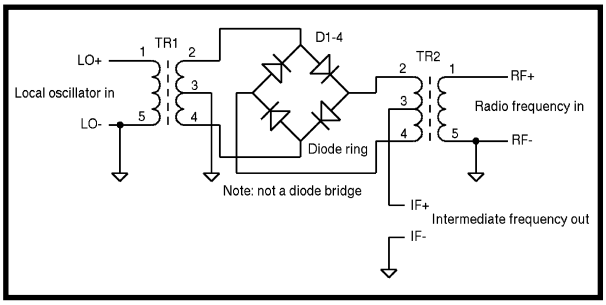


Figure 1—*The diode ring acts as a switch that connects the top or bottom half of the RF transformer winding to the LO transformer's center tap. This reverses the IF output's phase, which is equivalent to multiplying the RF by 1 or –1.*

A simple diode mixer, such as the one I examined in February, has both the LO and RF signals in its output plus all of their mixing products. For that reason, it's called an unbalanced mixer. A single-balanced mixer suppresses either the LO or RF frequency while passing the other input through. A double-balanced mixer prevents both inputs from appearing at the output. Even if the isolation isn't complete, the unwanted signal levels are low.

This mutual isolation simplifies the circuitry around the mixer. An LO signal appearing at the RF input could couple to the radio's antenna, resulting in spurious emissions, or causing unwanted mixing in other nonlinear elements. LO feed-through at the IF can be difficult to filter out if the LO lies too close to the desired IF frequencies. Any RF at the LO input can affect the stability and purity of the oscillator's output.

Achieving the precise balancing of the transformer windings and diode characteristics requires considerable effort, particularly at frequencies where parasitic capacitance and inductance become important. Exotic transformers wound on tightly specified ferrite cores, matched Schottky diodes, and symmetric layouts all contribute to mixers with up to 70-dB isolation.

As you saw in my February column, however, nonlinear mixing works perfectly well at audio frequencies, and, for demonstration purposes, I can use ordinary parts. Photo 1 shows a simple hairball-style mixer that's built from two audio output transformers and four ordinary diodes. These transformers normally match 1-kΩ drivers to 8-Ω outputs, but they're perfectly happy coupling low-level audio signals to and from a diode ring. Typical RF mixers have low-ratio windings, but you can deal easily enough with a 1:11 step-up by keeping the input levels down.

SWITCHED MIXING

Although you think of oscillators as producing tidy sine waves, the diode ring works best with a square wave LO. You can use a sine wave generator with the amplitude cranked up high enough that the clipped result resembles a square wave, but a low-level sine LO won't do the trick.

Commercial diode-switch balanced mixers are classified by the amount of LO power that's required for proper operation. Glancing through the Mini-Circuits catalog shows mixers rated from level 3 (3 dBm) to level 27 (27 dBm) LO input power. Those ratings correspond to 2 and 500 mW in a 50-Ω system.

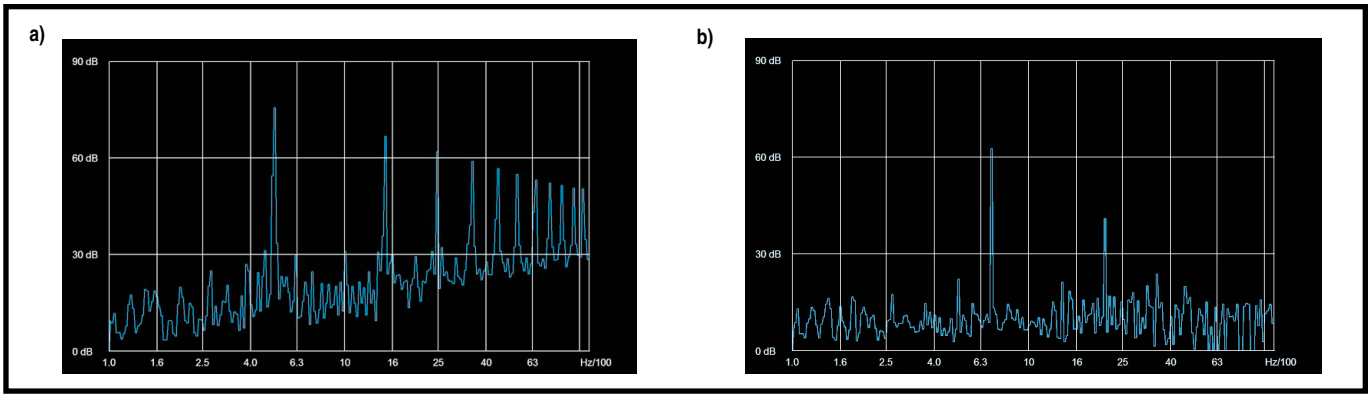


Photo 2a—*The 500-Hz square wave at the LO input shows the characteristic comb of odd harmonics.* **b—***The 700-Hz sine wave at the RF input has only one harmonic above the noise floor.*

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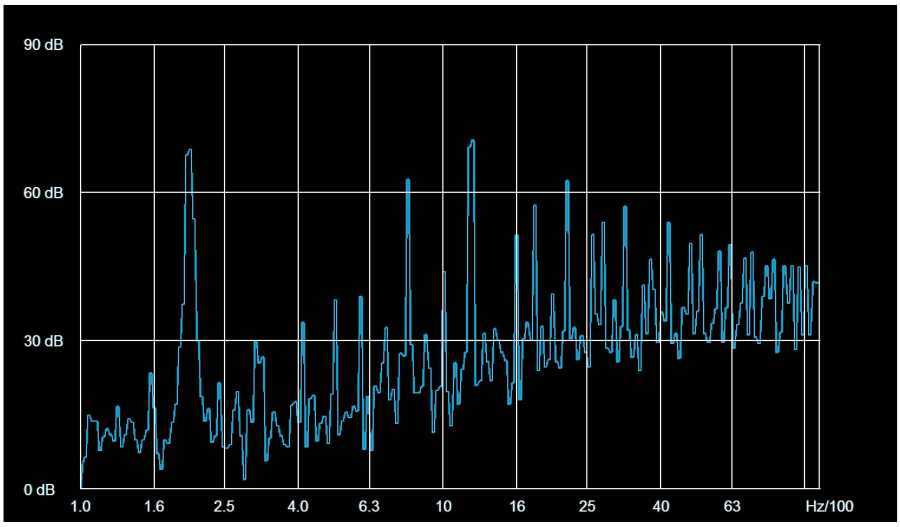


Photo 3—*The IF output has strong second-order products at 200 (700 – 500) and 1200 Hz (500 + 700). The 800- (3 × 500 – 700) and 2200-Hz (3 × 500 + 700) products are also second order from the third LO harmonic at 1500 Hz. The LO and RF inputs are 30 to 40 dB below their input levels.*

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As a result of the square or diode-flattened input waveform, the LO input's spectrum isn't a single spike at the LO frequency. I set my function generator to produce a 500-Hz square wave output. Photo 2a shows the expected series of harmonics making up a square wave. Each component will mix with the RF input to form different IF frequencies.

Photo 2b shows the sine wave RF input from my DDS generator set to 700 Hz. Its third harmonic component, about 15 dB down at 2100 Hz, will also mix with the LO frequencies.

The 90-dB logarithmic amplitude scale for these plots represents the total dynamic range available for an AC analog input digitized into a 16-bit number. The smallest possible input varies just the least-significant bit. Changing the next higher bit requires doubling the input voltage, which is equivalent to a 6-dB power increase, $20 \times \log(2)$.

Because you're looking at AC signals, the input represents a signed number with zero at midrange. The total amplitude range is 96 dB, but the largest AC peak is half that at 90 dB. If you were looking at DC signals, the total range would be 96 dB. Make sense?

Photo 3 shows the result of applying those RF and LO signals to the mixer. The two tallest peaks are the second-order products at 500 ±700 Hz. The 1500-Hz third LO harmonic mixes with the RF to form two large, second-order peaks at 1500 ±700 Hz.

Conspicuous by their absence, however, are peaks at the LO and RF frequencies. In fact, those signals are 30 to 40 dB below the second-order mixing products. The simple diode mixer I examined in my February column had huge spikes at the input frequencies, which is characteristic of an unbalanced mixer.

However, the same rules of nonlinear mixing apply to both circuits. The sum and difference of the input frequencies produce the second-order products, which means that all of the LO's harmonics contribute directly to the output. The forest of peaks on the right half of Photo 3 includes combinations of those harmonics with the 700-Hz RF frequency.

The third-order products appear at frequencies of 2 × LO ±RF and 2 × RF ±LO, along with the third harmonics of each input. When you include the fourth-order products, it's a jungle out there!

By examining this on your own PC, you can expand the frequency scale to reveal the close-spaced peaks. They occur every 100 Hz, the smallest difference between integer multiples of the inputs. The amplitude of the peaks varies widely, because several mixing products occur at the same frequency with different phases that can either add to or subtract from the final result.

FIXING THE MIX

As the names of their ports suggest, DBMs are generally used to convert incoming RF signals to a different intermediate frequency. Most radios convert a high RF frequency to a relatively low IF, where it's easier to build narrow filters that isolate the desired signal from all the other junk. In some cases, however, a high IF may better suit your purposes.

Because a switched-diode DBM produces a forest of mixing products above its square wave LO's third harmonic, it's better suited for applications that use a low IF. A glance at Photo 3 shows that a filter around 200 Hz (RF – LO) would be much easier than around 1200 Hz (RF + LO), because strong mixing products flank the latter frequency.

Mixers used at real radio frequencies, not the audio frequencies that I picked for these examples, require specific source impedances at all three ports—generally 50 Ω except in TV applications that use 75 Ω. Maintaining those impedances across all of the frequencies in use can be difficult, particularly when you must add filters to suppress unwanted signals that emerge from the various ports. RF filter design that takes into account the passband and stopband impedances demands an entire book—the *ARRL Handbook* is a good starting point.

Mixer datasheets provide the expected isolation between all three ports and the conversion loss from RF to IF. Those values depend on the actual RF and LO frequencies plus the LO drive level, so plan on spending some time poring over the numbers to ensure that the mixer actually does what you expect.

You must ensure that the RF input power lies within the mixer's dynamic range. The LO drive power, as well as the mixer's design, determines this parameter: higher RF power requires higher LO power to keep those diodes turned on, while lower RF power requires accurate component matching and a lower LO drive to reduce feed-through. The datasheet is your friend for these numbers, which are, of course, also frequency dependent.

Now, go forth and get in the mix!

CONTACT RELEASE

For this column, I used Visualization Software's Spectrogram program, because it has higher frequency resolution than True Audio's TrueRTA. Mini-Circuits has a wealth of mixer and general RF information on its web site. You'll even meet a triple-balanced mixer with excellent RF-IF isolation.

Ed Nisley, PE, is an electrical engineer and a ham radio geek (call sign KE4ZNU). You may contact him at ed.nisley@ieee.org.

RESOURCES

The American Radio Relay League, Inc., *ARRL Handbook for Radio Communications*, Newington, CT, 2002.

