

CIRCUIT CELLAR

THE MAGAZINE FOR COMPUTER APPLICATIONS

October 2010

Issue 243

SIGNAL PROCESSING

MCU-Based Doppler
Radar Transmission
& Reception

A Review of Essential
Frequency Domain
Instruments

Real-Time Feedback
with an LCD
Character Display

Build a Universal
Prototyping Board

PLUS

CPU TRANSPLANT

Use an FPGA to
Upgrade a Vintage
Calculator Design



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**Special offer for
electronica attendees!**
See p. 14

Low-cost Industrial Serial to Ethernet Solutions



- Instantly network-enable any serial device
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- Customize to suit any application with a development kit

SBL2e Chip

2-port serial-to-Ethernet server with eight A/D converter inputs and optional SPI, I2C, CAN peripheral device support



SBL2e 200

2-port serial-to-Ethernet server with four A/D converter inputs, optional I2C peripheral support and 10-pin header



SBL2e 100

2-port serial-to-Ethernet server with four A/D converter inputs, optional I2C peripheral support and RJ45 connector



SBL2e X

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SBL2e XA

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SBL2e 100	\$21.95 (Qty. 1000, Device P/N: SBL2e-100IR)
SBL2e X.....	\$79.00 (Qty. 1000, Device P/N: SBL2eX-100IR)
SBL2e XA.....	\$79.00 (Qty. 1000, Device P/N: SBL2eXA-100IR)

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Information and Sales | sales@netburner.com

Web | www.netburner.com **Telephone** | 1-800-695-6828

5 Competitive Advantages

Overseas Manufacturing

Imagineering, Inc. enjoys the reputation of being one of the most experienced & successful offshore PCB suppliers.

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Overseas Manufacturing

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Significant
Price Saving

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- Aluminum Metal Core Boards
- ...and many others

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Over the past 5 years, 70,000 prototypes have been successfully delivered from overseas to over 5000 customers



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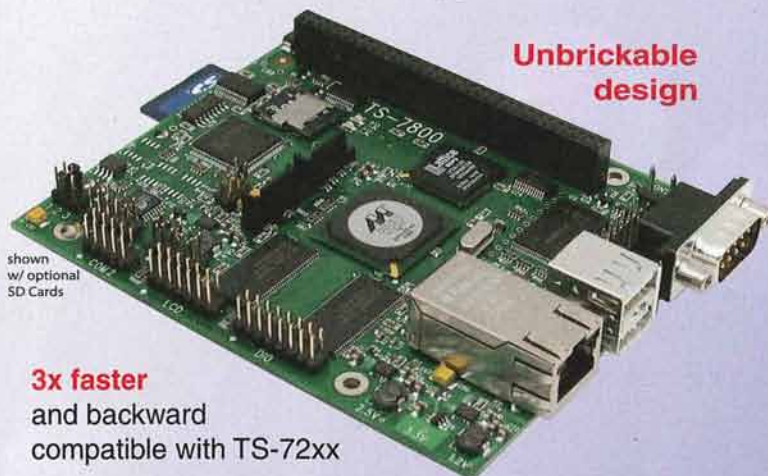
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- Gigabit ethernet
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- Sleep mode uses 200 microamps
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- Linux 2.6 and Debian by default
- 2 SD sockets
- 110 GPIO
- 2 SATA ports

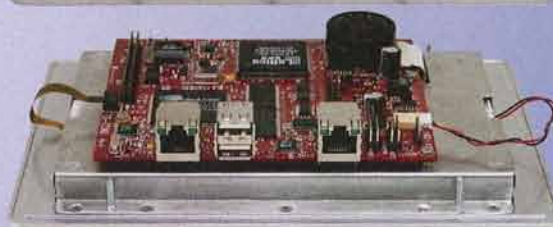
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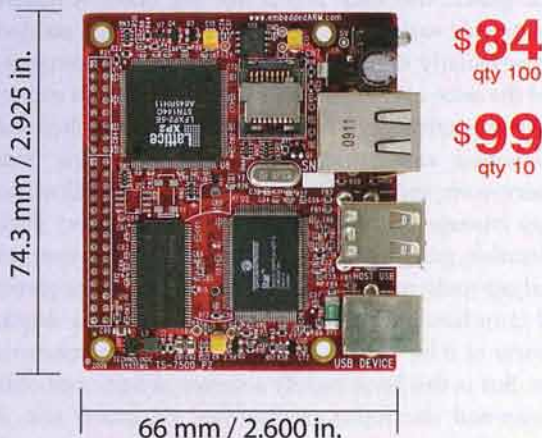
New Products

TS-7500 250 MHz ARM9

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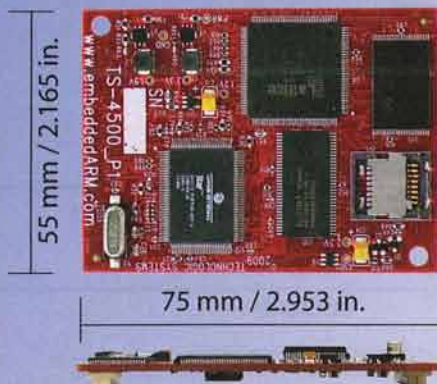


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- TS-4700: Marvell PXA168 with video and 1.2 GHz CPU
- TS-4800: Freescale iMX515 with video and 800 MHz CPU
- Several COTS baseboards for evaluation & development

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Embedded Design Basics and Beyond

At first glance, this issue seems like any other. It features articles on a wide variety of engineering topics. But if you look closely—particularly if you begin with the table of contents—you'll find the issue covers many of the most important subjects that comprise a university's EE or ECE curriculum: filter technology (low-pass and antialiasing); signal processing (radar design, microwave signals, and frequency shifting); calculation technology (vintage calculators and modern upgrades); FPGA implementation; prototyping (boards and MCUs); spectrum and signal analysis tools; robot design (robust design, failure prevention, and error-handling); graphics and real-time data display; and a review of 8-bit chip technology. Pretty comprehensive, right? Yes. But is this issue merely a survey of basic embedded technologies and electronics engineering? Of course not. As usual, our authors present insightful articles for professionals. They cover the basics and beyond.

There's no shortage of info about filters on the 'Net. But when using a filter in an embedded control project, you must find trustworthy content. George Novacek points you in the right direction with a refresher on low-pass, antialiasing filters (p. 12).

Between 2006 and 2008 Steve Lubbers published two articles in *Circuit Cellar*, both of which were about "sensing" and data analysis designs. In this issue he describes how to build a doppler radar system for tracking vehicle speeds (p. 16).

Whether or not you're intrigued by vintage technology, Monte Dalrymple's article on page 24 will pique your interest. He upgraded an old H-P calculator with FPGA technology.

I'm sure you're always working on one prototype or another. Turn to page 38 to learn how James Lyman built a universal prototyping board that he can customize for future projects.

On page 44, Robert Lacoste concludes up his two-part series about the essential equipment in his design lab. He focuses his attention in this article on frequency domain equipment.

Next, turn to page 54 to check out Ed Nisley's review of several robotics systems. Any decent engineer can build a working robot. But, as you'll see, it takes some serious know-how and planning to properly design against potential system failures.

Want real-time feedback from a design? Jeff Bachiochi suggests a character-based LCD module. It's a great choice for increasing a design's usability and performance (p. 62).

Tom Cantrell wraps up with a look at why 8-bit MCUs remain relevant (p. 68). Sure, 32-bit chips are used everywhere, but don't sound the death knell for the 8-bit chip quite yet.

Lastly, on behalf of the entire *Circuit Cellar* staff, I thank the more than 1,500 dedicated subscribers who took time out of their busy schedules to take our recent reader survey. Your input and thoughtful feedback will go a long way in helping us ensure *Circuit Cellar*'s publishing excellence for years to come.

cj@circuitcellar.com

C. Abate

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NXP and ARM/mbed challenge you to revolutionize the way people build prototypes! Build a reusable library, component interface, reference design or product prototype that can be shared on <http://mbed.org> to help others build their prototypes even faster, and you could be walking away with part of a prize pool worth \$10,000!

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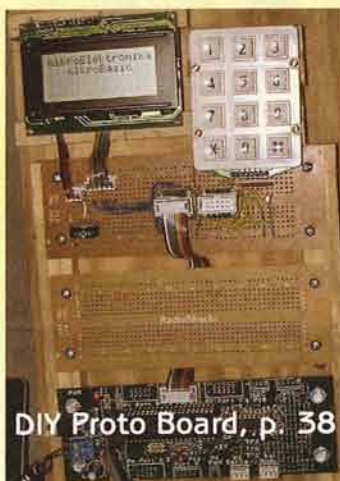
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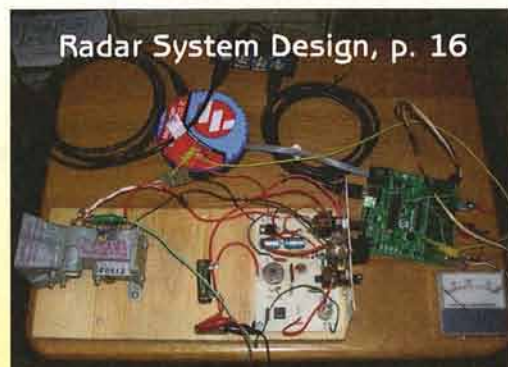
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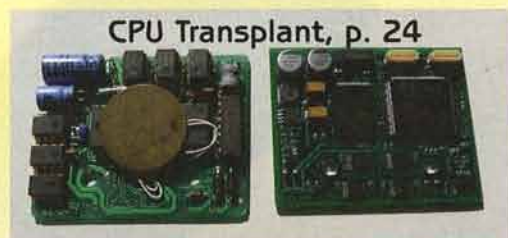
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Steve Lubbers
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Monte Dalrymple
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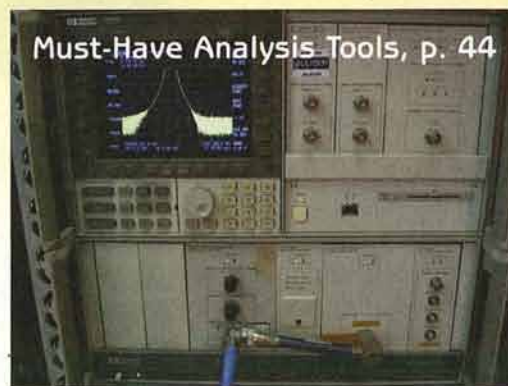
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In response to increased demand for gas sensors of all types and requests for low-power sensors, Synkera has introduced the first two products in the new **MikroKera** line. Designed for low power, reliability, and excellent performance, the new MikroKera H₂ and VOC sensors meet the needs of customers working on industrial health and safety, air quality monitoring, and process control applications. Both the new MikroKera and the current ProKera sensors accommodate the complex requirements of instrument and systems manufacturers.

The MikroKera family of sensors utilizes Synkera's unique micromachined, nanostructured, ceramic microsensor platform made from anodic aluminum oxide (AAO). This patented microsensor platform offers an unprecedented combination of performance, reliability, and scalability that will ultimately facilitate development of a complete family of sensors for existing and emerging industrial and commercial applications.

The first two sensors use the same sensing materials that have been successfully deployed in ProKera VOC and hydrogen (H₂) sensors, while reducing power consumption to approximately one-quarter that of the ProKera line, enabling new opportunities in portable and wireless applications. Additional MikroKera sensors for detection of chlorine (Cl₂), ammonia (NH₃), and hydrogen sulfide (H₂S) will be introduced later this year.

One-thousand-piece pricing starts at \$28 for the sensors.

Synkera Technologies, Inc.
www.synkera.com



NEW PRODUCT NEWS

Edited by John Gorsky

cleverscope

100 MHz MSO 8M Samples 14 bit



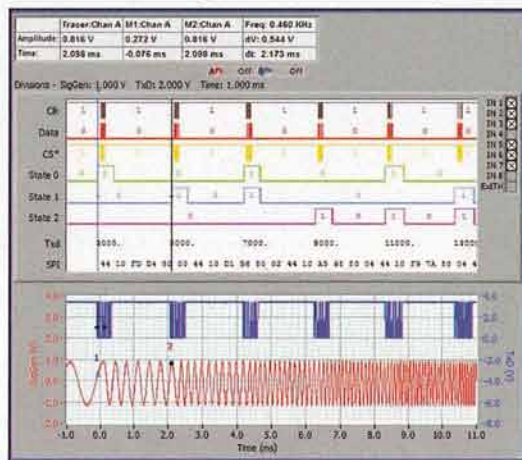
- + Two mixed signal triggers
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- + Ext Trigger, 8 Digital Inputs
- + 1 MSa/sec charting

Embedded Systems

Most embedded systems interact with the real world, and include analog and digital interfaces. State systems are often used for control, and to determine the system response to varying stimuli. Using Cleverscope's dual triggers you can capture a particular state, and verify that the digital and analog outputs are as expected.

www.cleverscope.com

Embedded Systems Development



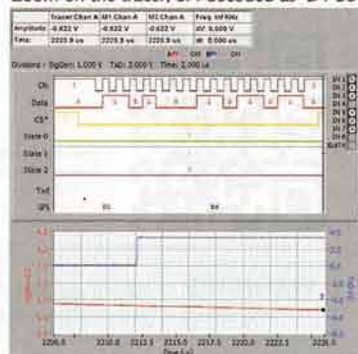
Example:

State based toy with sound. As each state is exercised, the controller sends an SPI message to the sound generator. Here a sinusoid is used for testing. Both the SPI message, and Uart test string are decoded and displayed. We triggered on State 001.

In the USA call:

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unique electronics
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Zoom on the tracer, SPI decoded as D1 B6



FLUSH DIAPHRAGM PRESSURE TRANSDUCER

The new **Model FT29xx** amplified pressure transducer is a rugged all-welded stainless steel sensor that combines a standard NPT male process connection with a flush diaphragm. In addition, the FT29xx pressure transmitter is designed with internal signal conditioning. Customers can select 4- to 20-mA current outputs, numerous voltage outputs, as well as digital outputs including RS-232, RS-485, and CAN-bus. The unique design of the isolation diaphragm reduces stress levels normally caused by torquing a tapered thread into the mating fitting. The FT29xx introduces zero dead volume to the fixturing and resists the accumulation of residue that can clog traditional pressure ports. The sensing element is machined from a single piece of steel, making the FT29xx insensitive to shock and vibration. This unit is ideal for metering and dispensing operations, for the application of sealants and paints, or anywhere a flush diaphragm unit is desired.

The FT29xx has an operating temperature range of -65° to 250°F (compensated: -30° to 170°F). Pressure ranges are available from 0 to 50 psi through 0 to 10,000 psig/a. Burst pressure is at least 3x F50 range. This compact sensor weighs about 8 oz, and delivers a static full scale accuracy of $\pm 0.25\%$ (BF5L). Each unit is shipped with a 19-point calibration record, traceable to NIST. The FT29xx integrates with a standard "bayonet"-style electrical connector. Options include alternative electrical terminations and NPTM pressure fittings.