Mixer and RF information, Mini-Circuits, www.minicircuits.com.

SOURCE

Spectrogram
Visualization Software, LLC
www.visualizationsoftware.com



Jeff Bachiochi

Intro to Mindstorms



Give Legos to a child and get half a multicolored airplane in return. But what happens when you give them to an engineer with a micro and motors? Before answering, let Jeff introduce you to the Mindstorms RIS.

After successfully cloning MIT's programmable brick research, the Lego Company hit the market with the Mindstorms Robotics Invention System (RIS)—an event that marked the beginning of another round of attempts to bring robotics into the mainstream. Although the $200 price tag seems extravagant, those of you who've purchased Lego construction sets in the past know that its prices have always been high. Nevertheless, these sets bridge generations, and quality remains a top priority.

I was brought up on Erector sets, so I know that Legos can bring out the creativity in a user. I say this tentatively, though, because many Lego sets are theme-based (e.g., the *Star Wars* Millennium Falcon), which begs leaving the finished product to collect dust rather than using its pieces to create new designs. In order to use Legos properly, you must disassemble projects to plant the seeds of creativity.

The Mindstorms RIS has 717 Lego blocks, but the diversion comes in the form of sensors, motors, a microcontroller, an IR computer link, and child-friendly software. After you sign into the software, you're presented with a full tutorial that explains how the system works. This includes the immediate hands-on testing of each sensor and motor with the RCX (micro). Communication between the software and micro is achieved via the USB (formerly serial) IR device that's included with the set. The step-by-step instructions help even the youngest of users to become (unconsciously) comfortable with the process before building a project.

In addition to two switches and a light sensor, the set includes two bidirectional motors. These items are integrated in the software with pre-built programs that let you experience the power quickly. You can write new programs by dragging and dropping routines (big blocks of code instructions (e.g., "turn right")) or instructions (small blocks (e.g., "motor A direction forward")) on the program chain. From the programming screen you can download any program or interactively control the inputs and outputs on the RCX controller. This communication link is live between the USB (or serial) IR port and the RCX. The RCX can store five separate programs in its memory. The RCX batteries supply power for these downloaded programs and the operating system. In this manner, the OS is upgradeable.

RCX

You'd think the micro inside this small unit would be equally as small, but actually it's a 64-pin Hitachi H8 (see Figure 1). Of the seven I/O ports (56 I/O bits), about half are used to interface external devices, such as 32 KB of RAM and motor control. Only 6 bits are used for real-world interfacing, including sensor (analog) inputs 1, 2, 3, and sensor (digital) outputs. There are a number of other inputs (e.g., RCX function push buttons, serial communication, and battery voltage) and outputs (e.g., speaker, serial communication, and LCD control), but these aren't available for additional sensor inputs or motor control.

The CPU has a downloader in ROM, so the operating system needs to be downloaded into RAM whenever the batteries have been removed. (An electrolytic cap keeps the system alive

for brief battery exchanges.) The brief IR communication that occurs whenever the PC software is started automatically checks with the RCX to see if this needs to be done.

The H8 does not have motor output bits to drive the motor A, B, and C outputs directly. The motor control is memory mapped off the processor at Fxxx. A single byte controls a motor driver IC (with H-Bridge) for each of the three outputs. My RCX uses Melexis MLX10402 motor drivers. Three pairs of bits (i.e., 0 and 1; 2 and 4; and 6 and 7) control the four functions of each driver IC: forward, reverse, brake, and off.

Using an H-Bridge has a few advantages, one of which is that the full voltage is applied to the outputs (minus internal FET drops). Another advantage is that an output of both polarities is available with a single supply. This works well with the Lego electrical connection system, which I'll describe shortly. Power control for the external motors (or whatever else is connected to the motor outputs A, B, and C on the RCX) is through PWM control signals. The PWM cycle is divided into eight 1-ms time slots. The power command has a control value with a range of one to eight.

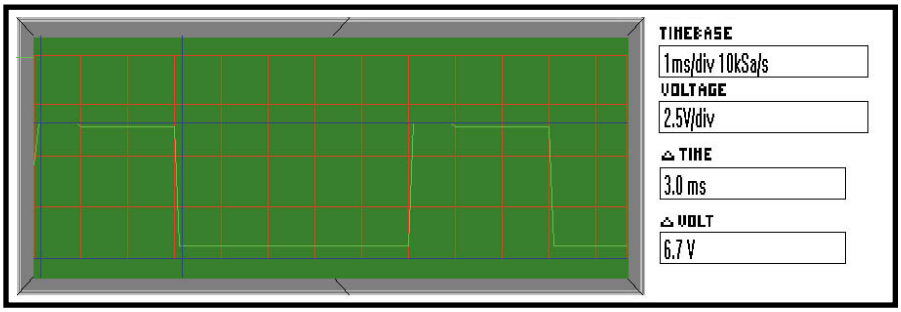


Photo 1—*This is a typical RCX output A (motor) waveform with a power value of three. The PWM period is 8 ms with a 3-ms on time. Each power value increases the on time by 1 ms.*

This value corresponds to the number of timeslots that are turned on in the PWM output cycle (see Photo 1).

The connections to and from the RCX are a simple, two-wire connection. This is simple for the outputs; however, most inputs (sensors) require some kind of power for operation. Transmitting power and ground over two wires isn't difficult, but what do you do with the sensor output?

The RCX multiplexes the power with the sensor's output to create an active and passive power cycle. The battery voltage (9 V) is switched on to the sensor in Active Power mode (by the RCX digital sensor outputs 1, 2, and 3). In Passive mode, power is switched off, and an A/D reading is taken of the sensor output via the RCX analog sensor inputs 1, 2, and 3. You can imagine that each sensor may require special circuitry to save power in Active mode for use in Passive mode. Take a look at Photos 2a and 2b for the input cycle times of the light sensor connected to my RCX. The A/D converter's upper reference seems to be that of V_{CC} (5 V), and the lower reference seems to be at 2.5 V.

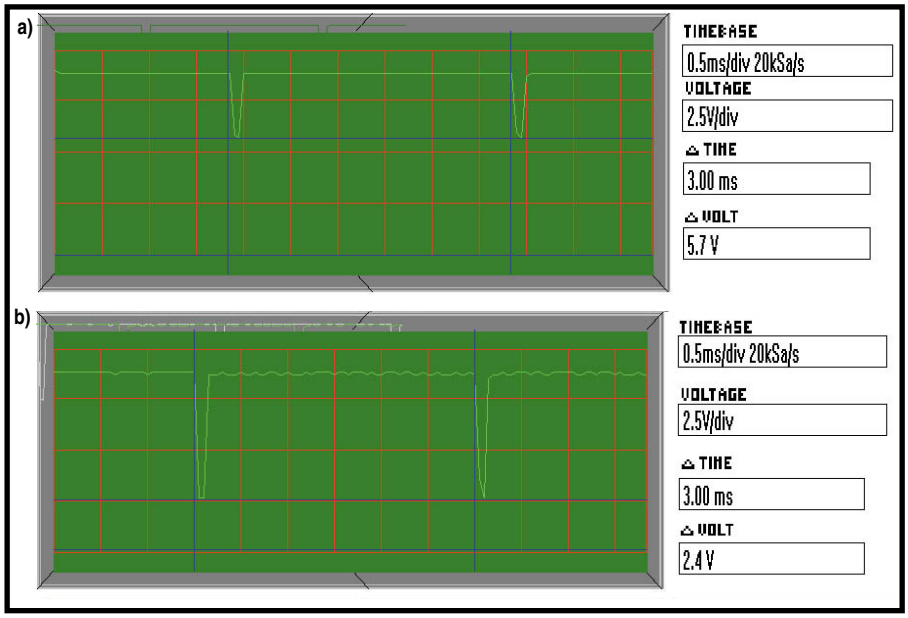


Photo 2a—*As you can see in this waveform of the RCX input 1 (sensor), the passive portion of the 3-ms period is about one-tenth of the full period. During the active portion (nine-tenths of the period), the sensor circuitry can store power.* **b—***The RCX's A/D converter samples the input during the passive portion of the input cycle (one-tenth of the period). After a sensor puts a greater load on the RCX input, it can pull the input to a lower value, as shown in this waveform. The lower the input voltage, the higher the raw numeric value (up to 1023).*

ELECTRICAL CONNECTIONS

The Lego electrical connection system uses modified Lego blocks as the electrical connectors for both input and output devices. Its unique design helps to simplify connectivity. Refer to Figure 2 for an X-ray view of the connection scheme.

Lego blocks can be connected in any of four rotations. The electrical contacts' unique design makes it impossible to short out connections, in any rotation. The worst thing that can be done is reversing the connections, which, in the case of an output, would cause a motor to reverse direction. Input sensors use a diode bridge to allow a reverse connection to be swapped electrically!

MOTORS A, B, AND C

Two motors come with the RIS. No other output devices are supplied with the RIS, so what can you do with the third output? Extra motors are included in some RIS expansion packages. You can also order them online for $15.99, because you'll most likely want to experiment with your own motors.

The Melexis IC is rated to approximately 0.5 A at 9 V. Your local hobby shop probably stocks RC servos. I used a Futaba servo and ripped out

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the servo parts to make a bidirectional DC motor (see Photo 3). Geared down to approximately 60 rpm, this has some major torque (i.e., approximately 50 oz. per inch in comparison to approximately 12 oz. per inch for the Lego motor). One caveat to keep in mind: not all RC servos can be altered for gear motor use. The Cirrus CS-50 I opened did not have a full final gear—it didn't have 360° of teeth! Because RC servos don't turn 360°, the final gear doesn't need to be complete.

If you want to play with a servo without altering it physically, visit the Hempel Design Group's web site (www.hempeldesigngroup.com). The site has a circuit for inverting motor output A, B, and C to make it look like the standard RC control signal. With the RIS software, you'll be able to drive the servo to either extreme (clockwise or counterclockwise). This isn't the best resolution, but it's useable for some push-pull movements. I'd like to monitor the motor output on an input pin of a small (i.e., 8-pin) micro and create real RC timing on an output pin.



Photo 3—*This servo fits nicely into a Lego box made of standard parts. I mounted a brick on one of the included servo arms. In the front of the unit, there is a spare servo arm and a few other Lego pieces that could have been used. I left the electrical connector loosely mounted on the top where it can be adjusted accordingly.*

SENSORS 1, 2, AND 3

There are two types of sensors used on the RIS: the digital sensor (i.e., switch) and analog sensor (i.e., light sensor). Both are read via the internal 10-bit A/D converter.

Earlier, I mentioned the Active and Passive modes of the sensor input. In Passive mode, the A/D converter provides the RCX with a raw input reading (zero to 1024). Depending on the

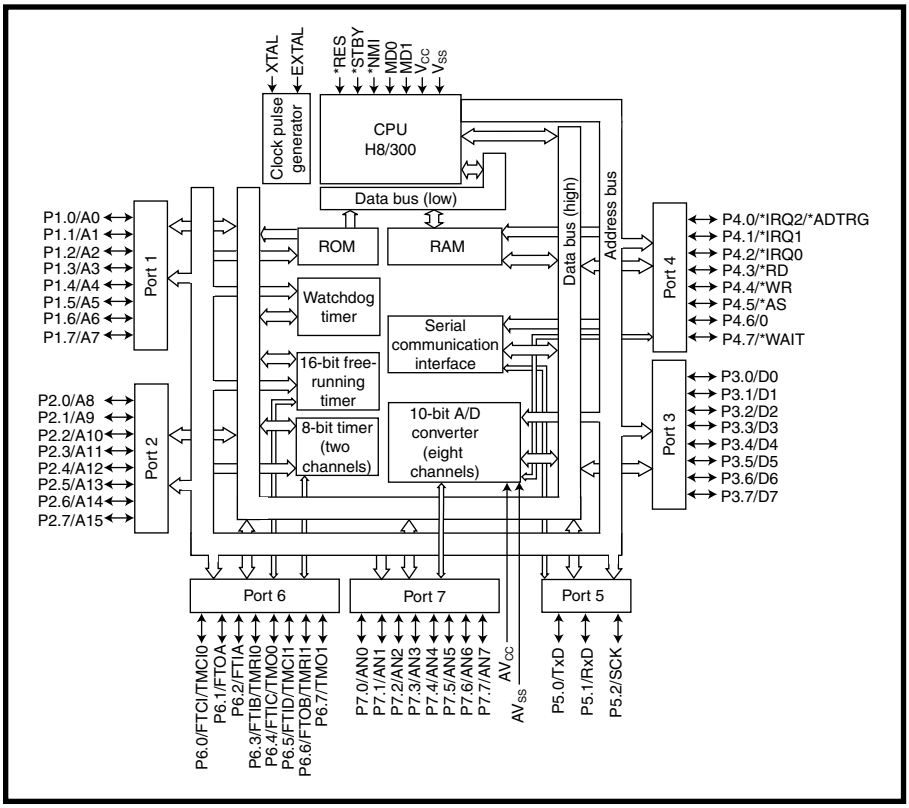


Figure 1—*The block diagram shows the innards of the H8 used in the Lego RCX controller. It's a rather extensive part for the simplicity of the end product. Half of the I/O is in support of the 32 KB of external RAM that holds the operating system and user programs.*

sensor mode, this value could be converted to a binary value for Boolean math, and edge or pulse counting, or scaled to a zero-to-100 value for user friendliness. Other sensors (i.e., angle and temperature) have been integrated into the software and come with expansion kits.

As I was testing the RCX, I found that the A/D converter had a high reference of V_{CC} (5 V) giving a low conversion value. The low reference was approximately zero, and it converts as a high conversion value. In addition, I found that the approximately 3-kΩ load was enough to drag the input down to the low reference. A load of approximately 1 MΩ was barely enough to lower the input below the high reference.

You can begin to see the window of input the RCX likes to monitor. This opens the door for many other sensors whose outputs fall at least partially into this window. Just about any resistive device can be used. The greater the resistive change the sensing device exhibits, the better. In Passive mode

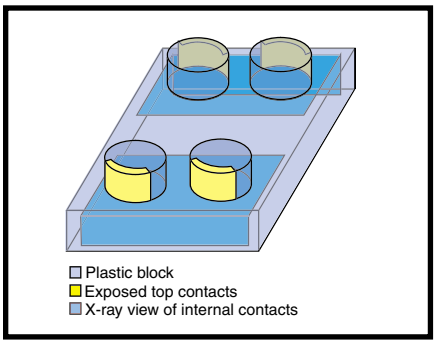


Figure 2—*A standard Lego brick is modified to accept metal contacts. Notice how the controlled exposure of the contacts through the top studs prevents the contacts from shorting each other out when two bricks are connected one atop another in any rotation.*

the input has approximately 10 kΩ to V_{CC}. The resistive sensor creates a voltage divider by connecting the input to ground through itself. When it changes resistance, the voltage at the input changes in proportion:

$$V_{IN} = \frac{5 \times R(\text{sensor})}{R(\text{sensor}) + 10\ k\Omega}$$

With a little ingenuity, you can use various other sensors. You can use a micro—an 8-pin micro would be a good choice—to create an inexpensive interface between sensor and the RCX.

Take a look Figure 3. The bridge allows you to connect the device without having to be concerned with polarity (the key to Lego user-friendliness). The sensor-side of the bridge will always have the correct polarity, allowing current flow through D1 to charge the gas tank capacitor, C1, during the Active mode of the input cycle. C1 stores energy to provide continuous power for the sensor (and circuitry) while the RCX is in Passive mode.

During the passive phase of the cycle, a load resistor, R1, drags the input down to the low level unless energy comes from somewhere to create additional voltage by dumping current through it. This current can come from a micro's DAC (or capacitor being charged by a PWM output). A change in pulse width charges the capacitor to a different level, resulting in a new voltage at V_{IN} of the RCX's A/D converter.

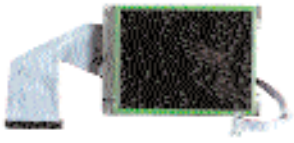
Digital potentiometers make great interfacing devices (e.g., Maxim/Dallas,

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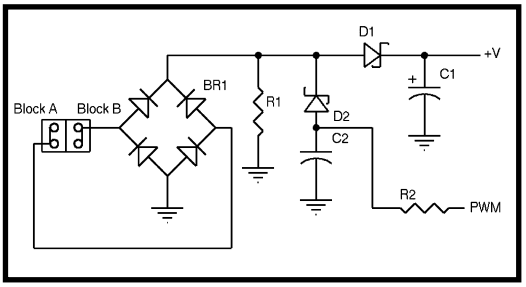


Figure 3—*This schematic shows how a PWM output from a small interfacing micro can control the voltage into an RCX's A/D input. During the active phase of the input cycle, the RCX provides power to C1 (and the rest of your circuitry through D1). During the passive phase, the RCX's A/D converter samples the voltage across R1 provided by the charge on C2 (the amount of which is dependent on C2 and R2, and also the PWM percentage).*

Xicor, and Microchip). You can find these having a maximum value of 100 kΩ and up to 1024 taps (e.g., the MAX5401 has 256 taps in an 8-pin SOT-23 package). In Figure 4, you can see how a digital potentiometer simplifies the circuitry. Digital potentiometers come in various interfaces that are easily controlled with a micro. One powerful advantage for using a micro is that you can customize the translation of a sensor's output to the micro's output by an offset or scale factor. You may even want to linearize or otherwise adjust the response curve of a sensor.

SUGGESTED SENSORS

Visit the *Circuit Cellar* ftp site if you're interested in checking out my suggestions for electronic sensors. For those of you looking for immediate gratification, there are plenty of companies out there that specialize in building sensors into Lego bricks. The majority of these companies buy Lego bricks and electrical connectors directly from Lego so their finished products look like and fit well with most standard Lego products.

Note that the 'Net is a great resource for purchasing electric plates (shop.lego.com/) and motors (www.pitsco-lego-dacta.com). The *Circuit Cellar* ftp site also includes a list of web sites that have information about ready-to-use sensors. If you're interested in learning more about Lego Mindstorms, you should start your investigation by visiting the official Lego Mindstorms web site (www.mindstorms.com). There you can learn more about the new open-source operating system and view a bunch of great hardware resource pages.

FUN FOR EVERYONE

Lego has done an outstanding job of making RIS easy to use. The RIS box states that the product is for designers ages 12 and up. I believe the company has underestimated the ability and curiosity of its youngest users. In addition, Lego has only just begun to realize how remarkably useful its tools are to the more mature designer.

As you're taking this stuff apart, please be careful because it's easy to damage. If you need to look inside, here are some suggestions. Although the IR tower and RCX disassemble with screws, there are small plastic parts that can fall on the floor. The light sensor is heat welded, so if you pry it apart you may need a spot of





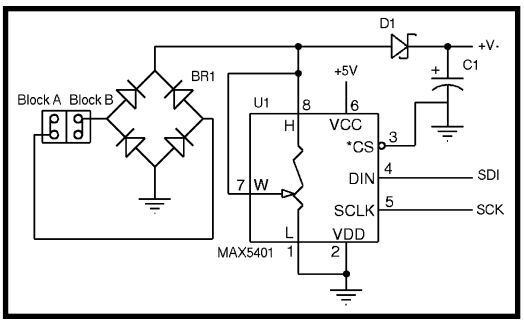


Figure 4—*This is a simplified interface using a digital potentiometer, which forms the bottom leg of a voltage divider with approximately 10 kΩ to V_{CC}. This digital potentiometer's wiper can select any of the 256 steps between ground and the digital potentiometer's value (100 kΩ). The device uses an SPI interface that's easily controlled with a microcontroller.*

glue to hold it together again. Almost everything else snaps together, and it can be pried apart if you're agile and have more than two hands. The motors are the most difficult to handle and are easily damaged, because the contacts in the front are soldered to the rear cover brushes. If you pry off the back, the brushes must be carefully unsoldered to remove the back from the rest of the assembly.

Have fun with the RIS (and remember to share it with your kids). When you think you've gone as far as you can go, just look at what is out there to explore. You can try a different operating system in your RCX or you can write your own, knowing that you don't have to build any hardware. Or, if you have solder running through your veins, you can design and build your own I/O devices without having to write any support code.

Jeff Bachiochi (pronounced BAH-key-AH-key) has been writing for Circuit Cellar *since 1988. His background includes product design and manufacturing. He may be reached at jeff.bachiochi@circuitcellar.com.*

PROJECT FILES

To download the sensors lists, go to ftp.circuitcellar.com/pub/Circuit_Cellar/2003/153/.

RESOURCE

MIT Programmable Brick
lcs.www.media.mit.edu/groups/el/projects/programmable-brick

SOURCES

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SATURDAY MORNING, FEBRUARY 1, 2003

I thought I was alone watching yet another space shuttle land after more than two weeks of rocketing around earth. This mission wasn't to visit the International Space Station; it was a totally scientific assignment to perform experiments in micro-gravity around the clock for 16 days.

I couldn't have been more wrong by thinking I was alone. America was watching. Thousands of Americans strained their necks to get a quick glimpse of Columbia as it slipped back into our atmosphere toward its final destination, the Kennedy Space Center in Florida. Early Saturday morning, as the shuttle passed over Texas, many people quickly realized that it would never make it. It was an anxious few moments for those of us living away from the shuttle's flight path. NASA reports were infrequent as they desperately tried to regain telemetry and contact. Elsewhere, on the commercial TV channels, the American public was beginning to learn of the horror via home video recordings. The major networks immediately began displaying evidence of the disaster. I related the first images I saw to those of a UFO hoax—abnormal streaks in the morning sky caught on amateur camcorders. But this was real. America was about to endure another national disaster.