The FT29xx is available now with standard pricing beginning at \$440.



Stellar Technology, Inc.
www.stellartech.com

LOW-POWER, LOW-NOISE ADC

The **AD9650** is a dual 16-bit, 105-MSPs, low-power, low-noise ADC designed for high-performance data acquisition systems in medical imaging, industrial, spectrum analysis, multimode radio, and radar applications. The AD9650 ADC consumes 328 mW per channel, which is half the power per channel of competing data converters while achieving an industry best SNR figure of 82 dBFS and SFDR (spurious-free dynamic range) performance of 90 dBc with a 30-MHz input.

Available in a compact 9 mm x 9 mm package, the AD9650 provides flexibility for engineers using proprietary differential inputs at frequencies up to 300 MHz and includes an on-chip dither option for improved SFDR performance with low signal level analog inputs. The new ADC is pin-compatible with ADI's previously released dual ADCs, including the AD9268 (16-bit, 125 MSPS), AD9251 (14-bit, 80 MSPS), and the AD9269 (16-bit, 80 MSPS), allowing system engineers to raise the performance of their data acquisition systems without changing the board layout.

The AD9650 operates from a single 1.8-V supply and a separate digital output driver supply, accommodating 1.8-V CMOS or LVDS outputs. The AD9650 is also available in speed grade options of 80 MSPS, 65 MSPS, and 25 MSPS.

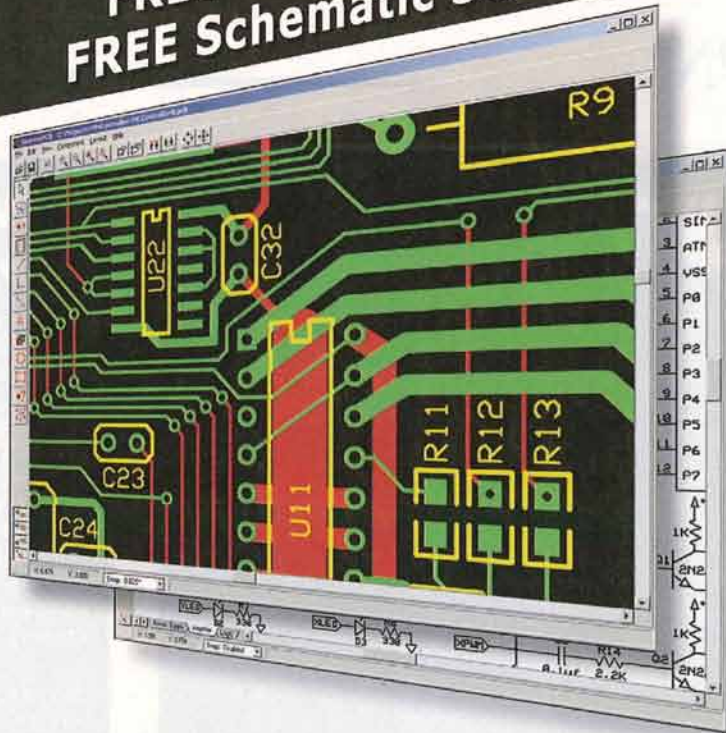
Pricing starts at \$52.50 for the AD9650-25 in 1,000-piece quantities.

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NEW IMS PROTOTYPING SERVICE

PCB-POOL has announced the introduction of a new metal core **Insulated metal substrate (IMS) PCB prototyping service**. Metal Core PCBs are designed to transmit heat away from operating areas on the PCB or components to less critical areas such as metal heatsink backing and metallic core.

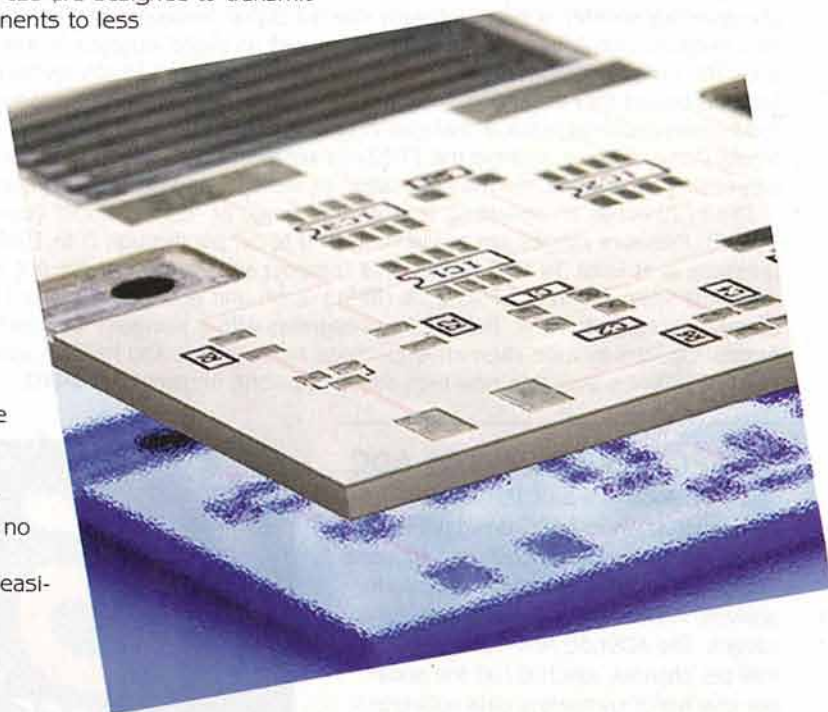
Designers of high-intensity LEDs, power converters, automotive applications, or any circuits requiring greater heat dissipation can now take advantage of reduced pricing and shorter lead times offered within this new service. Various machining methods have been integrated in the IMS manufacturing process. These include the ability to produce threaded drills holes, counter sinking, and controlled depth milling using the latest CNC technology.

Presently, one layer aluminum core printed circuit boards are being offered with core thickness of 1.5 mm, a 100- μ m isolation layer, and 35- μ m copper. The boards have a lead-free HASL surface finish and free laser SMT stenciling is available on prototype orders. There are no tooling or set-up charges, various solder mask and silkscreen colors are available, and there is no minimum order.

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Setting up a Panel PC can be a puzzling experience. However, the PPC-E7 Compact Panel PC comes ready to run with the Operating System installed on Flash Disk. Apply power and watch either the Linux X Windows or the Windows CE User Interface appear on the vivid color LCD. Interact with the PPC-E7 using the responsive integrated touch-screen. Everything works out of the box, allowing you to concentrate on your application, rather than building and configuring device drivers. Just Write-It and Run-It. Starting at \$495.

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Edited by David Tweed

ANSWERS for Issue 242

Answer 1—In synchronous digital transmission systems such as T1 or E1, data is transmitted continuously, packed into fixed-length "frames." For example, a T1 system carries 24 channels of voice-grade audio, using 64 kbps of data per channel. The data is taken 8 bits at a time from each audio channel, for a total of 192 payload bits per frame. The frames occur at a rate of 8,000 per second, and one bit is added to each frame to establish frame alignment, for a grand total of 1.544 Mbps.

Over a series of 12 or 24 frames, called a "superframe," the frame bit position contains (among other things) a fixed pattern of ones and zeros that allow the equipment receiving the signal to establish the correct timing that will allow it to extract the 24 individual voice channels from the data stream. This function is accomplished by a block of logic called the "framer."

The framer works by looking for that specific combination of fixed bits in the correct relative positions within the data stream. It is the predictability of those bits, as compared to the randomness of the rest of the data, that allows this process to succeed.

Answer 2—A sequential framer examines the incoming bits one at a time, and changes its internal state based on what it sees. It can typically only test one potential frame alignment at a time, which means that it may take up to N^2 bit times to find frame alignment on an N -bit frame, even when there are no bit errors in the transmission. This can be a very slow process, but it was a commonly used approach when the available digital hardware was limited to small-scale and medium-scale digital logic.

In contrast, a parallel framer contains a ring buffer that holds one or more frames, with suitable taps that allow all of the frame bit positions for a particular potential frame alignment to be examined simultaneously. This kind of framer can find frame alignment within one frame period in

an error-free transmission, and typically within a few tens of frames in the presence of bit errors. All modern LSI line interface chips use parallel framers.

Answer 3—When the transmission system has bit errors (and they all do, at some level), it is necessary for the framing algorithm to be robust in terms of recognizing the frame pattern even if a few bits are wrong. However, care needs to be taken so that random data patterns aren't accepted as true frame patterns.

The usual approach is to have two different thresholds for the number of erroneous bits, depending on whether the framer is currently "in frame" or "out of frame." When out of frame, the framer wants to be very conservative about going into frame—fewer bit errors allowed. However, once in frame, the framer wants to be more liberal—more bit errors allowed—before declaring itself out of frame. This approach creates a system that is relatively robust in the face of error bursts that may last for several frames. In digital telephony systems in particular, it's generally more acceptable to have a burst of noise in each channel than to have the whole system go mute for a while.

Answer 4—Absolutely! A radio time signal such as WWVB is highly predictable—in fact, except for a few bits relating to the UT1 offset and leap seconds, it's completely predictable. Therefore, even with the rather high bit error rate seen on these signals, a robust framing algorithm should be able to lock in on the signal—and the time of day—within a few minutes.

Given the low data rate (1 bps), even a rather modest microcontroller would have plenty of CPU cycles and memory to implement a very robust framing algorithm. It's just a matter of taking the techniques learned in the high-speed hardware framers and implementing them in software.

Contributed by David Tweed

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Filters, Filters Everywhere

There's no lack of information about filters and filter design on the Internet. But you need to know specifically how filters figure in embedded control systems. This means you must be familiar with low-pass, antialiasing filters.

It's hard to imagine a system where a filter of some sort would not be used. Communications, signal processing, controllers, power supplies: filters permeate all electronics. Based on their frequency response, we know low-pass, high-pass, band-pass, and band-reject filters. These can be further subdivided by the specifics of their frequency/phase response—such as Butterworth, Chebyshev, Bessel, elliptic—and can be realized in the frequency domain as analog or in the time domain as digital.

Analog filters, passive and active, utilize resistive and reactive components: resistors, capacitors, and inductors. A gain block, usually an op-amp, is added to make the filter active. There are many advantages to active filters, but their usefulness is limited to a few megahertz and relatively low-power applications. All filters generate a gain-versus-frequency slope of 20 dB/decade for each order (e.g., 40 dB/decade for the second-order filter).

Digital filters perform their task by computations and, therefore, process digital signals only. The three basic digital types are the finite impulse response (FIR), infinite impulse response (IIR), and fast Fourier transform (FFT). The switched capacitor filter is a hybrid, which should be more appropriately called "discrete time filter" rather than digital. It samples its input in discrete time intervals but processes analog signals.

Many books have been written on the subject of filters and their design. This month, I want to look at filters found in every embedded control system: the low-pass, antialiasing kind. Figure 1 is a block diagram of a simple closed-loop control system.

LOW-PASS FILTERS & ALIASING

We see low-pass filters preceding the ADCs on the command and feedback analog input signals. Their purpose is to limit the bandwidths

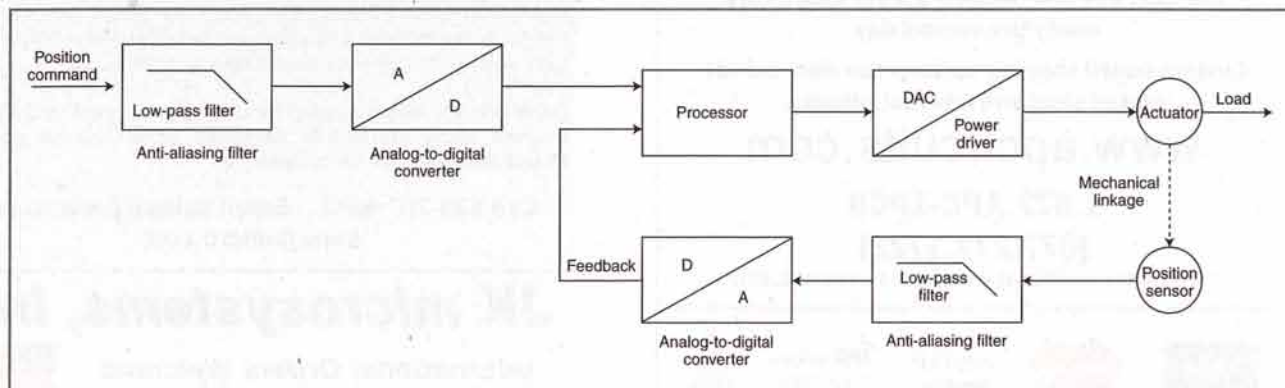


Figure 1—A basic closed-loop position control system

of those signals before digitization to prevent aliasing.

What is aliasing? You can see it in movies when the movement of propeller blades or a wagon wheel's spokes exceeding the frame rate can appear to move slower, even backwards. Nyquist's criterion tells us that the sampling frequency must be higher than twice the highest time-continuous sampled frequency in order to faithfully convert it to a time-discrete signal. Otherwise, a phantom frequency, equal to the difference of these frequencies, will become an integral part of the resulting digital signal.

CONTROLLER DESIGN

Let's say we are building a controller as in Figure 1 for a system to position an aircraft control surface. A typical control bandwidth of such a system would be around 5 Hz. We decide to digitize the control and feedback analog signals at 50 samples per second. In flight, the surface will be exposed to perturbations by air movement which the position feedback transducer is picking up as 51-Hz vibrations. If the 51-Hz signal is not sufficiently attenuated by the low-

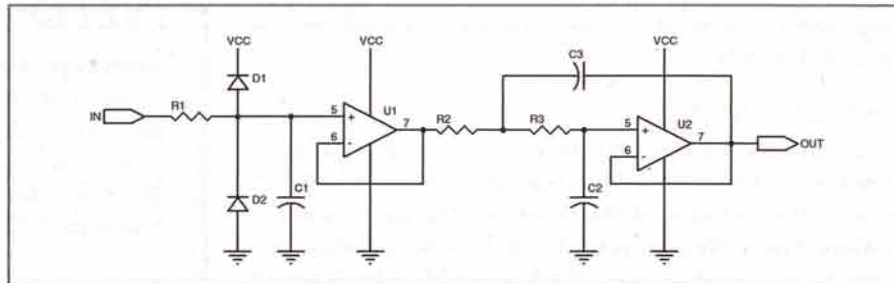


Figure 2—A low-pass antialiasing filter

pass filter, a new 1-Hz control signal will appear. Because 1 Hz is within the system control bandwidth, it will cause unwanted, erratic movement of the control surface.