Not unlike September 11, 2001, the citizens of America rallied together. By Sunday evening—roughly 30 hours after the tragedy—over 600 Americans had called to donate their video versions of the disaster and roughly 100 people had e-mailed photos. In addition, more than 1000 debris sites had been located within the 900-square-mile impact zone. Soon thereafter, this expanded beyond the state of Texas, and NASA was faced with the challenge of determining the root cause of the disaster for an otherwise perfect mission. But little did NASA realize the large part American citizens would play in investigating our nation's latest disaster. I look forward to a completed investigation that rivals the speed of public response.

I'm not sure if my fascination with space comes from a love of science fiction or vice versa. I'm reassured that I am not in the minority. I'm proud of my country's quest for the final frontier. Many Americans ask why we continue the space program. Space exploration goes beyond the adventure and quest of the unknown. For every $1 the U.S. invests in NASA, $2 will be returned in direct and indirect benefits. These come to us as advances in areas including technology and medicine. The International Space Station is a global project that the world cannot afford to be without. From orbit, it's clear that we are one people scattered across a fragile island, and we must work as one to protect it, or we run the certain risk of destroying it.

Unexpected death denied us the chance to say a final goodbye to the astronauts aboard Columbia. How unfortunate it is that it takes a disaster to create seven national heroes. This is the third American space tragedy: Apollo 1, Challenger, and now Columbia (seventeen heroes in all). I consider all astronauts to be heroes. And, if NASA needs volunteers, I'll fight to be first in line. Hail Columbia.

SHORT SOLUTION

Tom Napier

Get One-Chip Programmer Power

Have you been searching for one-chip programmer power? Look no further than your own workbench. In this article, Tom shows you how easy it is to build an LM78S40 converter chip to supply a PIC or PROM programmer with 5 and 13 V.

Over the years, I've built a number of EPROM and PIC programmers. Each time I've faced the problem that Fred Eady mentioned in *Circuit Cellar* 138: Where can you get 5 V and either 21 or 13 V for the programming voltage?

Some years ago, I built myself a PROM programmer in a 3.5″ × 5.5″ plastic project box. (I didn't bother to write it up, because Steve Ciarcia did a similar job in *Byte* back in October 1986. Steve's control chip was a Basic 8052. I used a PIC16C57.) The box had a compartment for a 9-V battery, so I designed a DC/DC converter to fit that space. It took 9-VDC from a wall transformer and converted it to a stable 5 V at up to 100 mA plus an unregulated 25-V, 50-mA supply. The controller chip was an LM339 quad comparator. An LM317 on the programmer board dropped the 25 V down to 5, 13.5, or 21 V as selected by resistors switched by the 16C57.

More recently, I built a serial programmer for PIC chips. This needed to supply either 13-V bias to a flash memory chip or 13 V at 30 mA to an EPROM chip. I threw together a board with a linear 5-V, three-terminal regulator driving a commercial 5- to 15-V DC/DC converter. Even unloaded, this kludge dissipated 1.2 W, which was a bit much for a little plastic box.

EXIT KLUDGES

Wanting something better, I had another look at my 5- to 25-V converter design and realized it was a fluke that it worked as well as it did. I buckled down to create a more conservative design: a forward converter with two independent output windings. The prototype worked nicely, but there was no way it would fit in a battery compartment. Even its predecessor had resorted to resistors mounted on end. This one needed room for two extra inductors. Back to the drawing board!

As Fred did, I used that old trouper of the converter chip world, the LM78S40. I'm not kidding about it being old. I use a 1978 application note to guide my designs. (Some chips just keep on going; their modern replacements may be discontinued tomorrow.) My thinking was that if the LM78S40 generated 13 V from the raw DC input, it wouldn't be too awful to use a linear regulator for the 5-V output. Then inspiration struck.

ONE CHIP, TWO SUPPLIES

The LM78S40 has a built-in op-amp that I've never had occasion to use. Somewhere in the datasheet there's a throwaway line about using it as a linear regulator. Sure enough, it has a current-source capability of 150 mA. The chip already has a 1.25-V reference. All it needs to make a regulator is two resistors to set the output voltage. Oh, and a current limiter. Sooner or later I'll put a part to be programmed backwards in the socket. Adding a current-sense resistor and PNP transistor fixed that. (It's just as well. I had put a bead capacitor backwards in the prototype, and I was wondering why the 5-V output was slowly going south. Without current limiting, I would've had smoke, fire, and a dead converter chip.)

My target specification was 5 V at 0 to 100 mA and 13 V at 0 to 50 mA. The LM78S40 is rated at 1.5-W dissipation at 25°C. As its switching section dissipates perhaps 200 mW, a 100-mA linear output is well within its ratings, particularly because the load is intermittent. Figure 1 shows the final schematic.

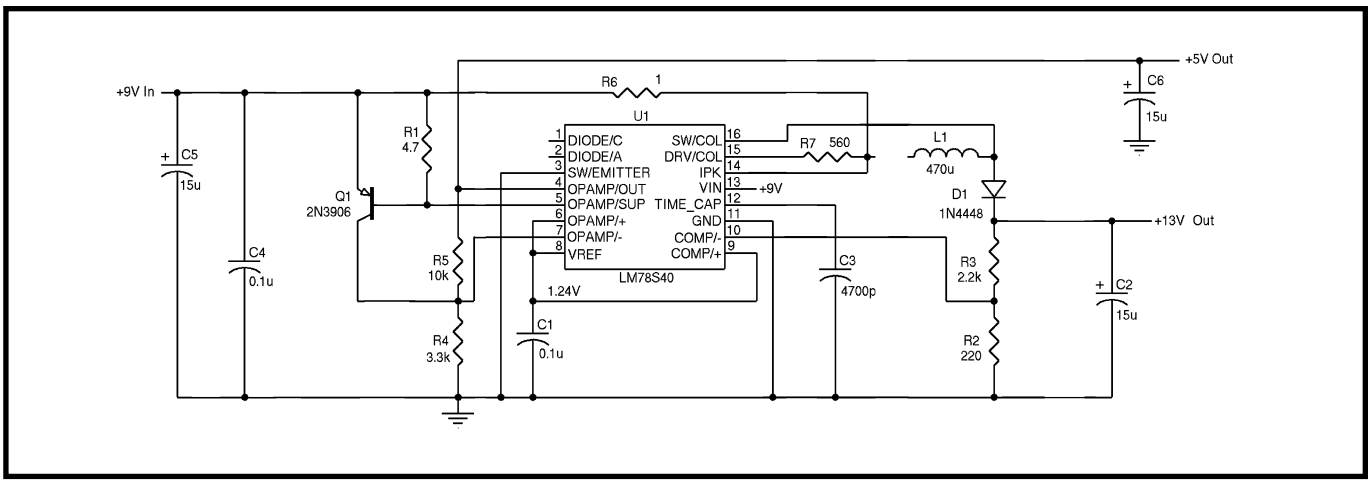


Figure 1—*This back-to-basics, 13-V switching converter supplies a regulated 5-V output, too.*

The converter uses the flyback configuration. This is not ideal when you want less than the maximum output current. On every cycle, the LM78S40 loads up the inductor with a standard amount of stored energy and then has nowhere to put it. EPROMs take current during programming but flash memory PICs take no current at 13 V. Their programming voltage is a signal, not power.

The answer is to use low-value resistors to sense the output voltage. These double as a permanent 5-mA load, so the oscillator period doesn't need to be infinitely long when the load current is zero.

THE HANDS-ON APPROACH

As Fred pointed out, the parameters of the inductor define the behavior of the converter. Rather than compute exactly the right component and then order it from a distributor, I wind my own. One converter has 130 turns (three layers) of 28-gauge wire on a 0.25″ diameter × 0.75″ long dust core. Wire-wrap pins epoxied across each end act as radial terminals.

A second converter had limited headroom; it got the low-profile (0.375″) version. This used a 0.3″ length of 0.25″ diameter ferrite antenna rod from an old radio. I glued a 0.5″ diameter disk of thin insulating sheet on each end to hold the winding in place. Two bent wire-wrap pins glued to one end made axial terminals. With 200 turns of 31-gauge wire, I had an adequate, if almost 3-Ω, 670-µH inductor. In retrospect, I would've been better off with 150 turns of 28-gauge wire.

It's hard to make a bad converter from an LM78S40, but it's difficult to make an extremely good one, too. I generally use an external switch FET and flywheel diode to boost the efficiency. Just an external 1N4448 diode improved the switcher efficiency from 75 to 80%. Because the linear 5-V supply is about 55% efficient, a Schottky diode is hardly worth it.

Some of the resistor values depend on the chip's exact reference voltage. Mine was 1.238 V, which is close to the typical spec. A 5-V divider using 10- and 3.32-kΩ 1% resistors was just about right. The 13-V output should be 13.2 V to allow for a saturating switch in the programmer. This gave a resistor ratio of 9.66:1. After a long hunt, the best match I could find among the 1% resistors on hand was 2.21 kΩ and 221 Ω. This gave me a 13.6-V output.

The 4.7-Ω current limiter for the 5-V output was also constrained by the parts available. This value is a tad high; the limiter kicks in at 95 mA. A 3.9-Ω resistor would be a better bet. The 13-V output is happy with a 60-mA load and could be easily pushed higher.

FABRICATION

The circuit board is 1.1″ × 2.1″ and cut from prototyping board with continuous copper strips on one side. Cut as necessary, these are the horizontal conductors.

The vertical lines are bus-wire interconnects on the component side of the board. (Two of them run under the chip.) You may download a diagram of the parts placement from the *Circuit Cellar* ftp site. The dotted line on the diagram is an insulated wire on the copper side that brings all the inputs and outputs to a common point. There's room to mount commercial inductors of various shapes if you balk at winding your own. Pick one rated for 400 mA or better. The finished board is stuck into the battery compartment with a dab of silicone rubber.

This device didn't start life as a product or even a reader project—it was a quick solution to a problem. I ended up with a converter that met my requirements, but it can be easily modified should they change. Let's hope it works for you too.

A former design engineer and manager, Tom Napier writes how-to articles and does electronics consulting work. Needless to say, he doesn't use hand-wound inductors when a customer is footing the bill.

PROJECT FILES

To download the parts placement diagram, go to ftp.circuitcellar.com/pub/Circuit_Cellar/2003/153/.

SOURCES

LM78S40 Converter chip
National Semiconductor Corp.
(800) 272-9959
www.national.com

SILICON UPDATE

Tom Cantrell

E-Chips



Some tickets allow you to see professional sporting events, others get you into amusement parks. This month, Tom familiarizes you with E-Chips—the newest and hottest tickets for accessing the I-way.

Those of us, ahem, of a certain age may recall a childhood visit to Disneyland. Back when Walt was in charge, Disneyland would sell you a book of ride tickets comprised of various combinations of denominations from A through E. The scheme had the effect of turning zillions of visiting kids into budding entrepreneurs, middlemen, and market makers. At a tender age, we learned the basics of free enterprise, everything from options and futures to black markets and monopoly power.

A-Tickets were only good for the Mickey Mouse amusements your kid brother might have liked. All the better if you could've conned him into trading a couple of deflated As for a crisp new pass to the most thrilling rides, the coveted E-Ticket.

Of course, you could've just tried lying, cheating, or stealing to get your hands on your little bro's tickets. But you didn't, knowing full well you'd get busted by the ever-vigilant FTC—father in total control—who'd likely lay a bit of cruel and unusual punishment on your behind. There's probably a lesson there.

Back in my February column, I pondered the choices designers face when deciding how to "network-enable" their embedded applications ("Working the 'Net," *Circuit Cellar* 151). I hope the message you took away was that it's important to understand the complexities and subtleties hidden behind the simple-sounding catchphrase. In that column, one thing all the solutions had in common was Ethernet, setting the stage for the emergence of a new class of Ethernet chips, or E-Chips—the E-Tickets you need to board that thrill ride known as the I-way.

PARC PLACE

Most of you are familiar with the Ethernet story, it being another of the pivotal advances in computing spawned during the glory years at Xerox's heralded Palo Alto Research Center, a.k.a. PARC. [1] That was a time when much of what we experience today as computing—networking, object-oriented languages, laser printers, bitmap displays, and even the ubiquitous mouse—floated to the top of the primordial brew at PARC.

In fact, the roots of Ethernet go even further back, in particular to the Aloha network developed at the University of Hawaii. [2] Aloha actually evolved as a packet radio protocol, but the fundamental issue of multiple users contending for access over a shared medium translated nicely to Xerox's goal of hanging a bunch of Alto workstations and laser printers on a single wire.

Ethernet passed many milestones during the long journey from Bob Metcalfe's mid-70s brainstorm and 2.94-Mbps prototype. The Ethernet ball really got going in the late 1970s thanks to the so-called DIX consortium (DEC, Intel, and Xerox) that successfully standardized and commercialized the concept.

The next level came as a blessing from the IEEE with the first of the now myriad 802.x LAN standards. Actually, the standard codified a number of changes to the DIX version that led to a period of confusion as the number of implementations and upgrade proposals proliferated.

However, within the last few years, the situation has been resolved—first in favor of 10BaseT and subsequently

100BaseTX. One or both of these is behind the "Fast Ethernet" RJ-45 jacks on typical PC and network gear of recent vintage. The compelling advantage for these two versions of the standard is that they are upward/downward-compatible (i.e., ports are increasingly dual-speed 10/100 capable) thanks to the fact that they use the same wiring (shielded twisted pair) and pin assignment.

It's still called Ethernet, but along the way even the fundamentals have been changed. For instance, taking advantage of the extra wires in the cable, modern Ethernet configurations are increasingly point-to-point, full-duplex links versus the shared-wire, half-duplex scheme of the original. With full-duplex links, you get twice the speed and don't have to worry about carrier sensing, multiple access, and collision detection (i.e., CSMA/CD).

Of course, the headlines these days are about the new 1-Gbps (and even 10-Gbps) versions of Ethernet on the horizon. For now, I'll leave those to the performance-at-any-price and big-iron infrastructure crowd. On the embedded front, the challenge is to find a simple and inexpensive way to drop a standard 10/100 Ethernet interface into practically anything. And, thanks to the Silicon wizards, it's easier than ever to do just that.

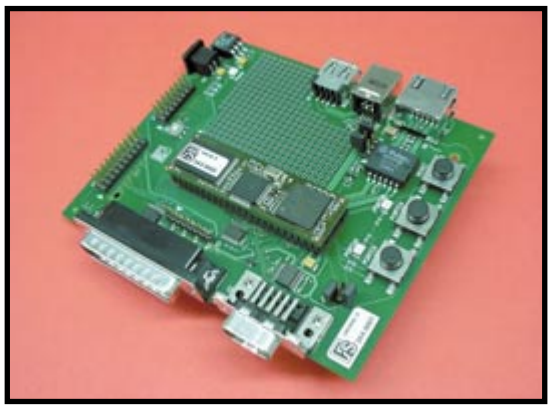


Photo 1—*The UNC20 imodule (here mounted on the evaluation kit's base board) is an easy and low-cost way to get under the hood or quickly to production with a NetSilicon NS7520-based solution.*

MAC ATTACK

Let's take a look at five—count 'em, five—new chips with built-in Ethernet. Indeed, the pace of announcements may indicate Ethernet—like UARTs, I²C, and SPI ports before it—is well on its way to becoming standard equipment.

What's impressive is the range of performance and I/O capabilities represented, which are summed up in Table 1. That means choosing an integrated Ethernet solution need not be an exercise in compromise. Covering a range from 8 to 32 bits and everything in-between, one of these parts is likely a close fit with your application requirements. If not, just wait awhile, and no doubt there will be even more E-Chips to choose from.

Give NetSilicon credit for being one of the first companies to kick things off with their NET+ARM product line, which was introduced five years ago. As the name implies, NET+ARM combines an ARM chip, Ethernet, and the required stacks of RTOS, network protocols, and development tools.

What's striking about the latest incarnation, the NS7520, is what's missing, notably the most significant digit of the price tag. The sticker for this little puppy is a mere $7.95 (10,000 quantity), and that's today, not some future price projection. As I've said all along, the penetration of networking into embedded apps is only limited by the cost, and chips like the NS7520 will further the cause.

The NS7520 extends its cost-cutting aspirations from the chip price itself to the entire system's cost. Budget-burning extremes typically associated with 32-bit chips (factors such as clock rate, power consumption, packaging, and glue logic) are avoided.

Consider that the entry-level, no-cache ARM7TDMI core runs at a leisurely 55 MHz off a plain 18.432-MHz crystal. Furthermore, that core includes the denser Thumb 16-bit code option, reducing the software footprint. There's a full-fledged, no-glue-logic bus interface for direct connection to all the popular memory chips: SRAM, flash memory, and DRAM/SDRAM (the latter via built-in address multiplexing and refresh). Dynamic bus sizing and programmable wait states support a mixture of 8-, 16-, and 32-bit add-ons.

In many respects, the NS7520 is more like a controller than a processor. There's a decent set of peripherals including timers (two general-purpose 16-bit, watchdog, and bus error), 16 general-purpose I/O lines (four programmable as interrupt inputs), and two high-performance UART-, SDLC-, and SPI-capable serial ports.

The built-in 802.3u-compliant Ethernet media access controller (MAC) supports both traditional 10BaseT half duplex (i.e., multidrop) and increasing-

	NetSilicon NS7520	Motorola MCF5282	Zilog eZ80F91	Rabbit R4000	Maxim DS80C400
CPU	ARM7TMDI (55 MHz)	ColdFire V2 (66 MHz)	eZ80 (50 MHz)	Rabbit 4000 (70 MHz)	C390 (75 MHz)
On-chip memory	2.5-KB SRAM	512-KB flash memory, 8-KB SRAM, 2-KB cache	256-KB flash memory, 16-KB SRAM	None	9.5-KB SRAM, 64-KB ROM
Expansion bus	26-bit address, 8-, 16-, and 32-bit data	24-bit address, 8-, 16-, and 32-bit data	24-bit address, 8-bit data	20-bit address, 8-bit data	24-bit address, 8-bit data
Ethernet	10/100 MII	10/100 MII	10/100 MII	10BaseT full-duplex only	10/100 MII
Peripherals	Timers (4), serial ports (2)	Timers (17), serial ports (3), clock-serial ports (2), eight-channel 10-bit ADC, CAN	Timers (6), serial ports (2), clock serial ports (2)	Timers (12), serial ports (6), quadrature decode, slave interface	Timers (5), serial ports (3), 1-wire port, CAN
Power (est.)	1.5-V core, 3.3-V I/O, 0.5 W	3.0 V, 0.5 W	3.3 V, 0.2 W	2.5-V core, 3.3-V I/O, 0.2 W	1.8-V core, 3.3-V I/O, 0.2 W
Package	177-pin BGA	256-pin BGA	144-pin QFP	144-pin BGA	100-pin QFP

Table 1—*Start thinking "Ethernet," because the E-Chips are coming to town.*

ly popular 100BaseTX (point-to-point) links via 512-byte transmit and 2-KB receive FIFOs. A 13-channel DMA controller does the heavy lifting, servicing the network and all the other on-chip and off-chip peripherals.

That's a lot of functionality compressed into a 177-pin BGA package less than 0.5" on a side. However, despite external appearances, this is a 32-bit chip after all, and power consumption is a non-trivial 500-mW peak (55 MHz) regardless of the low 1.5-V core and 3.3-V I/O (5-V tolerant) voltages. Of course, you can cut power by running at a slower clock rate and using application-level power management.

The chip may be a bargain, but just don't forget to budget for the development tools. NetSilicon uses proven industrial-strength software from Express Logic (ThreadX RTOS) and Green Hills (IDE and C++ compiler) as well as the former Pacific Softworks (TCP/IP stack), a company NetSilicon purchased a couple of years ago. There is also a GNU-based tool suite, but even that will set you back a cool $1500.



Photo 2—*Batteries may not be included, but everything else is in the Zilog eZ80F91 evaluation kit.*

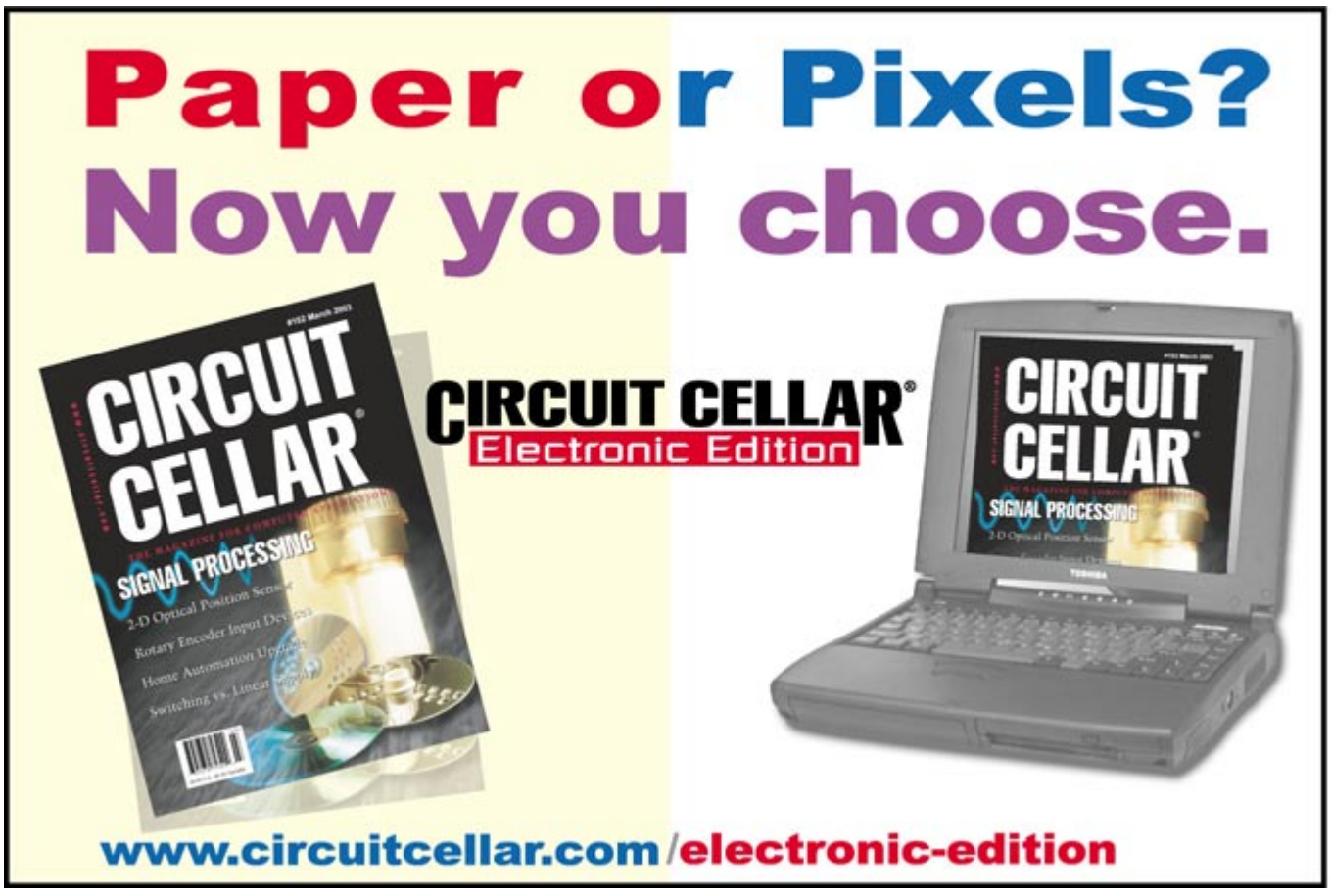
For a more budget friendly option, consider the $299 NS7520-based universal network controller (UNC20) development kit from Embedded Solutions (see Photo 1). Two versions of the kit are available. One runs uClinux on the board and uses Linux-based GNU tools. The other version sticks with the ThreadX RTOS (i.e., the same as NetSilicon's NET+OS package), but uses GNU tools and Cygwin running on a PC host.