The data acquisition part of the design will be a trade-off between the sampling rate and the order of the filter required to attenuate all out-of-the-band frequencies to an acceptable level. I personally like to use no more than the fourth-order filters. With the sampling frequency 10× the bandwidth, the resulting -60-dB attenuation of the third-order filter in Figure 2 should be sufficient. The system designer, however, not you, must specify the magnitude and the spectrum of out-of-the-band signals to be encountered.

You can use analog filters, passive or active, or switched capacitor. It is my personal preference to use a passive first-order filter followed by a buffer, followed by a Sallen-Key second-order filter, as shown in Figure 2, for the -60 dB/decade slope. R1 being typically 100 kΩ can ensure lightning Level 5 (the highest) and electro-static discharge (ESD) are sufficiently suppressed by inexpensive signal diodes D1, D2, and capacitor C1. (Make sure R1 can survive the high voltage without flash-over.) Sallen-Key filters are simple to design and the setup has always satisfied my requirements. I try to keep my circuits simple for robustness, to achieve high reliability, and to minimize defects in manufacturing.

A low-pass Sallen-Key filter and its derivatives do not continue to attenuate at the same slope forever. Depending on the op-amp's bandwidth and its open-loop gain, the output will begin to rise at some point. This can be compensated for by the preceding first-order filter and the buffer's bandwidth. The result is shown in Figure 3.

With increasing popularity of delta-sigma ADCs, antialiasing filters can be reduced to simple RC, while internal digital filters do the rest. Choosing a digitizer is a matter of analyzing the trade-offs between performance, resolution, component count, reliability, cost, obsolescence, and other engineering considerations.

Once the signals have been digitized, digital filters can be employed. In the closed-loop controller, they usually are a part of the processor software, typically performing the PID (proportional, integrating, derivative) compensation. PID is still the most common compensation in use, but

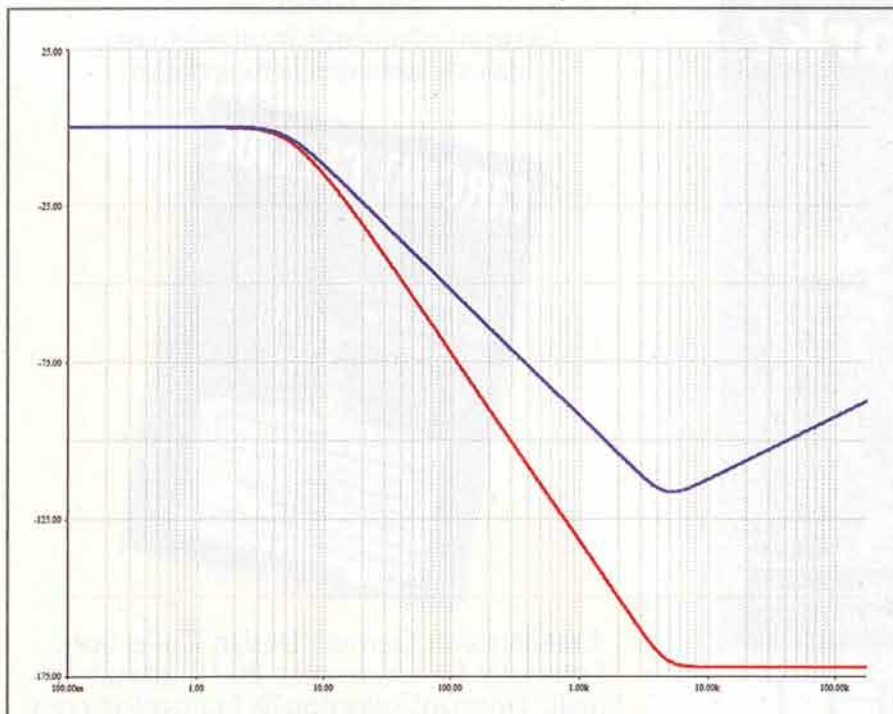


Figure 3—The frequency response of the antialiasing filter in Figure 2. The blue trace is the Sallen-Key filter alone. The red trace is the entire filter. Note the decreasing attenuation of the Sallen-Key filter above 5 kHz.

more sophisticated filters—such as adaptive and Kalman—are gaining in popularity.

UNDERSAMPLING

Since I touched upon Nyquist's criterion, I'd like to finish with a few words about undersampling, which some call a violation of the criterion. The name is misleading. Harry Nyquist postulated that the sampling rate must be greater than twice the bandwidth. Also being the highest frequency is only a special case. Undersampling is of great use in digital communications.

Imagine that we have a 70-MHz intermediate frequency (IF) carrying data within bandwidth $B = 4$ MHz. To satisfy Nyquist's criterion, we can sample at $2.5\times$ the bandwidth—that is, at 10 MHz. The 70-MHz IF and the 10-MHz sample rate will alias, fold back, and recover the data in a DC-to-less-than-5-MHz baseband.

"There are many ways to skin a cat," goes a popular saying. Engineering is about choosing the best way. Your engineering duty is to consider all the often contradictory requirements, make the trade-offs, and come up with the best design. ■

George Novacek (gnovacek@nexicom.net) is a professional engineer with a degree in cybernetics and closed-loop control. Now retired, he was most recently president of a multinational manufacturer for embedded control systems for aerospace applications. George wrote 26 feature articles for *Circuit Cellar* between 1999 and 2004.

NEED-TO-KNOW INFO

Knowledge is power. In the computer applications industry, informed engineers and programmers don't just survive, they *thrive* and *excel*. To learn more about some of the topics covered in George Novacek's 243 article, the *Circuit Cellar* editorial staff recommends the following:

No Fear with FIR

Put a FIR Filter to Work

by Robert Lacoste

Circuit Cellar 207, 2007

Working with finite impulse response (FIR) filters isn't black magic. Robert covers the basics and touches on the mathematical concepts you'll need to understand in order to put a FIR filter to work. Topics: Filters, FIR Filter, Fourier, DFT, IDFT

Time-Triggered Technology

by Robert Lacoste

Circuit Cellar 231, 2009

With cascaded integrator-comb (CIC) filters, you can tackle signal-processing problems. With them and some multirate signal-processing techniques, you have an option when a FIR filter doesn't fit the bill. Topics: Filters, CIC, FIR, Sampling Rate, Digital Mixing

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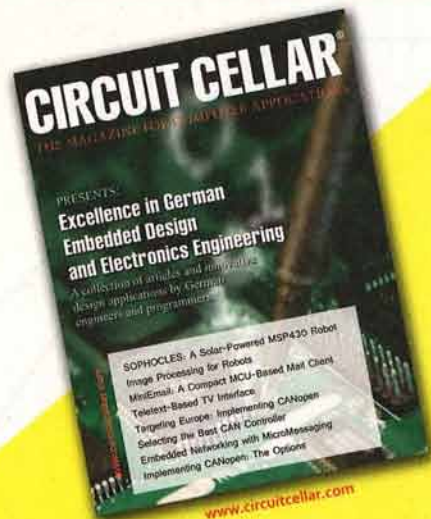
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Doppler Radar Design

A Doppler radar system can enable you to track speeding vehicles. This design generates a microwave energy burst with a 10-GHz transceiver. The microwave signal bounces off a moving vehicle and the frequency shift is measured to determine its speed.

In 1988, Steve Ciarcia and Ed Nisley introduced the "Neighborhood Strategic Defense Initiative" by going high-tech to launch plastic soda bottles.^[1] Generally, strategic defense initiatives include radar tracking systems. So, in 2007, I created a Microchip Technology dsPIC30F4012-based Doppler radar system of my own (see Photo 1). Perhaps we should collaborate to launch soda bottles at cars that speed through my peaceful neighborhood. What do you think, Steve?

RADAR

Radio detection and ranging (RADAR) has been around since the 1900s when Nickola Tesla proposed the principles for radar operation. In the years leading up to World War II, radar technology advanced to the point that countries were able to develop basic systems for the detection of and defense against aircraft and ships.^[2] Today, radar is commonly used for meteorology and air traffic control. I use my project for traffic enforcement.

Radar examines a returned radio signal to discern several facts about the signal reflected from a target. If the antenna

rotates, the position of the antenna indicates the direction to the target. The transit time between the transmission and the reception of the transmitted signal indicates the distance to the target. The phase of the returned signal can also indicate the distance to the target. The size of a target is indicated if you have both the distance and signal strength. The Doppler shift of the received signal indicates the relative speed of the target. The absolute frequency shift of the signal indicates if the target is coming or going.

To implement basic traffic speed radar, I only need to measure the Doppler shift of a reflected radio signal. The frequency shift of the reflected signal is directly proportional to the target's speed. I'm saving the other embellishments for more sophisticated radar for another day and another project.

A common example can illustrate how Doppler works. Imagine a railroad train approaching a crossing. You hear a high-pitched horn as the oncoming train compresses the audio wave. The horn lowers in pitch after the train passes and the audio wave extends. The change in the horn's tone is caused by Doppler. If you know the actual frequency of the train's

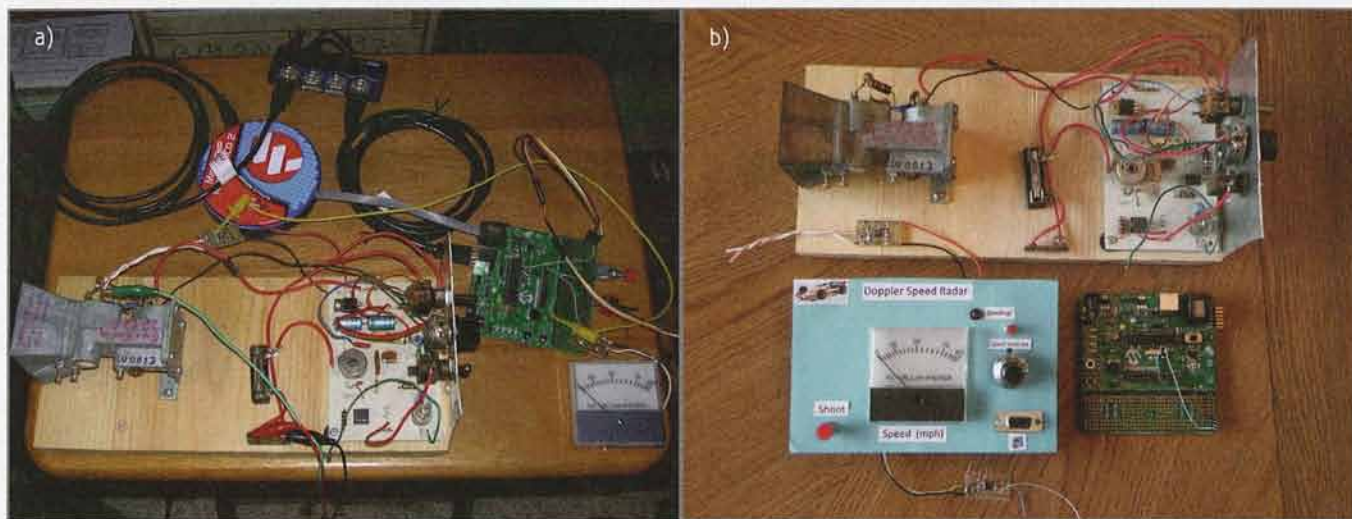


Photo 1a—This is the Doppler radar design. b—I disassembled the Doppler radar system so you can see its major components. The microwave Gunnplexer is located on the upper-left side. It is connected to its power supply and the remains of an amateur radio microwave transceiver. Below the Gunnplexer is the RF amplifier circuit. A Microchip starter board (right) contains the CPU and the digital electronics. Speed is displayed on the control panel shown on the left. Below the speed display is the analog meter driver circuit.

horn, you can determine the train's speed by measuring the frequency shift.

I constructed my own speed radar in 2007 by connecting a microwave transceiver to a dsPIC processor. A radio signal was "bounced" off of a target and the frequency (Doppler) shift was measured to determine the target's speed.

PROJECT GUIDE

I built my Doppler radar to learn about radar, to experiment with microwave radio transmissions, and to participate in the Microchip Technology 16-Bit Embedded Control 2007 Design Contest. Since I am primarily a software engineer by profession, this project provided a great learning experience! If you are looking to learn, use my project as a guide. Please note that the RF section of this project (primarily the Gunnplexer) is rare and expensive. Once upon a time, Gunnplexer-based microwave systems were used as the sensor for automatic door openers at supermarkets. In those days, reproduction of this project would be simple. Assorted types of Gunnplexers were easily found at electronics surplus houses.

Today, alarm systems use passive infrared (PIR) and automatic entry doors use integrated RF systems, so Gunnplexers have fallen out of favor and have become obsolete collectors' items. How many of you still have 8" floppy disks? However, a suitably motivated individual should be able to track down the parts at an electronic flea market or in an online auction. The pair of Gunnplexers that I experimented with were borrowed from a fellow ham and represented about \$1,000 worth of electronics.

While a door opener operates as an unlicensed radio transmitter, my radar used a transceiver that was tuned to 10.250 GHz in the amateur radio 3-cm band. Frequencies in the range of 8 to 12 GHz are referred to as X band, so that makes my project an X-band radar system. My extra-class ham license was required to legally operate this particular system. Amateur radio operators traditionally direct signals at the moon and meteor showers for modes known as "moon bounce" and "meteor scatter," respectively. It might be fun to actually make a two-way radio contact using "school bus scatter."

If you are just looking to clock the speed of your tennis serve, I can recommend a lower-cost radar kit. Use my article to learn how a radar gun works and then buy the kit to play with it in the backyard. If you are looking to experiment like I did, then be prepared for a search and a rewarding education.

SYSTEM OVERVIEW

With knowledge of how radar works and how the Doppler shift represents an object's speed, you can build a system to track vehicles' speeds. Grab the Gunnplexer and point it at a moving vehicle. Press the Shoot button. Refer to Figure 1 as I describe the inner workings of the system.

The Shoot button triggers the software to generate a burst of microwave energy at 10 GHz using a 10-mW Gunn diode. The waveguide and feed horn concentrate and focus the energy pulse at the car down the street. The transmit power may be low, but it is concentrated, so don't look into the end of the antenna when it is energized.^[3] Just imagine this as a miniature microwave oven and use a little bit of caution!

The microwave energy hits the oncoming vehicle and scatters. A portion of that scattered energy reflects back into the horn-shaped antenna at the end of the Gunnplexer. The reflected signal is Doppler-shifted based on the motion of the vehicle. The receiver provides a fixed amplification to the

signal, and a programmable-gain amplifier (PGA) can provide additional amplification.

An analog-to-digital converter inside the processor collects and converts the received signal. When its buffer is full, the transmitter is turned off and processing begins.

A 256-point FFT processes the collected data and returns the strongest frequency component. This is assumed to be caused by the car now driving past you. The frequency component is converted to the vehicle's speed and displayed on an analog panel meter. If the indicated speed is greater than a set speed threshold, an LED illuminates to indicate that your neighbor is speeding.

You know how the overall system works. Now let's examine the hardware and software that make it all happen.

MCU & GUNNPLEXER

The Doppler radar hardware shown in Photo 1 consists of a microwave Gunnplexer hooked to a microcontroller evaluation board. Since the project was created as an entry for a Microchip embedded design contest, the evaluation board of choice is the Microchip 28-pin starter board. The Gunnplexer provides the microwave front end. An op-amp-based amplifier section is used to condition the receive signal. The Microchip starter board pulls together the digital hardware components of the system.

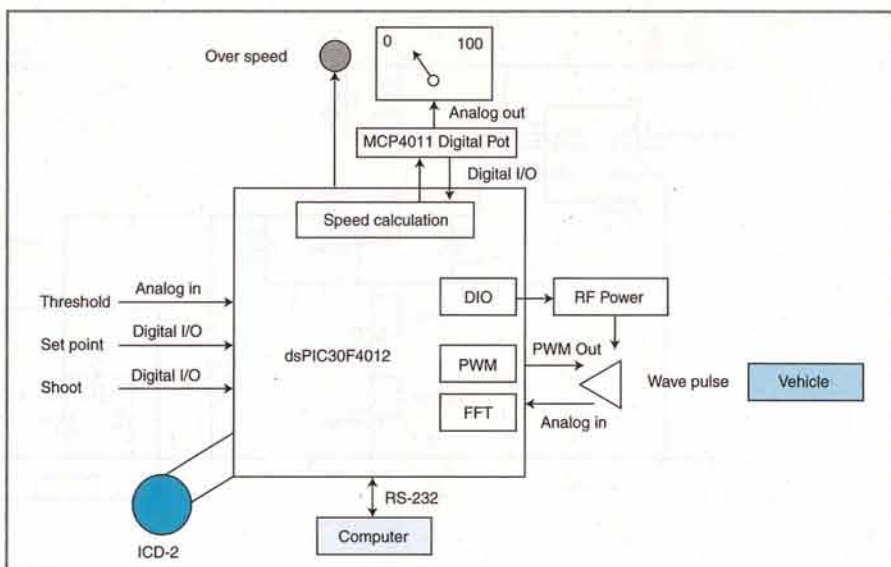


Figure 1—My Doppler radar system is built around an RF system and a dsPIC. A few simple peripherals like an analog meter and some push buttons complete the system.

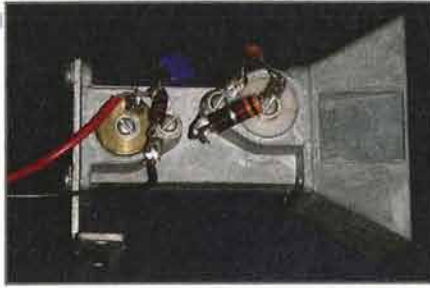


Photo 2—The SOLFAN Doppler module is a transmitter, a receiver, and an antenna all rolled into one. On the left is the Gunn diode transmitter. In the center is the mixer diode receiver. The flared metal at the right is the antenna.

The contest suggested (and provided) a selection of components that, if used well, could earn a participant a bonus prize. Where possible, these components were selected for use in the hardware.

My Doppler radar uses a Gunnplexer for the RF transmitter and receiver. The SOLFAN Doppler module shown in Photo 2 and Photo 3 is a commercial Gunnplexer microwave unit that combines a Gunn diode microwave oscillator transmitter with a microwave mixer diode receiver. The receiver's local oscillator injection comes from the Gunn diode. The transmitter and receiver come mounted in a horn-type waveguide antenna.^[4]

Gunnplexers operate around 10 GHz,

with a power output of 5 to 10 mW. Gunnplexers were manufactured for use in alarm systems and automatic door openers. The usual mode of operation for a Gunnplexer is wideband FM. By modulating the power to the Gunn diode, a wideband FM signal is created that is received by the receiving mixer diode. This method requires an FM demodulator in the receiver.^[5]

A simplified mode of operation can be used to get just the Doppler shift from the Gunnplexer. An unmodulated Gunnplexer will receive a beat note in the mixer diode. The frequency of the beat note can be converted to the speed of the Gunnplexer's target. I will use this simplified method in my Doppler radar. The addition of FM demodulation hardware (or software) could be added to the receiver to produce a more robust system. The existing software would remain essentially unchanged.

TRANSMIT CONTROL

The Gunnplexer circuitry shown in Figure 2 operates on 8 VDC.^[6] A TC4427A low-side MOSFET switch allows the dsPIC to turn on the transmitter to measure the target speed and then turn it back off again. The radar operates in full-duplex mode with both the transmitter and receiver operating simultaneously, but unless there is a



Photo 3—Since the average digital engineer may not be too familiar with RF, I've provided a second view of the Gunnplexer. Toward the top of the picture is the horn-shaped microwave antenna. You can see the mixer diode inside the cavity. At these frequencies, plumbing becomes electronic wiring.

steady stream of traffic, you won't need the radar system turned on constantly. If you enhance the system to use an FM signal in place of CW, the dsPIC has internal PWM circuitry to generate a tone.

RECEIVER AMPLIFIER

Experimenting with the Gunnplexer, I discovered that the mixer diode delivers an AC-coupled peak signal of approximately 50 mV with approximately 70 kHz of noise. This signal is not well suited to the analog input converter in the dsPIC chip. The Rx amp circuitry shown in Figure 3 will amplify

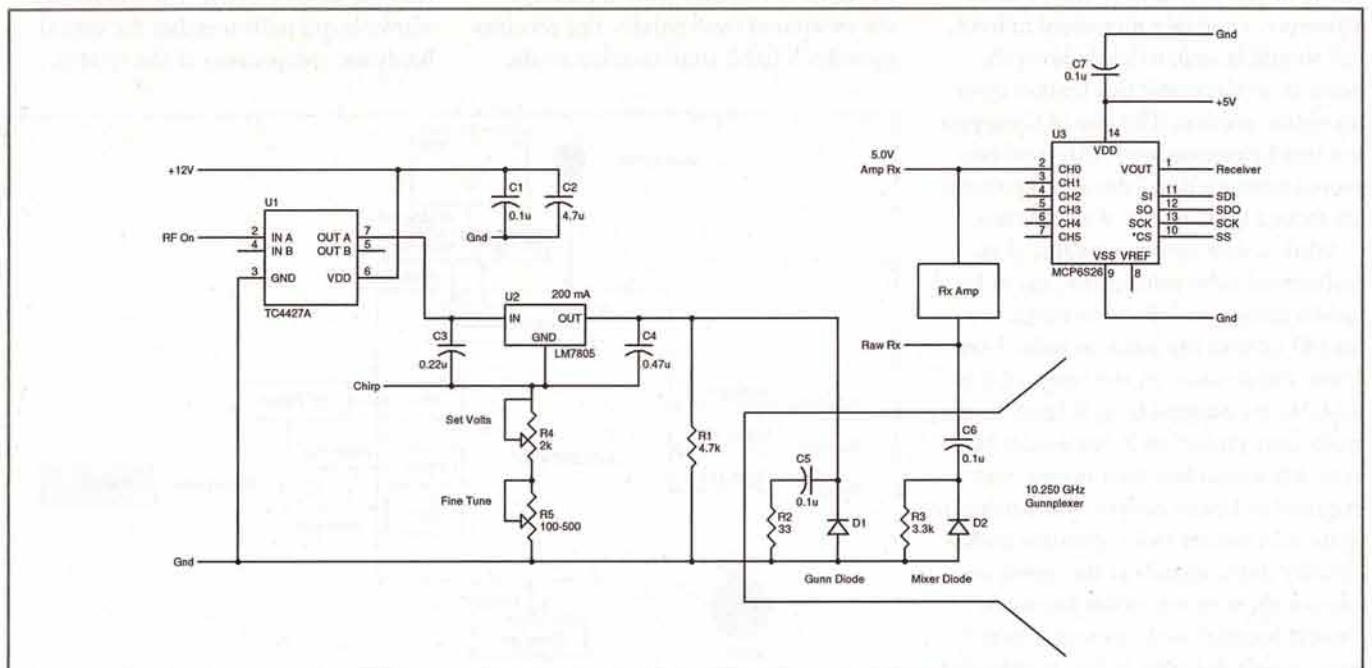


Figure 2—An FET switches the microwave Gunnplexer transceiver on and off. Adjustments are provided to bias and tune the Gunn diode around 8 V. Optional receiver amplification is provided by an MCP6526 PGA.

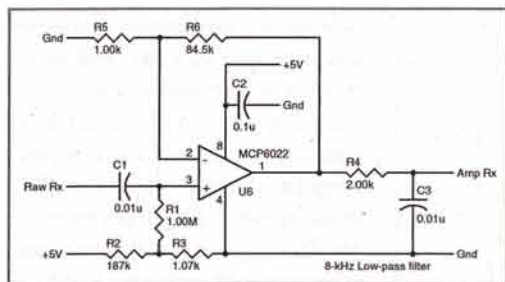


Figure 3—The receive signal obtained from the mixer diode is insufficient to provide meaningful information to the CPU. To compensate, a gain of 87 is applied using an amplifier. The signal is offset to 2.5 V to arrange the signal for processing by the DSP algorithms.

and condition the signal for the PIC's analog-to-digital converter.

The receive amplifier circuit is based on a Microchip Technology MCP6022 dual rail-to-rail amplifier with a bandwidth of 10 MHz. One amplifier is AC-coupled to the Gunnplexer mixer diode and provides a gain of 87 $\times$, offset by approximately 2.5 V to center the signal about the ADC's zero point. A passive RC low-pass filter removes high-frequency noise from the receive signal. The second half of the op-amp was reserved for the possible active filtering of the receive signal.

I anticipated implementing variable gain on the receive signal. To this end, I added a Microchip Technology MCP6S26 PGA in line with the received signal. Two problems were

encountered in this area, so the software is left incomplete, and the MCP6S26 operates in its default mode as a unity-gain buffer.

The dsPIC SPI port shares the serial data pins (SDI and SDO) with the in-circuit debugger. I was unable to quickly resolve the conflict with these signals while still allowing the debugger to operate. A second problem occurred by amplifying the now DC-coupled receive signal. Both the signal and the offset were amplified, quickly saturating the amplifier. I'm sure that the software problems can be resolved, and my friend the analog designer promised a hardware solution, but time was running short, so I left the amplifier at 1 $\times$ gain and moved on to other parts of the project.

In practice, the Gunnplexer with a fixed-gain amplifier was able to clock the speed of cars a few houses away in my residential neighborhood. Thus, my project was a success in spite of the incomplete amplifier section.

CPU

My Doppler radar required a microcontroller with DSP capabilities. The microcontroller features enabled the I/O and control features required by the project. The DSP capabilities were required to perform signal processing on the

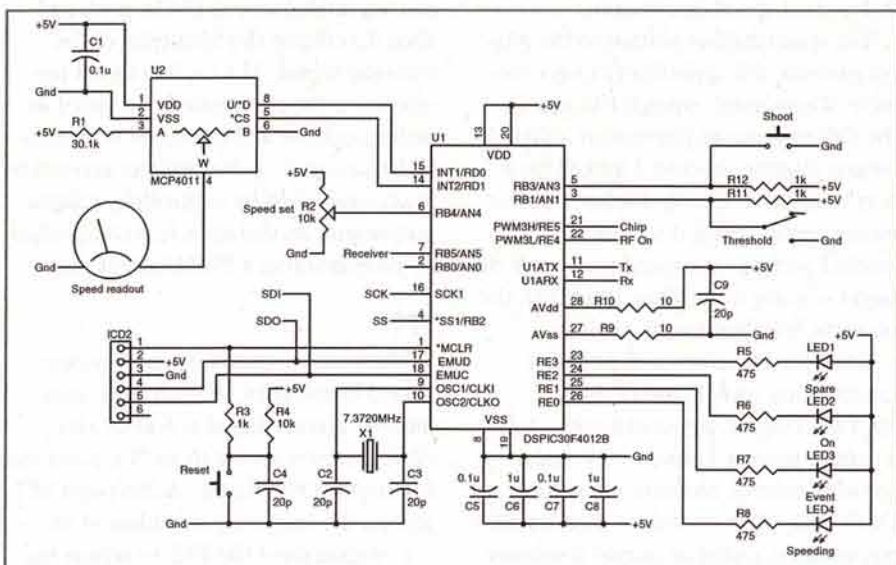


Figure 4—The Doppler radar design is built around a dsPIC30F4012. The PIC's basic wiring is based on the Microchip 28-pin starter board. A digital potentiometer drives an analog meter as the primary user interface.

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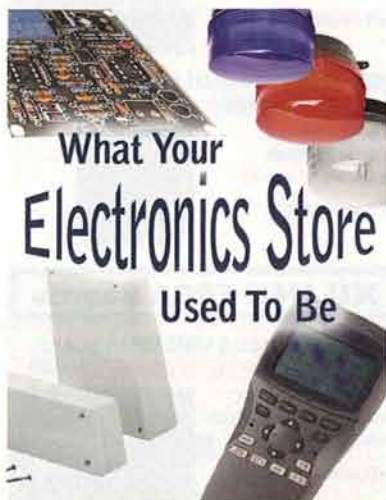
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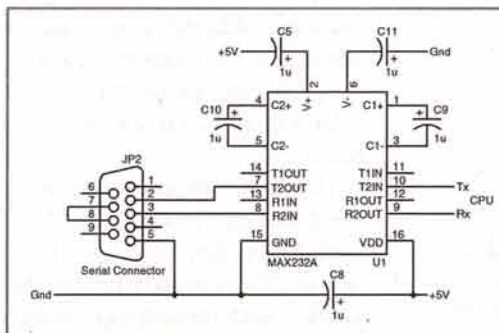


Figure 5—Data logging is one of my system's extra features. A MAX232 voltage-level converter enables the radar gun to connect to a PC's serial port.

received radio signal. The dsPIC30F4012 CPU fulfilled all of the processor requirements. It features an ADC for RF input capture, PWM output for transmit signal modulation, and general-purpose I/O to control the remaining hardware features. Software development and debugging was eased by using the Microchip ICD2 interface. I chose the dsPIC's 28-pin DIP package so I could use a Microchip 28-pin starter board as the base of the digital hardware (see Figure 4).

USER INTERFACE

Operating the speed radar is quite simple! Just "point and shoot." You aim the Gunnplexer radar antenna at a moving target. Press a transmit switch to measure the speed and display it. For versatility, there are two possible speed displays. There is an analog display needle and a serial-speed datastream.