KITCHEN SINK

Motorola always impresses me with the sheer amount of stuff they cram on their parts. Over the years, they've developed an impressive portfolio of silicon IP to draw from, which is a strategy that has paid off with the ability to quickly spin highly integrated chips. Check out the new MCF5282, and you'll see what I mean (see Figure 1).

First off, this is a true 32-bit MCU with a 66-MHz ColdFire V2 core complemented by a healthy 512 KB of flash memory and 64 KB of SRAM. If that's not enough room for you, never fear, there's a full-fledged 32-bit expansion bus to hang on extra memory chips.

Quite a bit of thought was put into maximizing memory bandwidth. After all, there's no sense jacking up the clock rate if the end result is just



more wait states. The basic flash memory access cycle is two clocks, but interleaving and speculative loads reduce the average below that. In any case, there's also a 2-KB, direct-mapped cache that can be configured for code, data, or both. Of course, the SRAM, which can be used for code and data, delivers single-clock access.

What does the '5282 have under the hood when it comes to peripherals? A better question might be: What hasn't it got? Let's see, there are four 32-bit timers, which are notable for excellent 15-ns resolution, and three UARTs, not to mention separate SPI and I²C clocked serial interfaces.

Apparently, the '5282 never met a timer it didn't like. In addition to the four 32-bit units, there are eight 16-bit timers with the requisite input capture, output compare, and PWM features. Throw in a watchdog and four periodic interrupt timers for the software guys, and that makes a grand total of.Oh, what the heck, who's counting?

As I've said before, the '5282 is a true microcontroller, and what MCU

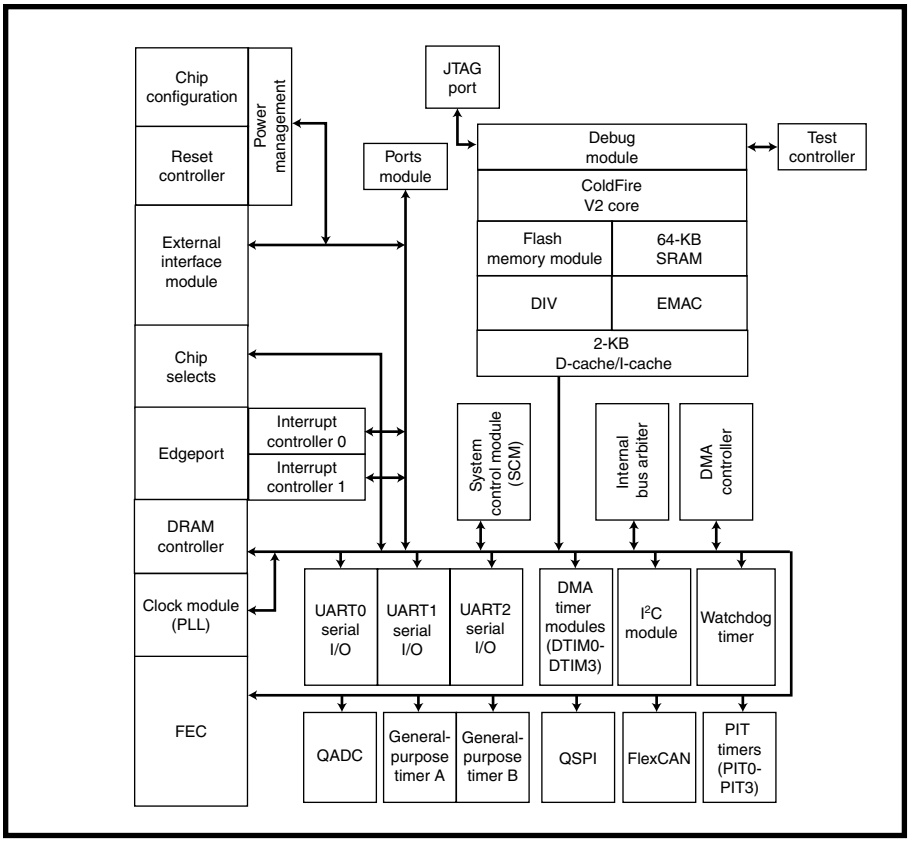
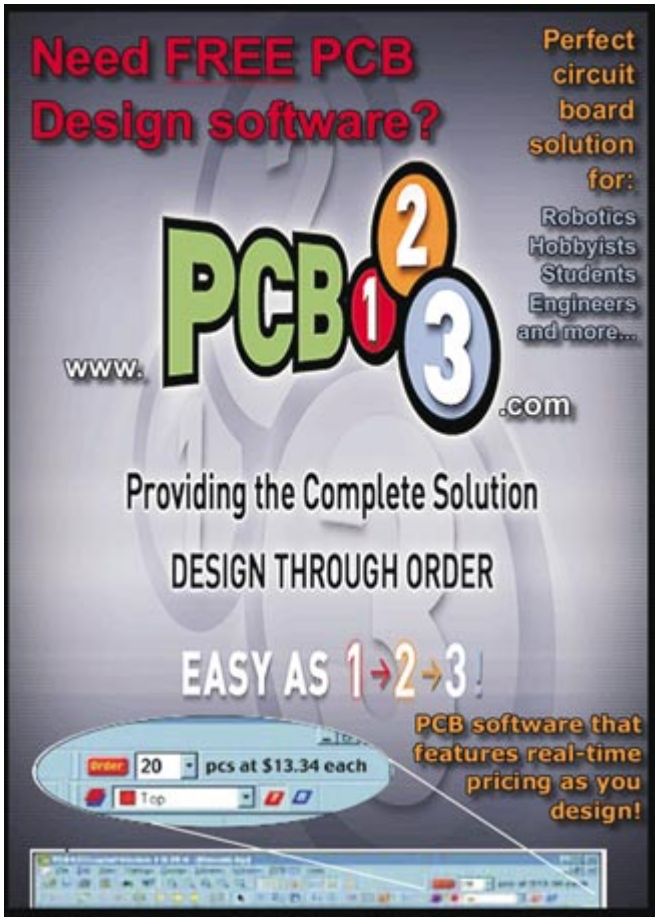


Figure 1—*Motorola outdoes itself on the integration front with the MCF5282. The addition of a CAN interface highlights the likelihood of Ethernet migrating to industrial applications.*





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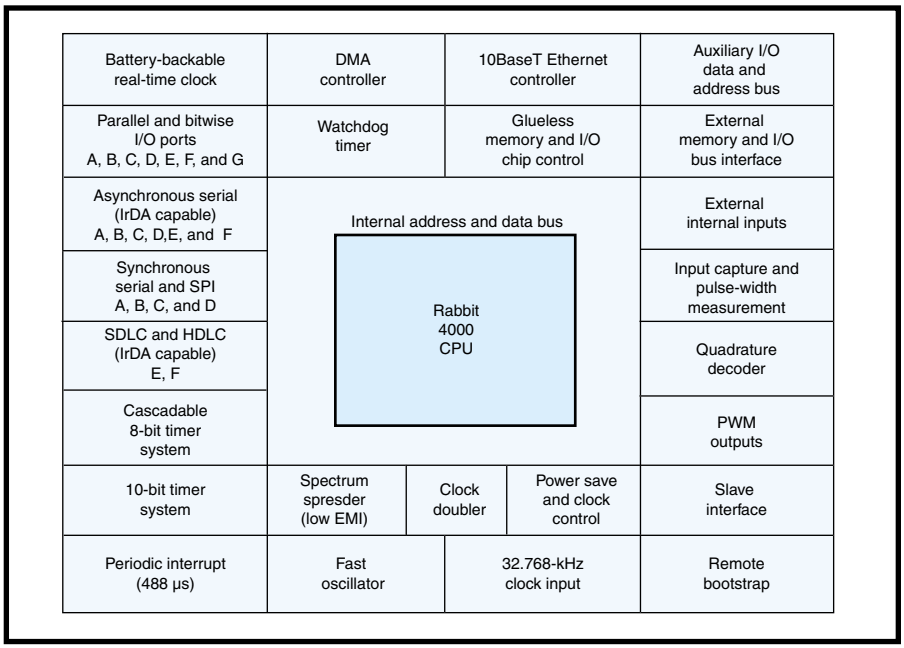


Figure 2—*The earlier Rabbit 2000 and 3000 chips have been making network connections for a long time, so it's no surprise to find on-board Ethernet in the new Rabbit 4000.*

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doesn't come with an A/D converter these days? There's nothing extraordinary about the raw specs for the '5282 converter itself (i.e., 10-bit, 100-KHz), but it's surrounded by an entire smart-queued subsystem that's comprised of internal (eight-channel) or external (18-channel) multiplexing, automatic scan sequencing and timing, dedicated results RAM, and user-defined channel-control processing.

It's overkill if you just want to check a temperature sensor or potentiometer from time to time. But, for sophisticated analog processing, the QADC offers the promise of offloading the CPU of a huge amount of handholding.

It's all the better that the '5282 also features an EMAC math accelerator that cranks 32 × 32 multiply results into a 48-bit MAC in a single clock. Unlike the early-out, two-bits-per-clock multiplier built into the ColdFire V2 core, the EMAC is not only much faster, but the timing is completely deterministic, which is a must for signal processing.