The speed display portion of the project gave me the opportunity to get creative. There aren't enough I/O pins in the DIP package to implement a digital output scheme. Instead, I looked for a way to drive an analog display. I had an analog meter scaled 0 to 100, which seemed perfect for a speed readout. If the target is going faster than 100 MPH, the operator is in big trouble anyway.

Since the PIC chips lack a DAC, I invented my own. I wired a 6-bit MCP4011 digital potentiometer to select a voltage ranging from 0 to 5 V under software control. Shazam! I now have a DAC. The 6 bits provide 64 discrete output voltages, giving an output resolution of under 2 MPH. The first meter I tried to use overloaded the digital pot by exceeding its current carrying capacity. I found

that the 10-k Ω version of the pot has sufficient current capability to drive a microammeter.

In order to enforce the neighborhood traffic laws, my Doppler radar has a discrete LED that illuminates when a vehicle exceeds 25 MPH (a local limit). A secondary user interface is supplied by the RS-232 interface in Figure 5. The serial interface can be used to trigger the radar transmitter. The speed determined by the radar is displayed back to the serial port. The serial interface can be connected to a PC to collect a record of the speed of all of the cars that drive down the street.

SOFTWARE

Microchip was kind enough to provide its MPLAB IDE (v7.52) and C30 compiler to participants in the 2007 design contest. At the completion of the contest, the software reverted to the free edition. I didn't require any special features from the C compiler, so when the license expired, I was able to generate the same executable code as during the contest license period.

Recall that the Gunnplexer returns a frequency that is proportional to the speed of the object reflecting the transmitted signal. This applies to both an unmodulated (CW) signal and a modulated FM signal. In its simplest form, the software needs to activate the transmitter, modulate it if FM is used, and then determine the frequency of the received signal. The receive signal frequency is then converted to a speed in miles per hour and the speed is presented (see Listing 1). Transmitter activation is accomplished by controlling a digital output pin. Modulation is accomplished by programming a PWM output pin.

FFT

The receive signal frequency is determined by using an FFT. An ADC samples the receive signal at 8 kHz. The ADC samples are fed to an FFT (from the Microchip DSP library). A 256-point FFT reports the frequency to within 31 Hz.

I programmed the FFT to return the two largest frequency components. When the radar gun is used from a fixed position, the largest frequency

Listing 1—The main software loop makes understanding the operation of the radar system simpler. The transmitter is activated, the reflected signal is buffered, and the signal is turned off. The strongest receive component is converted to target speed, and the speed is displayed on an analog meter.

```

Chirp_On();                // Modulate the transmitter
ADC_Collect_uWave();        // Collect samples from receiver

                             // Wait for ADC sampling to complete
while (!ADC_SamplingComplete()){

Chirp_Off();               // Stop transmitter modulation

if ( Cals.FunctionEnable.SpeedFFT ) {    // Execute FFT on receive data
    FFT_main(&F1, &F2, &M1, &M2);
    // Calculate Speed
    S2 = F1 * SHOOT_FFT_SLOPE;
    ScaledSpeedInput = S2 + SHOOT_FFT_INTERCEPT;
    TargetSpeed = ScaledSpeedInput;    // Remember last speed for user Inquiry.
} else {
    TargetSpeed = ScaledSpeedInput;    // Remember last speed for user Inquiry.
}

Needle_Speed(TargetSpeed);    // Display target speed and set speeding LED

```

component represents the speed of the target. The second frequency component is used with moving radar. When a police car is in pursuit, the strongest frequency component represents the speed of the police car. The second frequency component represents the speed difference to the target. The difference between the two frequencies represents the absolute speed of the target. Either the peak frequency or the difference frequency could be displayed, depending on whether the radar is fixed or chasing a bandit.

SPEED & USER DISPLAYS

The receive frequency is converted to speed, where 30 Hz is approximately 1 MPH. The conversion constant can be fine-tuned by using the radar to report the speed of a car traveling at a known speed. Finally, the speed result is presented to the user via an analog display or a serial port interface.

The primary output of my Doppler radar is the target's speed displayed on an analog meter. An LED accompanies the meter to indicate if a preset threshold has been exceeded, and the target is "speeding." The analog display is driven by an MCP4011 64-position digital pot, which the dsPIC controls using two digital output lines. One line controls the direction of change (up or down). The second output line is toggled to step the pot in the desired direction. Refer to the software

module Needle.c and the MCP4011 datasheet for specific details on the sequencing of the control signals.^[7]

Since the digital pot can only move by steps up or down, the controlling

software must remember the current display position. At start-up, the position is moved to zero, assuming the pot is at the upper limit. Future changes move the position based on the internal

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stored pot position. Feedback can be obtained from an unused ADC input, but that modification is an exercise for you.

Speed readings are scaled between 0 and 100, giving the display a resolution under 2 MPH. The new position is compared against the old position, and the difference is applied to the pot controls to display the new value. If the new value exceeds the preset threshold, the LED illuminates. If the new speed is below the threshold, the LED is cleared.

A second output for my Doppler radar is an RS-232 serial interface. The serial interface allows a computer to request a speed check from the Gunnplexer. The calculated target speed is displayed back to the serial port.

The serial datastream contains the time of day so that a time log of speeds can be recorded. Additional serial commands for system testing and debugging are available. Refer to the software modules Serial.c and Keyboard.h to explore them.

The serial port software uses the dsPIC UART, using its alternate I/O pins. The hardware UART offers a wide variety of buffering options for the incoming and outgoing data. Only the simplest single-character buffered interrupts are required for this project.

AUTOMATIC GAIN CONTROL

My original design concept called for the SPI port to control a PGA that could be used for an automatic gain control. The PGA would allow the software to adjust the receive amplitude as required.

The SPI basic software is included with my project. I experienced difficulties using the ICD-2 and the SPI, likely due to their shared pins. Fortunately, the radar gun functions without the aid of automatic gain control.

FUTURE UPDATES

My Doppler radar project proved to be an educational exercise. Continuing education could make the radar more useful. Commercial traffic radar uses the phase of the received signal to indicate range and a modulated tone to indicate if the target is "coming" or "going."

I use the Gunnplexer's default mode, which returns a "beat" frequency that Doppler-shifts based on the movement of the reflector. This signal is subject to noise and interference. The ham radio community has found that a wideband FM signal is more robust.^[5] Use of a modulated tone on an FM signal would allow phase and frequency determination while providing a more reliable product.

Once I am tired of watching cars, I might turn to the weather. The National Weather Service uses Doppler radar to track weather patterns and storms. I wonder if my radar can bounce a signal off of raindrops or clouds. And what would the return signal tell me?

Right now, my radar system is definitely experimental. But a little work on an enclosure and a portable power supply would go a long way toward making this an easy-to-use mobile device. ☐

Steve Lubbers (KE8FP@arrl.net) started his budding electronics career in the days of "Ciarcia's Circuit Cellar" when he designed an 8080-based computer as a high school science fair project.

Since high school, Steve has achieved an extra class amateur radio license and a B.S. in computer science. He currently builds amateur radio embedded systems for fun and embedded automotive electronics for profit.

PROJECT FILES

To download the code, go to ftp://ftp.circuitcellar.com/pub/Circuit_Cellar/2010/243.

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SG7 Speedy Radar Kit

Ramsey Electronics | www.ramseyelectronics.com

24-GHz Gunnplexers

SHF Microwave | www.shfmicro.com

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by Peter Baston

Circuit Cellar 215, 2008

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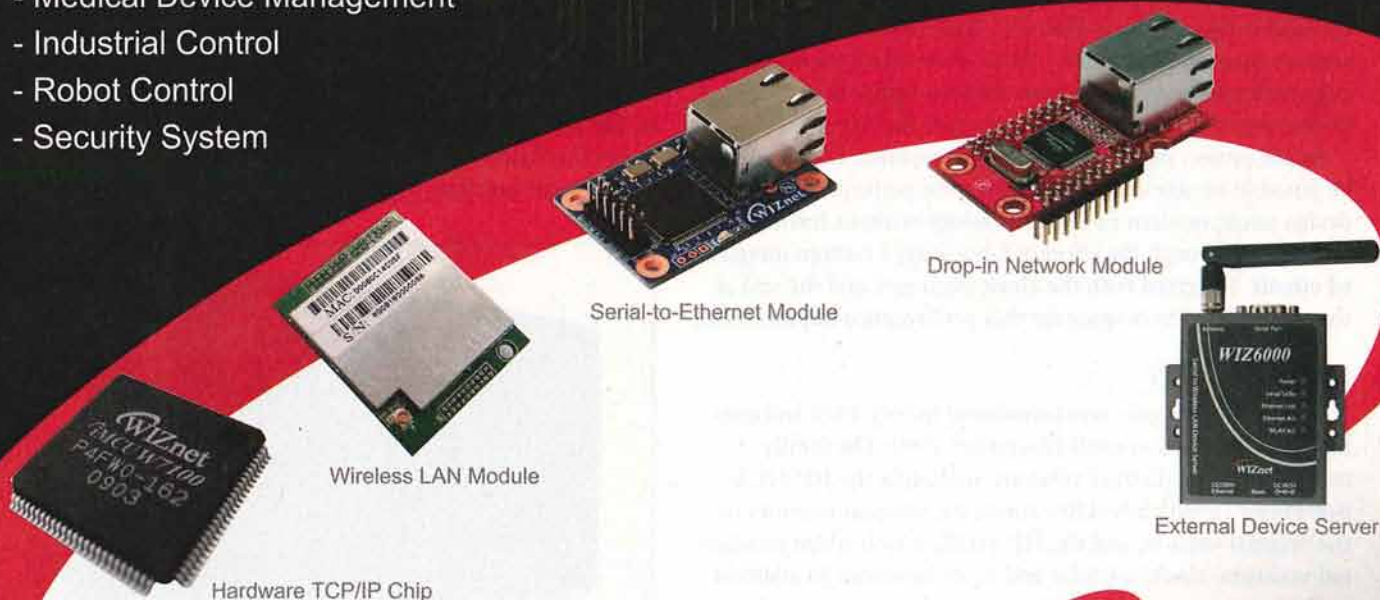
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Calculator Brain Transplant

Update a Vintage Design with FPGA Technology

Do you remember the glory days of Hewlett-Packard calculators? Here you learn how to replace the CPU in a 30-year-old calculator with an improved FPGA implementation.

If you look inside a modern hand-held calculator, you'll probably find a standard microcontroller, standard static RAM, and perhaps flash memory. But as late as 2003, at least for Hewlett-Packard calculators, you would have found only custom integrated circuits, highly optimized for performing BCD floating-point math while using miniscule amounts of power. While this change is understandable given time-to-market pressures, using off-the-shelf components is less than optimal in terms of either performance or power. But many times I have heard that the main reason for the change is that it is "too expensive to develop custom integrated circuits." While this is true for leading-edge technology, this assertion does not apply here. This project started as a way to demonstrate this fact.

As the project progressed, it became apparent that it would be possible to significantly improve the performance of the design using modern FPGA technology without having to actually go through the effort of fabricating a custom integrated circuit. I targeted both the clock frequency and the size of the processor address space for this performance improvement.

HP-41C FAMILY

The HP-41C family was introduced in July 1979 and continued in production until November 1990. The family included several distinct versions, including the HP-41CV (see [Photo 1](#)), which had five times the internal memory of the original version, and the HP-41CX, which added an internal real-time clock/calendar and more functions in addition to the extra memory.

For several reasons, many consider this family to be the pinnacle of HP calculator technology. Perhaps the most compelling reason is that the HP-41 was more than just a

calculator; it could legitimately be called a handheld computer. The block diagram for the calculator is shown in [Figure 1](#). Note that all of the buses are one bit wide, and there are no chip selects for the ROMs and RAMs because each custom chip had a hardwired address range.

The four I/O ports provide access to the internal bus, and a number of peripherals were available. Peripherals included a miniature magnetic card reader for permanent program storage, several different printers, a floppy disk drive, a barcode wand for program input, an RS-232 interface, a video interface, and more.

One plug-in connected to a proprietary serial bus interface, called HP-IL (Hewlett-Packard Interface Loop), which allowed an HP-41 calculator to control any piece of HP test equipment that had an HP-IL interface. Another peripheral was available to interface to HP-IB (Hewlett-Packard Interface



Photo 1—This HP-41CV is older than any of my kids. It is still the first calculator I reach for while at my desk. I've only gone through half a dozen sets of batteries in over 25 years of operation.

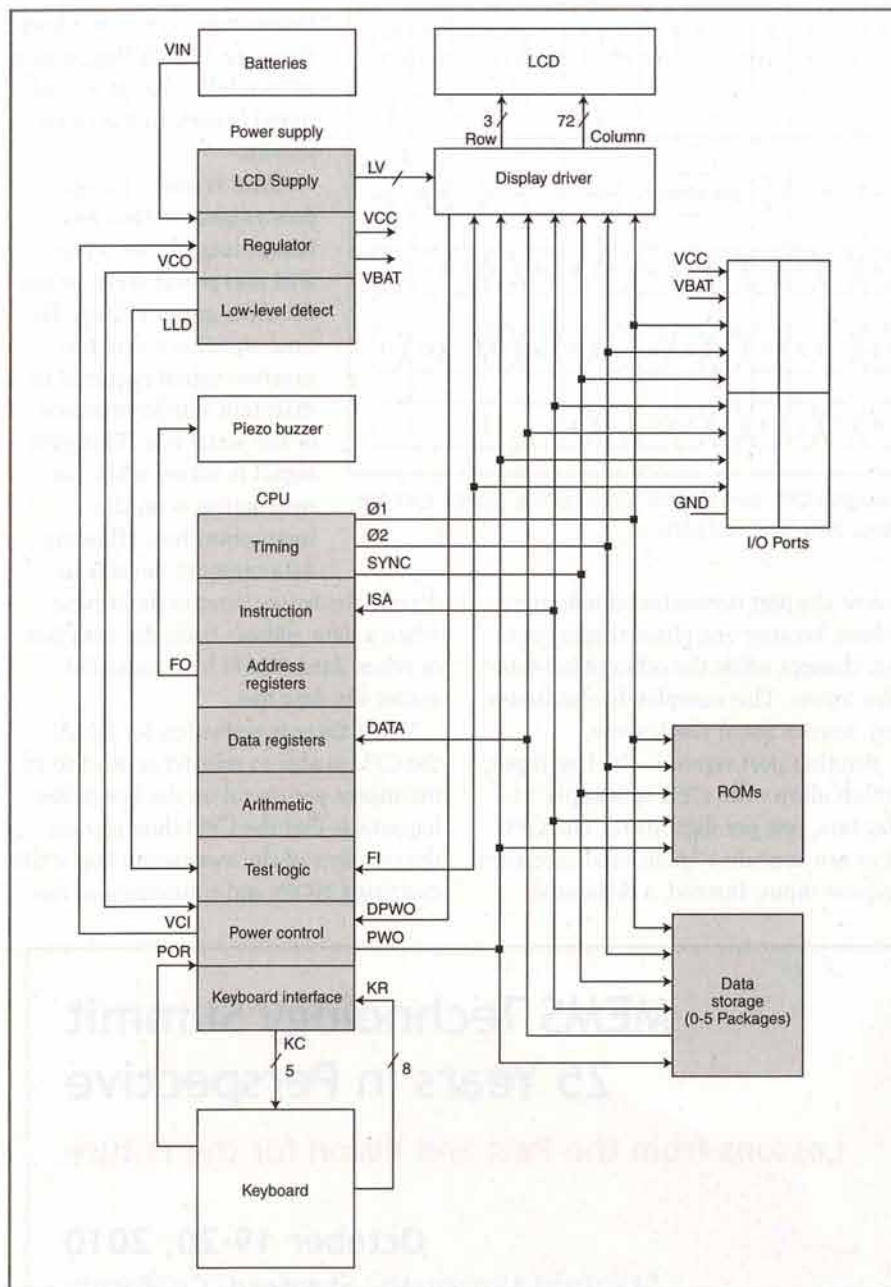


Figure 1—The calculator hardware looks like any other embedded computer system. The shaded portions are on the daughterboard. Two connections within the I/O ports are hard-wired so that each port is unique.

Bus), which later was standardized as IEEE-488.

But the primary use for the ports for most users was to hold RAM or preprogrammed ROM modules, and there were too many different types of these modules available to list here. My objective of increasing the processor address space came about so that images of these ROM modules could be included internally using standard memories and virtually plugged into a calculator port under software control.

The internal construction of all but

the last revision of the family is one key to the success of this project. In the majority of HP-41 calculators, the keyboard, port connectors, display, and display driver were on one PC board, while the CPU, memory, and power control circuitry were contained on a small daughterboard. This daughterboard was not soldered to the main board, but connected through 32 circuit board pads using a pair of flexible “zebra” type connectors. This made it theoretically possible to design a form-fit-function replacement processor board.

The second key element for this project is the fact that Hewlett-Packard released the specifications for most of the custom integrated circuits used in the calculator, along with the source code for the operating system software. Now, let’s take a look at the custom microprocessor that is the brain of these calculators.

CPU & SYSTEM TIMING

The CPU used in the HP-41C family traces its roots back to the original HP scientific hand-held calculator—the HP-35—which was introduced in 1972. The processor operates on data bits serially, which requires both the fewest transistors and the least amount of power per operation. This also has the advantage of requiring very few pins on packages, which helps with both cost and circuit board area. Keeping this bit-serial operation makes it easy to fit the design into a very small FPGA (see [Photo 2](#)).

The CPU uses 56-bit data words, organized as 14 nibbles or digits (see [Figure 2](#)). These 14 digits correspond to the native floating-point format, which includes a two-digit exponent, a digit for the exponent sign, a 10-digit mantissa, and a digit for the mantissa sign. While in normal operation, the digits are BCD numbers. The CPU contains a mode bit, which allows the digits to be treated as regular binary. This is necessary because the data words can also hold alphanumeric data (for programs and the display) as well as memory address information. It’s interesting to note that this CPU was also used in a number of other HP calculators, including the HP-12C, which continues in production today (albeit with a different CPU internally).

With 56-bit data words, the CPU operates with a 56-clock-cycle machine cycle, with most instructions requiring just one machine cycle. Only program branch instructions and one Load Immediate instruction use two machine cycles. The bit-serial operation mandates that the instruction fetch and execution be pipelined, so the instruction fetched during the current machine cycle is actually executed during the subsequent machine cycle.

The processor employs a Harvard architecture, with completely separate program and data address spaces. So,

while the data is 56 bits wide, instructions themselves are only 10 bits wide. Instruction memory addresses are 16 bits, while the data memory addresses are 12 bits. Being serial, the instruction and data buses each require just one pin. This makes the system bus on the port connector much simpler, requiring only seven signal lines.

The instruction bus carries both the instruction address and the instruction itself during each machine cycle, while the data bus carries either the data address or the data during each machine cycle. Because data addresses don't change very frequently, the address for the data memory is explicitly transferred to the memory devices rather than being available in every bus cycle.

A two-phase clock is used, so this is two more of the port signals. The choice of a two-phase clock makes the timing

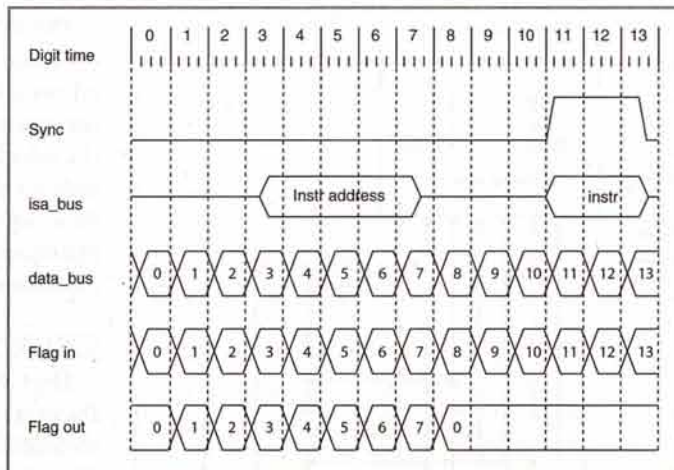


Figure 2—The original CPU uses a serial bus interface. Speed isn't the objective; package pins (and cost) are.

across the port connectors much more robust, because one phase triggers output changes while the other phase samples inputs. This completely eliminates any worries about clock skew.

Another port signal is the flag input, which allows the CPU to sample 14 flag bits, one per digit time. The CPU does not contain a traditional interrupt request input. Instead, a dedicated

instruction is used to check the state of each flag, which is then followed by a conditional branch to a service routine.

There is also a power-down signal so that anything plugged into a port will also power down when the CPU goes to sleep. The final signal is a synchronization signal required to maintain synchronization of the serial bus. This sync signal is active while the instruction is on the instruction bus, allowing data memory devices to

decode the instruction to determine when a data address is on the data bus or when data should be transferred across the data bus.

While there is no facility for DMA, the CPU is able to transfer control to an intelligent peripheral on the bus. What happens is that the CPU then ignores the contents of the instruction bus while executing NOPs and continuing to run

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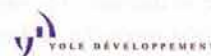
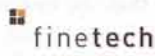


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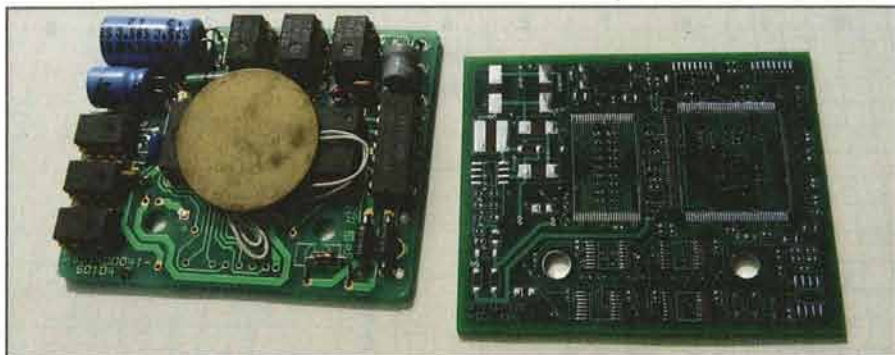


Photo 2—An original CPU board is on the left, while the new replacement CPU board is on the right. Note the stacked 8-pin DIPs on the original. Each memory chip decoded a unique address range, allowing them to be connected in parallel.

through machine cycles and incrementing the program counter. The intelligent peripheral interprets the instructions fetched during this time. Control is returned to the CPU when a specific bit of the instruction is set.

Two other features of the CPU should be mentioned. First, there is a flag output that operates much like the flag input, except in the opposite direction. There are only eight unique flag output bits though, with one bit remaining for seven digit times. In the HP-41, this

signal is used to drive a piezoelectric buzzer to provide audible feedback to the user. The calculator software uses timing loops to generate different tones.

Lastly, there is a dedicated keyboard scanner. Seven column strobes activate sequentially during the first seven digit times, while nine row inputs are sampled at the same time. This dedicated keyboard scanner is one of the things that makes the HP-41C keyboard so reliable.

Part of the keyboard scanner remains active during power-down to watch for

a key press of the On button on the keyboard. There must also be a way for a peripheral plugged into a port to turn the calculator on. This is accomplished by sampling the address bus during power-down, watching for the signal to be pulled high. The fact that some circuitry must remain active during power-down complicates the design, as I'll discuss shortly.

Working from the original HP chip specification, I implemented the CPU in Verilog HDL for maximum design portability. The entire design requires only 18 pages of code and took about six weeks, working in my spare time, to complete.

INCREASE CPU PERFORMANCE

The original CPU used a 360-kHz clock, which might seem absurd given today's multi-gigahertz processors, but this speed coupled with the optimized architecture gave the calculators plenty of performance. The only case where more performance would be nice is when running large user programs.

To account for this case, I wanted to provide a way to run the CPU faster.



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Register nibble	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Program MMU					page				bank	0	enab		ph addr	
Write Logical					logical address				bank	2		write data		
Write Physical					physical address					3		write data		
MMU Disable										6				
MMU Enable										7				
Disable Turbo										8				
Enable 2× Turbo										9				
Enable 5× Turbo										A				
Enable 10× Turbo										B				
Enable 20× Turbo										C				
Enable 50× Turbo										D				

Table 1—All of the new features are controlled by one previously unused instruction, with the actual operation selected by the contents of nibble 4 in the main CPU data register. This allows full program control, with minimal changes to the CPU design itself.

This is much more complicated than simply increasing the clock frequency though, for two reasons. First is the fact that both the display and the I/O ports connect to the system bus, which means that there is a hard frequency limit on this bus. Second is the fact that the calculator software uses timing loops.

Using standard memories for both the operating system software and the RAM means that most of the time the serial

system bus is not being used for anything. So, while the CPU is running faster than normal, a separate state machine continues to drive the signals on the serial system bus with what looks like continuous NOP instructions.

Whenever the CPU fetches an instruction that needs to be seen by devices on the system bus, the CPU automatically halts on the current machine-cycle boundary and synchronizes with the system bus. Two normal-speed machine

cycles then allow both the fetch and execution of the special instruction to be seen on the system bus.

This takes care of the known special instructions, but what about timing loops? For this case, I can take advantage of the fact that the instruction width is 10 bits. Since I am using standard memories, there will be unused data bits in memory. Two of these bits are used to tag instructions for fetch and execute at normal speed. Then I just

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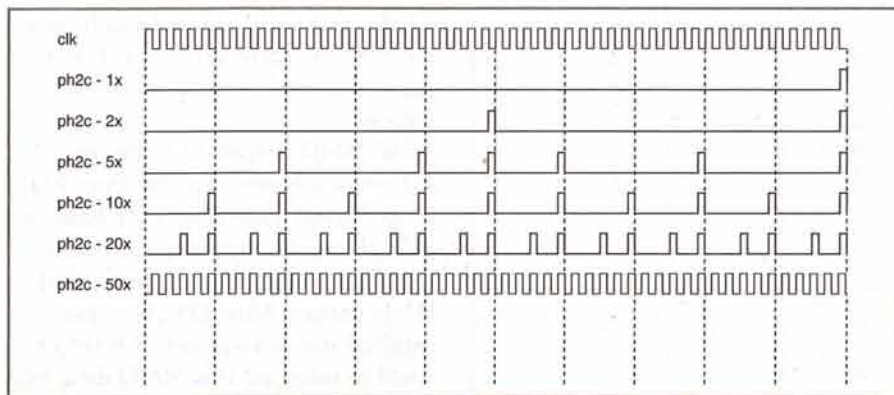


Figure 3—Turbo mode is easy once there is a fast clock available. Slow-speed operation is accomplished by “swallowing” clocks. The clk signal is the oscillator output, while the ph2c signal is the actual processor clock.

need to identify the timing loops or other sections in the calculator software that always need to run at regular speed.

At the start of the project, I wasn’t sure how fast the design would be able to run, so I chose a fairly conservative 50× oscillator frequency, or 18 MHz. Besides 1× and 50× speeds, the design supports a number of other options in between. I call all of the higher speeds turbo modes, and added an instruction

to allow software to switch between the different speeds (see [Table 1](#)).

Switching the clock for a processor on the fly can lead to all kinds of complications, so I chose to implement the variable frequency using pulse-swallowing. When operating at normal speed, 49 out of every 50 clock pulses are inhibited. Running 50× passes all of the clocks, while other dividers pass some number in between

these two cases (see [Figure 3](#)).

EXPANDING THE MEMORY

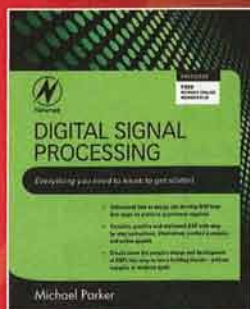
The second main objective of this project was to use standard memories and to provide a way to store images of ROM modules internally on the new processor circuit board. Since there are many more ROM images available than the address space of the CPU can accommodate, some way to expand the address space was needed. The only way to do this while maintaining software compatibility was to use a memory management unit (MMU) to translate the CPU (logical) address into a memory (physical) address.

The original CPU divides the program memory space into pages that are indexed by the upper 4 bits of the 16-bit program address. Most of these 4K × 10-bit regions can further hold four “banks,” with the bank switching under software control.