Oops, I almost forgot the 10/100 fast Ethernet controller (FEC) that's carried forward from the earlier MCF5272. At this point you shouldn't be surprised to find that the unit features it's own dedicated DMA (i.e., in addition to the chip's four-channel, general-purpose DMA controller) and RISC sequencer.

Finally, yes finally, there's even a controller area network (CAN) interface. The combination of CAN and Ethernet isn't as odd as it may seem. Ethernet is poised to make a big move into industrial and factory-floor applications, and it may happen sooner than you think.

The announced price for the '5282 is $17.86 (10,000 quantity), which is higher than some, but arguably a bargain considering all the stuff that's built in. Metrowerks (owned by Motorola) offers a combination of their popular CodeWarrior toolchain and an EV board for $600. Note that the package includes a royalty-free special edition of an RTOS and network stack (RTXC Quadros) that includes the basic network protocols. The more complete and configurable "Standard" and "Professional" editions cost $20,000 and $50,000 per project, respectively.

I also hear that Netburner has a '5282-based module in the works, which is no surprise, because it easily leverages the know-how and tools of its '5272-based design that I covered in my February column.

THE 80 WAY

These days, you don't necessarily need a 32-bit chip to get on the I-way.

A lot of interesting applications have low data rate requirements and don't necessarily need every protocol in the alphabet soup.

New chips from Zilog and Rabbit make the point. Although only eight bits in spirit (i.e., actually 24- and 16-bit ALUs, respectively), they demonstrate that although less may not be more, it may be enough to get the job done.

In my original article covering the then new eZ80 (*Circuit Cellar* 139), I proposed that it would be a good idea for Zilog to add built-in flash memory and an Ethernet MAC. Enter the eZ80F91. Starting with a 50-MHz version of the CPU core, the 'F91 adds 256 KB of flash memory to the original's 8 KB of high-speed SRAM. In addition, the 10/100 Ethernet MAC gets its own 8 KB of packet RAM to play with.

As an aside, note that Zilog is also introducing other versions (e.g., 'F92 and 'F93) without the Ethernet that have less memory and cut the clock rate to 20 MHz. Prices range from about $8 to $16 (10,000 quantity), accordingly.

Peripherals include the usual suspects: four timers, two UARTs, SPI, I^2C, a watchdog timer, etc. I noticed that the UARTs have a specific built-in IRDA capability. With all the buzz around wireless networking, I wonder if infrared shouldn't get a little more attention. Admittedly, the IRDA story has been complicated over the years by some fits and starts in terms of protocol complexity and feature creep; however, the recent widespread use of IR in PDAs should encourage designers to take another look.

As I write this column, Zilog is running a $399 special on the 'F91 development kit. That's a good deal considering the package includes everything: an evaluation board, C compiler, emulator, and TCP/IP stack (see Photo 2).

As for Rabbit, it's no surprise their upcoming R4000 makes an Ethernet play. Rabbit and its sister company Z-World have been leaders in bringing networking to blue-collar embedded apps. Currently, I don't have a full spec for this third-generation follow-on to the R2000 and R3000, but let me talk about what I know so far (see Figure 2).

Considering the subject at hand, the built-in Ethernet deserves the first look. Here, Rabbit takes a bit of a different tack than most others by eschewing a full 10/100 MII interface in favor of a leaner-and-meaner 10BaseT full-duplex-only setup.

Some of you will question the compromise, but I'm giving Rabbit the benefit of the doubt based on their historic experience in (and my own take on) the embedded network marketplace. Simply put, the Rabbit 4000 is more about cost than bit-blasting bragging rights, and their decision cuts the fat in a number of ways.

First, an official 10/100 MII interface calls for 18 pins to an external transceiver (PHY) chip. In contrast, Rabbit claims the '4000 will direct connect to the Ethernet with a mere $1 of external parts. Furthermore, making an honest effort to support the higher 100-Mbps data rate (not to mention 200-Mbps full duplex) demands a lot of dedicated hardware (i.e., the specialized DMA, buffer managers, packet RAM, etc. found on the other E-Chips). On the contrary, the '4000 can handle 10 Mbps in an entirely conventional manner with cycle-stealing DMA to and from main memory.

Ditching half duplex also simplifies the silicon, because you can say bye-bye to all of the baroque trinkets (e.g., collisions, back-off, retries, etc.) associated with CSMA/CD. In Rabbit's view, it's better to apply that silicon to the bottlenecks that real-world applications are likely to encounter. For instance, the '4000 includes a dedicated public key encryption calculation engine that cuts the time for serving a secure web page by a factor of 10 (from 20 to 2 s).

TINI THE TIGER

Last up is the Dallas (now Maxim) DS80C400. It starts with the 80C390 hyper-'51 core, which you may be familiar with. Even though it can mimic a traditional '51, the '400 goes way beyond the original with four-clock (versus 12-clock) operation at up to 75 MHz, large 16-MB address space, multiple data pointer registers, a 16/32-bit math accelerator, and so on.

It also has an expanded complement of the traditional '51 peripherals, including four timers and three serial ports, the latter of which comes with IRDA capability. Other additions include a one-wire controller for the company's clever multiplexed power and data scheme, a CAN interface (there it is again), and, of course, the 10/100 MII Ethernet MAC.

There's 9 KB of SRAM for scratchpad and Ethernet buffers, but the '400 really stands out from the crowd by virtue of its

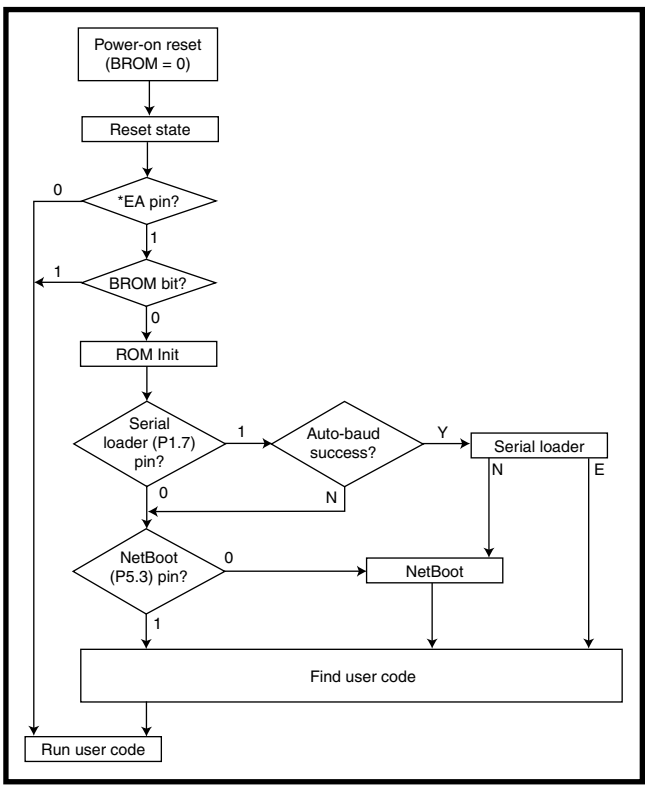


Figure 3—*The hardware is nifty, but the Maxim 80C400 is unique by virtue of its on-board ROM-based software suite including built-in network boot capability.*

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64-KB ROM that codifies a surprising amount of functionality. Sure, there's a serial monitor with the usual commands (e.g., display memory, load a .hex file, etc.), but that's just the beginning. In fact, there's also a TCP/IP stack that seems quite serviceable (even including some IPV6 functionality) considering the relatively small size of the ROM.

In turn, TFTP (a simplified file transfer protocol) is layered on top to provide a NetBoot capability (see Figure 3). That means at reset the '400 can download its code from the network, which has a number of ramifications, the most obvious being easy application code fixes and upgrades. Network booting also gives you the option of just using RAM to store both the application code and data. Alternatively, the feature has enough smarts to program certain types of flash memory chips as well.

Hooks are provided for your own application code to call useful routines in the ROM. These include networking (e.g., sockets, DHCP, TFTP, etc.), utility (e.g., initialization, random number generator, and one-wire driver), and even a tiny RTOS.

According to the web site, a '400-based version of the (currently '390-based) tiny Internet interface (TINI) development board will be available soon—likely by the time you read this because the schematics are already posted.

SOFT SELL

There you have it: five E-Chips ready and willing to do your embedded-network bidding. Thanks to the march of silicon, all of these look like a snap to design in. One caveat though: it appears the hardware side of the equation is much simpler than the software.

The fact is, when it comes to TCP/IP stacks and such, it's hard to discern claims from reality. As odd as it may seem, the networking software arena is remarkably devoid of formal performance and compliance testing. It's pretty much a "plug-it-in-and-see-what-happens" situation. Oh well, I suppose it wouldn't be an E-Ticket ride if it wasn't a little scary, right?

Tom Cantrell has been working on chip, board, and systems design and marketing for several years. You may reach him by e-mail at tom.cantrell@circuitcellar.com.

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[2] N. Abramson, "The Aloha System," *AFIPS Conference Proceedings*, AFIPS Press, Montvale, NJ, 1970.

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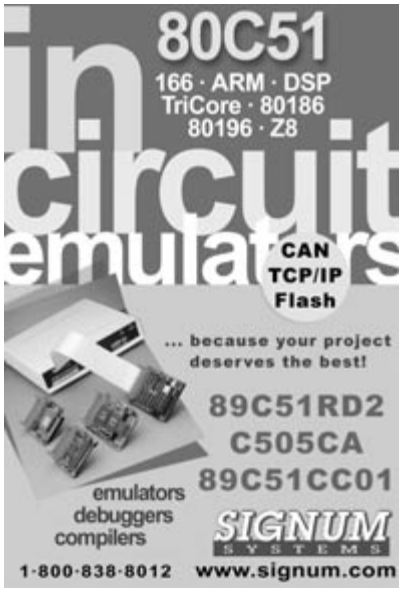
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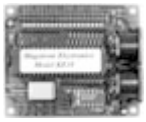
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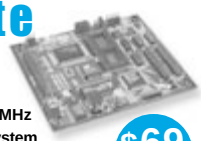
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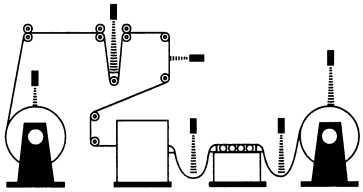


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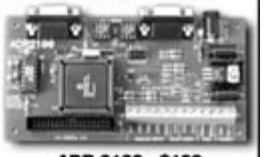
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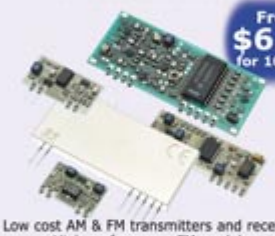
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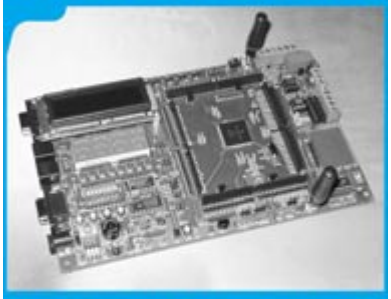