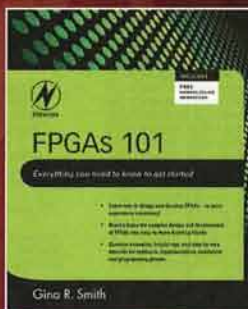
This native division of the program address space makes it convenient to use a 4K page size for the MMU mapping to the physical memory. Since

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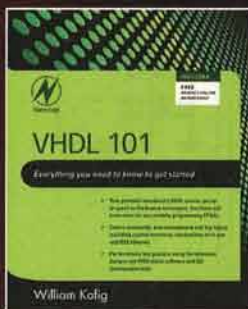
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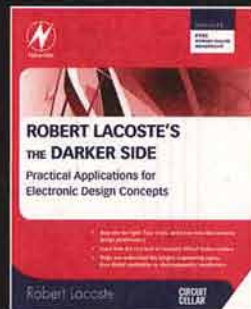
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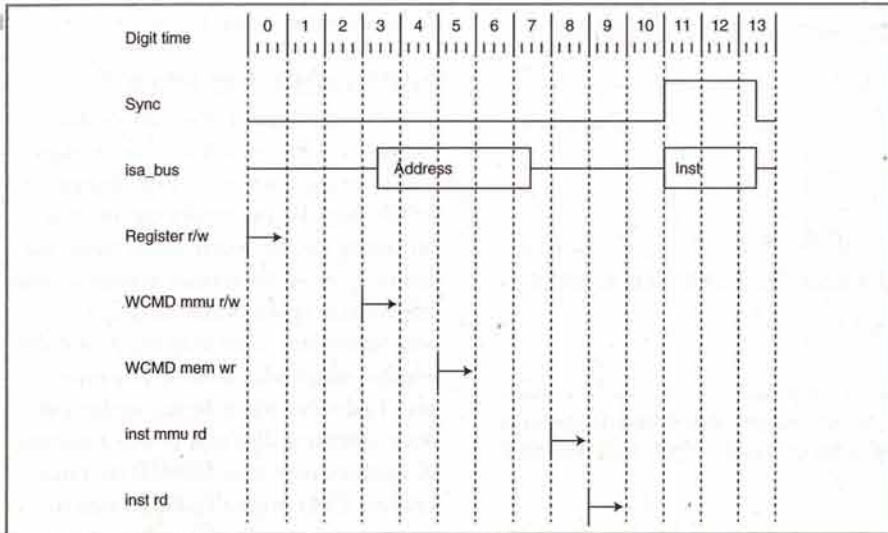


Figure 4—The serial nature of the bus leaves plenty of time to access the parallel memories. Only the register (data memory) read and write is time critical, because the data has to be driven on the serial data bus.

the data address space is $1K \times 56$ bits, mapping the data memory requires the

use of two adjacent physical memory pages. The data memory is always in

RAM and doesn't ever need to be relocated, so the hardware maps these two pages to a fixed physical memory address.

The MMU consists of 12 bits of address to substitute for the upper 4 bits of the logical address for each bank in each 4K region. Sixteen pages, each with four banks, means a total of 64 MMU entries. Most FPGAs of the required size have plenty of RAM on board to integrate this MMU data, but that would mean leaving the FPGA powered all the time.

For reasons that I'll cover shortly, this is not feasible, so the MMU entries also need to be stored in the external memory and accessed automatically prior to accessing program data (see Figure 4). But because the data address space is always mapped to a fixed physical address, no MMU access is required for data memory.

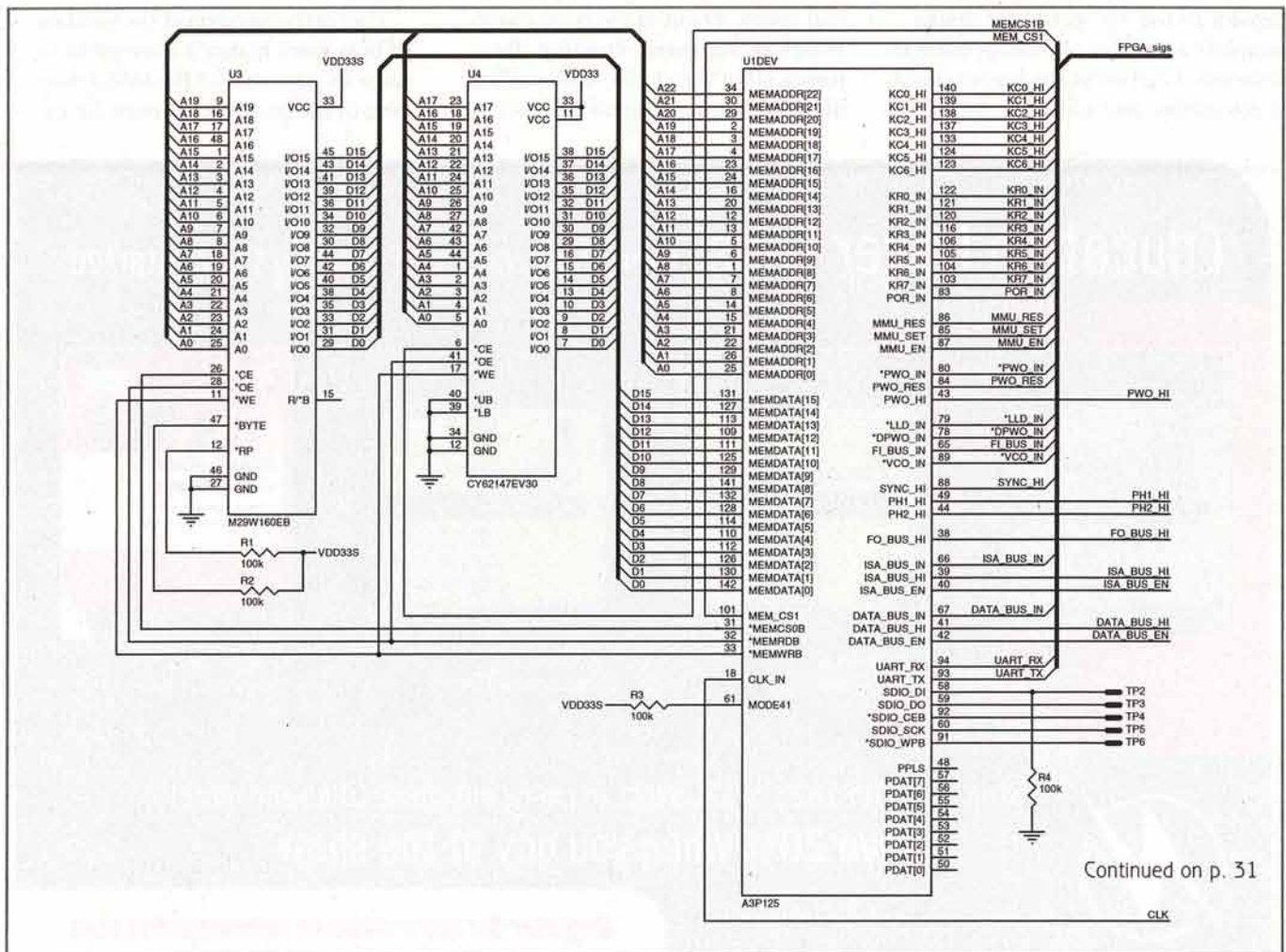


Figure 5—The core of the design looks much like any other embedded system. While in the power-down state, only the CPLD and the static RAM remain powered. The JTAG programming ports for the FPGA and CPLD have to be separate power planes because the devices are on separate power planes.

Continued on p. 31

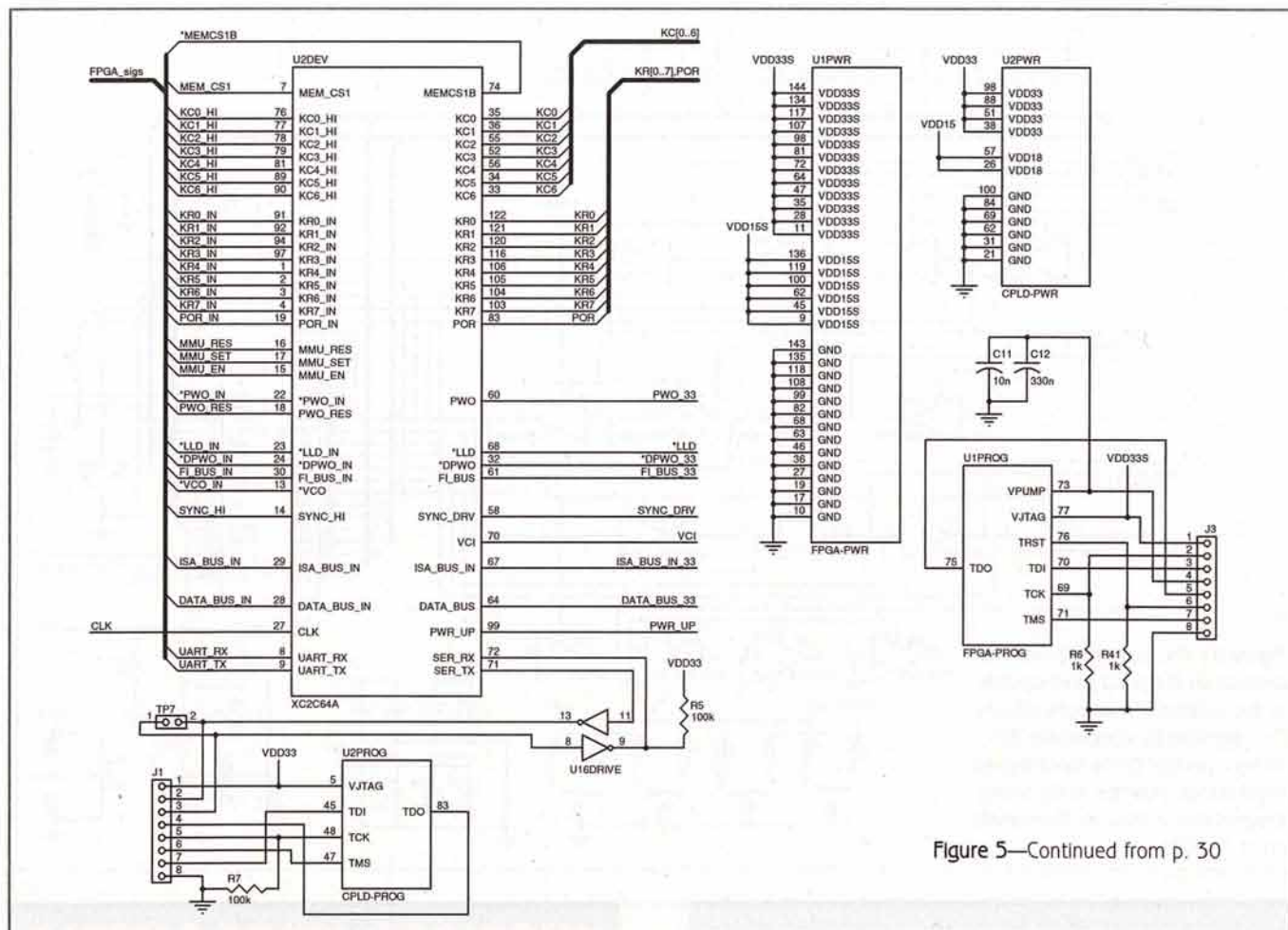


Figure 5—Continued from p. 30

Each MMU entry also contains a "valid" bit. This valid bit allows the hardware to determine whether the address range of a port should be mapped to the internal physical memory or remain active at the port. This allows modules to still be used in the calculator, either for execution or for transfer into the internal physical memory.

In addition to the individual enable bits, there is a global MMU enable bit. The global enable is required because at first power-up, the individual enable bits and MMU entries in the RAM will not be valid. The calculator operating system polls the program address space at startup, and invalid MMU contents would lead to unrecoverable errors. This global enable bit must exist in the logic of the design rather than in the RAM, and be cleared by power-on reset.

With a Harvard architecture, there is no provision for writing to program memory. Since I wanted to provide a way to transfer the contents of a

module plugged into a port into the internal memory, I added options to poke data into physical memory using the same instruction that is used to set the turbo mode and program the MMU.

POWER MANAGEMENT

One of the hallmarks of the HP-41 series was the miniscule power consumption, typically 10 μ A while off and only 10 mA while running. If I were implementing this design in a custom integrated circuit, minimizing the power consumption would be fairly straightforward, because without a clock, CMOS circuitry draws almost no power. But using FPGA technology makes the task much more complex (see Figure 5).

Historically, power consumption seems to have been a secondary concern for FPGA vendors, and it's only recently that low-power devices have become available. Even so, "low power" is a relative term, with the lowest-power FPGA (Actel's IGLOO

family) still requiring about 20 μ A while in Sleep mode. And FPGAs using static RAM to hold their configuration are at least an order of magnitude worse.

In the end, I decided that the best solution was to power down the FPGA while the calculator is off. This means I'll want to use a flash-based FPGA to avoid having to load the configuration every time the calculator is turned on. The issue isn't the configuration time; it's the power required during the configuration.

This implementation uses Actel's proASIC3 family. I couldn't use the IGLOO family because the size I needed was only available in BGA packages, and I wanted to be able to assemble the board myself.

The flash memory is powered down at the same time as the FPGA, but the static RAM must always remain powered to save both the MMU contents and the calculator data memory. When you have a design that is partially powered down, you have to be

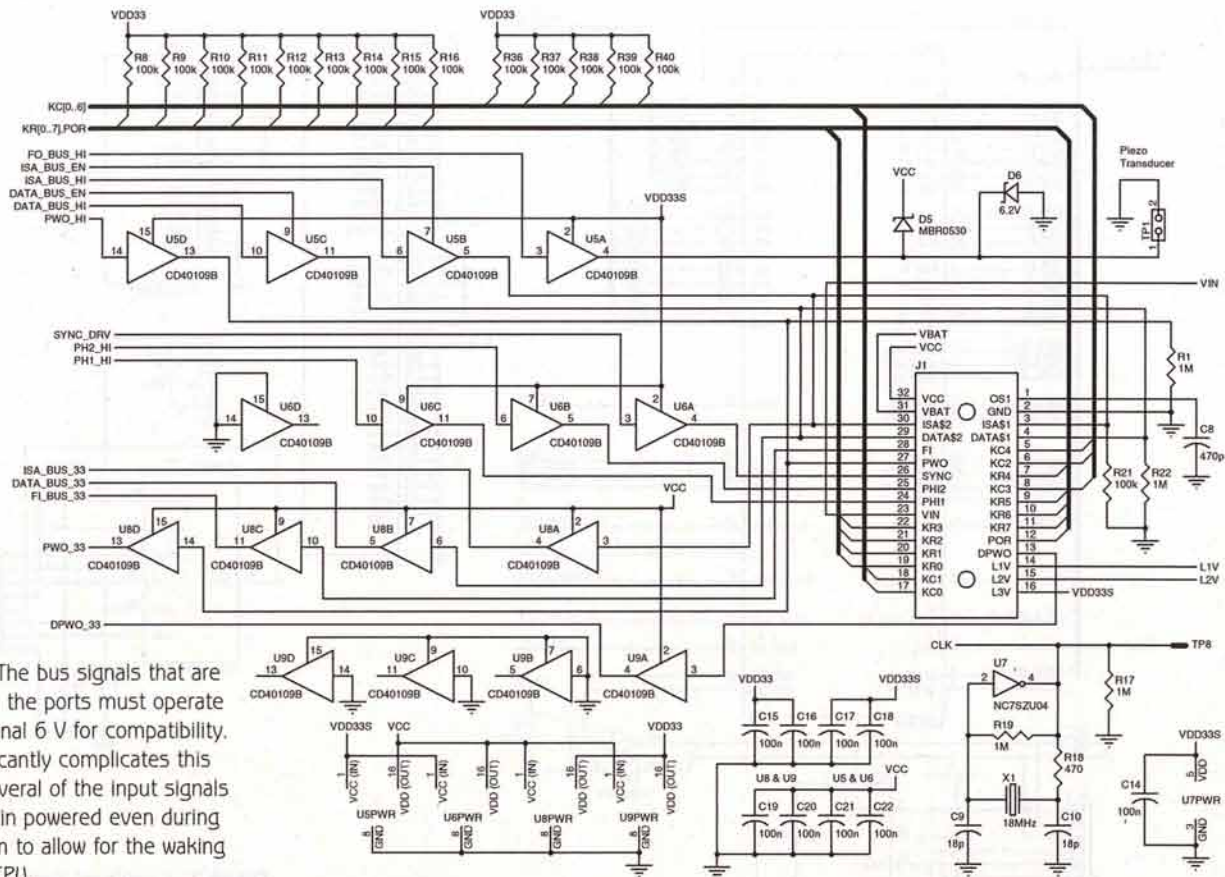


Figure 6—The bus signals that are present on the ports must operate at the original 6 V for compatibility. This significantly complicates this design. Several of the input signals must remain powered even during power-down to allow for the waking up of the CPU.