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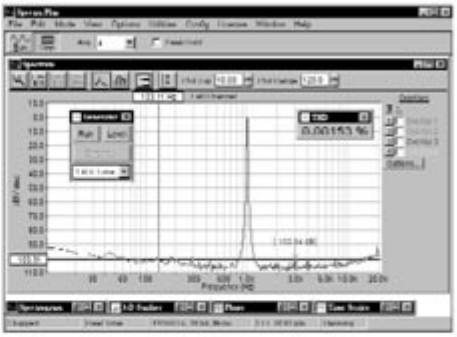
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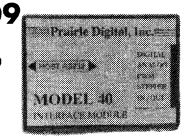
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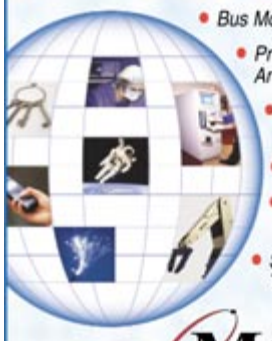
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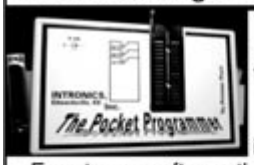
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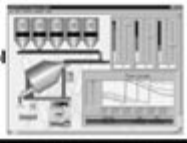
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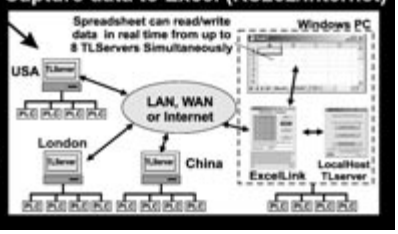


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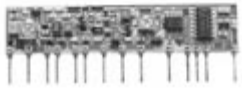
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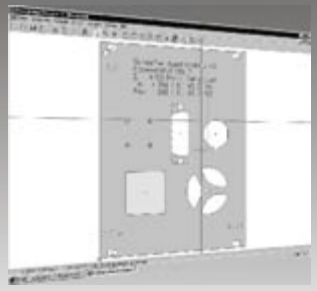
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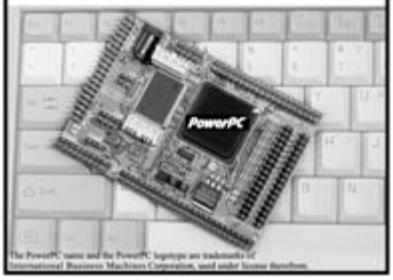
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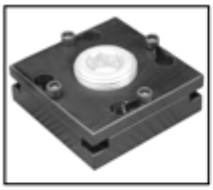
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The Advertiser's Index with links to their web sites is located at www.circuitcellar.com under the current issue.

Page		Page		Page		Page	
91	Abacom Technologies	87	EE Tools (Electronic Engineering Tools)	2	Link Instruments	56	R2 Controls
16	Acroname Inc.	29	EMAC, Inc.	69	Linx Technologies	33	R4 Systems Inc.
86	ActiveWire, Inc.	87	Embedded Micro Software	57	MaxStream	17	Rabbit Semiconductor
84	All Electronics Corp.	91	EmbeddedPCI.com	90	MCC (Micro Computer Control)	74	Remote Processing
87	Amazon Electronics	63	Embedded Systems Conference	11	Microchip	90	RLC Enterprises, Inc.
93	AP Circuits	89	EVBplus	88	Microcross	5	Saelig Company
7	Atmel	26	ExpressPCB	92	microEngineering Labs, Inc.	87	Scidyne
93	Avocet Systems, Inc.	86	FDI-Future Designs, Inc.	34	Micromint	3	Scott Edwards Electronics Inc.
91	Bagotronix, Inc.	9	Flash Innovation 2003 Design Contest	88	MJS Consulting	88	Sealevel Systems
48	Basic Micro	92	Front Panel Express	49	Motorola	87	Senix Corp.
91	Bellin Dynamic Systems, Inc.	86	Hagstrom Electronics	9	Motorola Contest	95	Sierra Proto Express
61	BMT Microelectronics Center	25	HI-TECH Software, LLC	50	MVS	85	Signum Systems
39	CadSoft Computer, Inc.	92	HVW Technologies Inc.	86	Mylydia Inc.	90	Softools
85	Caliber Instruments, Inc.	24	ICOP Technology Inc.	C2	NetBurner	93	Spectrum Engineering
68	CCS-Custom Computer Services	89	IMAGEcraft	88	OKW Electronics, Inc.	85	Square 1 Electronics
32	Cogent Computer Systems, Inc.	89,93	Intec Automation, Inc	29	On Time	93	TAL Technologies
92	Conitec	86	Intrepid Control Systems	87	Ontrak Control Systems	C3	Tech Tools
11	Connecticut mircoComputer, Inc.	91	Intronics, Inc.	74	PCBexpress	40,41	Technologic Systems
92	Cyberpak Co.	68	Intuitive Circuits, LLC	81	PCB123	88	Technological Arts
1	Cypress MicroSystems	93	Ironwood Electronics	C4	Parallax, Inc.	89	Tern Inc.
90	CWAV	23	Jameco	85	Phytec America LLC	91	Triangle Research Int'l, Inc.
72	Datadog Systems	64,86	JK microsystems, Inc.	85	Phyton, Inc.	26	Trilogy Design
91	DataRescue	18	JPA Consulting Ltd.	90	Picofab Inc.	82	Trinity College
86	Decade Engineering	68	JR Kerr Automation & Engineering	89	Pioneer Hill Software	93	Weeder Technologies
88	Delcom Engineering	35	K-Team S.A./Hemisson	72	Polydroids	93	Xeltek
89	Digital Products Co.	72	LabJack Corp.	90	Prairie Digital, Inc.	87	Z-World
65	Dreamtech Computers	35	Lakeview Research	90	Pulsar, Inc.	35	Zagros
73	Earth Computer Technologies	81	Lemos International	85	QKITS.COM	88	Zanthic Technologies Inc.
						15,47	Zilog, Inc

Preview of May Issue 154
Theme: Analog Techniques

Automotive G-Force Meter—Challenging the Factory Specs

DTMF-Controlled Switching System

Blueport—Bluetooth Interface for Embedded Systems

Updating the Home Control System—Part 3: The Complete Upgrade Solution

Nine-Band Spectral Sound Analyzer

Automatic Temp Controller

General-Purpose Cable Tester—Stand-Alone or with a GUI Front-End

- **Applied PCs:** Fresh ICE—MPLAB ICE 2000 Replaces PICMASTER
- **From the Bench:** Making Sense of the Gerber File Format
- **Silicon Update:** Digilog Déjà Vu

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What You Don't See Counts



People who consciously choose to be involved in the early stages of a revolution often face the consequences. No, I'm not talking about marching up to the guillotine while Marie-somebody is yelling about eating cake. I'm talking about our technical revolution and just what has happened in the past 25 years.

I tend to be Mr. Gambler when it comes to new technical stuff. I had one of the very first cell phones sold in Connecticut. It was back in '81 or so and it sounded like a great idea. I guess I just loved the old movies where the good guys had car phones. I had looked at getting one of those before the age of cell phones, but there were problems. Like Taxi Cab medallions, there were a limited number of phone frequencies and they were all taken. Someone had to either move out of state or die for you to get a license. The concrete on the first cell tower wasn't even dry when I ordered a phone.

The bad news was that my original cell phone weighed about 10 pounds and took a whole briefcase to carry it. I can remember that for about three years there wasn't even any coverage within 25 miles. If you lived in Fairfield County near New York there was coverage, but northeastern Connecticut was a communications wasteland. I could bore you to death with descriptions of other early experiences with videocassette recorders, stereo systems, digital cameras, digital audio recorders, and DVD players.

Today's challenge is HDTV. I bought my first high-definition TV, a 55″ Samsung rear-projection set, three years ago. Although there were no high-definition signals available to use it with, I justified the purchase with the thought that it could take the XVGA output from my laptop (for presentations or slide shows) and display progressive-scan DVDs. Of course, it was another year before somebody made a progressive-scan DVD, and laptops in the bedroom are about as useful as a car jack.

About a year ago it looked like the industry was finally getting its act together. HDNET started broadcasting a real 1080i signal via DirecTV, and some local stations were supposedly broadcasting high-definition signals in primetime. I decided to get a second-generation HDTV with the hope that the industry finally figured it all out. This time it is was a 65″ Mitsubishi Diamond rear-projection set. Of course, if you actually want high definition, you have to throw in another grand for an HDTV tuner.

My reason for describing all of this is not because I'm starting a chapter of high-tech buyers-anonymous. It's to warn you about the things they don't tell you when it comes to HDTV.

There is a tremendous difference between my first- and second-generation sets. I'm not familiar with everything being sold on the market today, but some manufacturers may still be offering what I call first generation as their introductory or lower-cost products. These are TVs that, although 1080i-compatible, don't offer the second-generation bells and whistles to keep from self-destructing. Let me explain.

HDTVs have screens with 16:9 aspect ratios. This is wonderful except that for the last three years, and still mostly today, there is little 16:9 programming. These sets are designed to show regular 4:3 aspect ratio NTSC programming by centering the image on the screen and having the rest of the screen blanked (usually with black vertical bars). The good news is that you can see regular TV. The bad news is that after a year or two of showing 4:3 content on a 16:9 screen, the first time you use 16:9 content you notice you have two bright vertical bars burned onto your screen. You'd think that the idiots who designed these things must use screen savers on their PCs, so they wouldn't be quite this clueless when designing TVs.

First-generation sets have limited capability to protect against this. They might provide digital picture stretching or something similar, but their conversion utilities between 4:3 and 16:9 don't offer enough versatility to actually use, so you always show 4:3 as 4:3. For the most part, the second-generation sets have significantly more digital processing capabilities that help you avoid burn-in. Selecting among Expand, Zoom, Stretch, or Narrow functions, you can typically fill the 16:9 screen with something that doesn't look too irritating.

Many people think that dropping $5K to $10K on a plasma HDTV solves everything. A plasma-screen TV does offer a less-cumbersome set with razor-sharp picture; however, you have to weigh its considerable advantages over its disadvantage, namely burn-in. Like CRTs, plasma has the same propensity to change brightness with age. I'm told that burn-in can actually be worse than CRTs. The only technologies that are not susceptible to burn-in are LCDs and digital light processing (DLP). Very little signal manipulation is applied when displaying a 1080i image, so both first- and second-generation HDTVs show high-definition pictures with exceptional quality. When you look at the high-definition picture on either one in the showroom, it's hard to understand why there can be thousands of dollars difference between the sets.

Unfortunately, present-day HDTV-broadcast content probably isn't much more than 5%. That means that 95% of the time you have to be careful how you use your set if you don't have an immune display technology or digital processing that evenly ages the display screen. The lesson is not to look at the great high-definition pictures in the store. They all look great. Put on a 4:3 NTSC station and ask the salesman how he deals with what you don't see.

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