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very careful to guarantee that there are no sneak paths for current through the inputs of chips that are powered down. This is one reason that the design is partitioned with some logic in a small CPLD.

This CPLD isolates the FPGA from parts of the system, like the keyboard, that must still be active while the calculator is off. It also holds the status bits that must be valid at first power-up like the global MMU enable.

When the logic in the CPLD detects a valid start-up condition, it takes care of enabling the power to the remainder of the system. Since the main oscillator is powered down with the FPGA and flash, the CPLD also contains a small counter, running off of the oscillator output, which holds the FPGA in reset until the oscillator is actually outputting a clock. This duplicates functionality that was in the power-supply chip in the original design.

Nearly all of the FPGA inputs come from the CPLD, which holds these signals low during power down. The flash inputs all come from the FPGA, so they will be not driven during power down. But the chip select for the RAM has to go through the CPLD to guarantee that this signal remains inactive (high) while the system is off.

VOLTAGE COMPATIBILITY

The original CPU board used a single regulated 6-V supply, but that is not possible with this replacement board. In fact, the most complicated part of this design has to do with the various power supplies and signal levels required.

The bus signals clearly must be identical to the original design electrically, which is a huge problem at 6 V (see Figure 6). Driving signals at this level requires special isolation buffers, with the appropriate power connections, as shown in the schematics. I originally intended to use discrete transistors to do the level shifting, until I found exactly the function I needed in a nearly obsolete CD40109 CMOS device.

Level shifting for the inputs is done

with the same isolation buffers, operating in the opposite direction. Because two of the bus inputs can be used to wake up the CPU, these buffers must always be powered, with pull-downs on the bus input signals.

The next complication is the supply voltages for the LCD. The LCD controller uses the 1.1-, 2.2-, and 3.3-V levels to create the various positive and negative voltage levels across individual LCD segments. The 3.3 V would seem easy, because that is what the rest of the board uses. But careful inspection of the HP specifications revealed that these three voltage references must be capable of both sourcing and sinking current. In the end, I used op-amps to buffer voltages generated off of a resistive divider to create these supplies.

The flash memory and RAM on the board require 3.3 V, so that set the I/O voltage requirements for the FPGA and the CPLD, but the core of the FPGA requires 1.5 V while the core of the CPLD requires 1.8 V (see Figure 7). Add to this the requirement

to power-down the FPGA, and I'm glad I don't normally do board design for a living.

THE EXTRA GATES

This was my first time using an Actel FPGA, so I wasn't really sure which size device to target. I optimistically chose the smallest size and went through the synthesis, only to discover that the design needed 125% of the available resources. Targeting the next larger device gave a 70% utilization number. These results highlight one of the problems with FPGA technology, namely the granularity of the available gate count.

Using only 70% of the available gates seemed wasteful, so I decided to add a few additional new features. This was an iterative process of adding features, synthesizing and repeating. In the end, I added a combination async/clocked serial port and a byte-wide parallel output port to the design, bringing the FPGA utilization up to 90%.

It should be obvious that none of

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these features will be useful in an unmodified calculator, because there are no connections available to connect outside of the body of the calculator. In addition, there is no existing software to make use of them. But they did come in handy during the debug of the entire design, and the HP-41 was always a hacker's delight, so someone may find a use for them in the future.

DESIGN MIGRATION

As I mentioned previously, designing the CPU only took about six weeks. Simulation, to make sure that everything was working properly, took another six weeks. But actually getting a circuit board designed seemed to take forever, mainly because I had to learn to use the necessary tools.

After learning the tools, laying out the board was a nontrivial task. This is because the pitch of the various

package pins is near the limit of what most board houses can do without extra expense. This means that the pinouts of the FPGA and CPLD need to be chosen very carefully to minimize signal crossovers and vias. And don't even think about running tracks between package pins. I had recognized this problem early in the design process, but it still required some juggling during the board layout. The ability to rearrange pins is another advantage of programmable logic over an ASIC.

Laying out a PCB this small (it's only 53 mm × 66 mm) with 44-, 48-, 100-, and 144-pin devices, while working around a fixed 32-pin connector template, made me really appreciate the serial nature of the bus in the original design. While the original CPU board used what looks like 20-mil traces on a two-layer board, I had to use 8-mil traces on a four-layer board

to make everything fit.

I think this project has demonstrated that it is neither hard nor expensive to migrate a design to a different technology. In fact, because the board design took so long, I actually retargeted the design to a newer FPGA technology, without having to change anything in the Verilog code. Although this version only runs at 18 MHz, the synthesis tool reports that I should be able to achieve nearly triple that speed with the FPGA that I'm using.

But that performance is only part of the story. As an exercise, I did the synthesis for an ASIC version. Using a 0.35-μm gate array technology, the design will run at nearly 150 MHz and would cost less than \$1 per chip. Using a more aggressive technology doesn't make any sense given the miniscule gate count, because the size of the chip will be determined by the number of package pins. So moving a

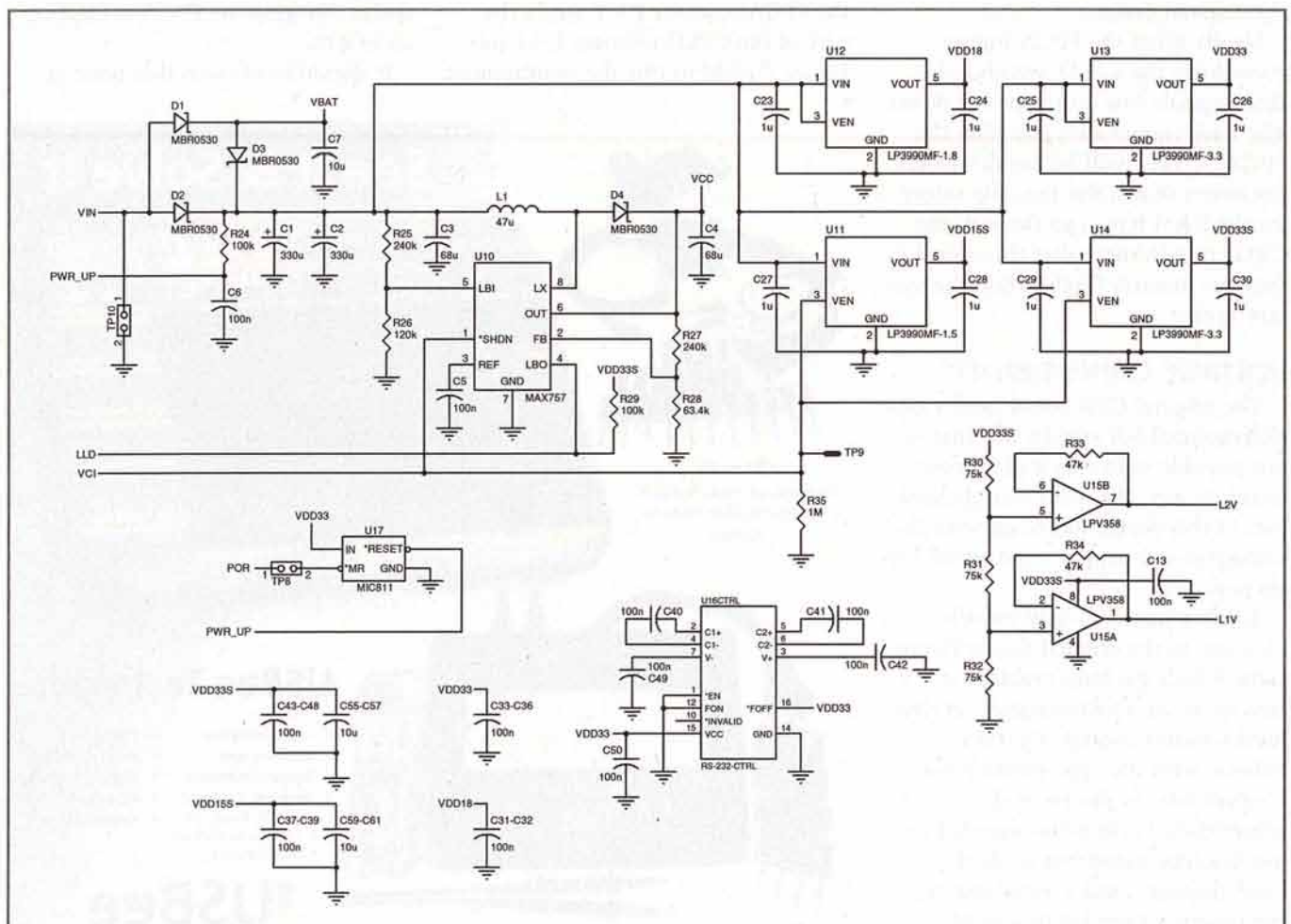


Figure 7—Power control is complicated by the voltage requirements of the FPGA as well as the LCD. Most of this circuitry fit in one custom bipolar chip in the original design.

design to a new technology isn't really that expensive after all.

In the end, I now have a calculator that no longer needs separate plug-in modules and runs significantly faster when I need it to. But it still has the same look and feel of the trusted tool that I have used for almost 30 years. 📖

Monte Dalrymple (monted@systemyde.com) has been designing integrated circuits for over 30 years. He holds a BSEE and MSEE from the University of California at Berkeley and has 15 patents. He is the designer of all five generations of Rabbit microprocessors. Not limited to things digital, he holds both amateur and commercial radio licenses.

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A3P125 ProASIC3 Flash FPGA

Actel Corp. | www.actel.com

XC2C64A 64 Macrocell CPLD

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NEED-TO-KNOW INFO

Knowledge is power. In the computer applications industry, informed engineers and programmers don't just survive, they *thrive* and *excel*. For more need-to-know information about topics covered in Monte Dalrymple's Issue 243 article, the *Circuit Cellar* editorial staff recommends the following content:

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by Stephen A. Edwards

Circuit Cellar 233, 2009

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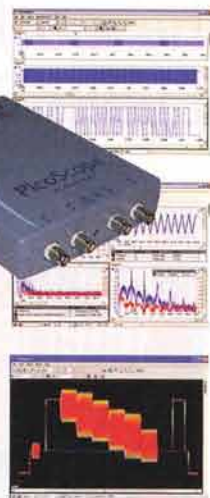
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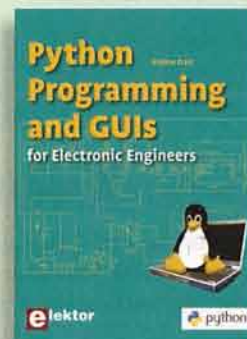
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For years I have used RadioShack's 6" Experimenter PC Board (P/N 276-170) for prototyping projects, both for business and personal projects. I've found them ideal for electronic designs involving integrated circuits, especially digital designs. Using wooden supports, I can easily cascade these boards together using ribbon cables to prototype large complex circuits that are modular and thus easier to work with. I use these boards so much that I often buy out the store. The major drawback comes when using 40-pin DIP devices, such as microprocessors. It quickly becomes difficult to connect the microprocessor's various ports to adjacent board modules; I rapidly run out of room for connectors. Many of my projects involved devices like Microchip's PIC16F877 (an example is shown in [Photo 1](#)), which was the impetus for doing this project. Each time I used such microprocessors, I spent considerable time and tedious effort trying to cram everything onto the board and then wiring it together. Parts such as the dual inline header or the resonator don't readily fit the hole pattern (the upper center of the board, see [Photo 1](#)), necessitating cutting of lands or jerry rigging parts into odd positions. And there is always the fear of running out of board before all the ports are connected. In [Photo 1](#), note the limited space where connectors for the remaining four ports must still go.

Then came a bit of inspiration. Why not make a universal circuit board with the same outline as the prototype board and having the options needed for most of my applications? In this article, I'll describe how I planned and then built a universal prototyping board.

GETTING STARTED

Once I knew I wanted to build a universal board, I took pen and pad in hand and decided what I wanted for options. Foremost

would be headers for each port, as well as RS-232 and I²C/SPI, the pulse-width modulation (PWM), and a header to reprogram the device using Microchip Technology's PICkit 2 development programmer/debugger.

The most important question was the pinout configuration for connecting the ports to other boards. This was solved by using the same pinouts used by MikroElektronika (www.mikroe.com) on its EasyPIC4 development board. That way, I could use my EasyPIC4 to test and develop circuits and software and then add them to the prototype by merely plugging in the module. To divert a bit, for those of you who haven't heard, MikroElektronika's development system is probably the very best buy ever in microprocessor development systems. For just \$250, you get a super universal development board that allows you to use most of Microchip's F-series microprocessors. It has a system that allows you to plug in various peripherals such as LCD displays, buttons, RS-232, LEDs, and even USB and PS/2 keyboards. Plus, their software has the libraries supporting these various goodies.

For software you have a choice of three languages: Pascal, BASIC, or C. Being a long-time BASIC man, my choice was obvious. I've used a few other PIC BASICs (including one that cost as much as Mikro's software and development board combined) and this one is, by far, the best. It has true procedures including local variables that allows you to easily build

your own procedure libraries to use in different programs without worrying about duplicate variable names. Unlike my other BASIC compiler, Mikro's easily handles interrupts in real time. Also included is full floating-point math capability and a nice integrated development environment (IDE) with a programmer on the development board. You just write your

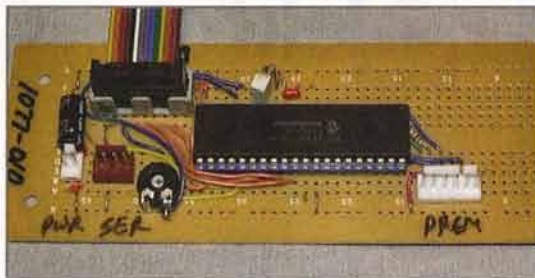


Photo 1—The microprocessor on the proto board

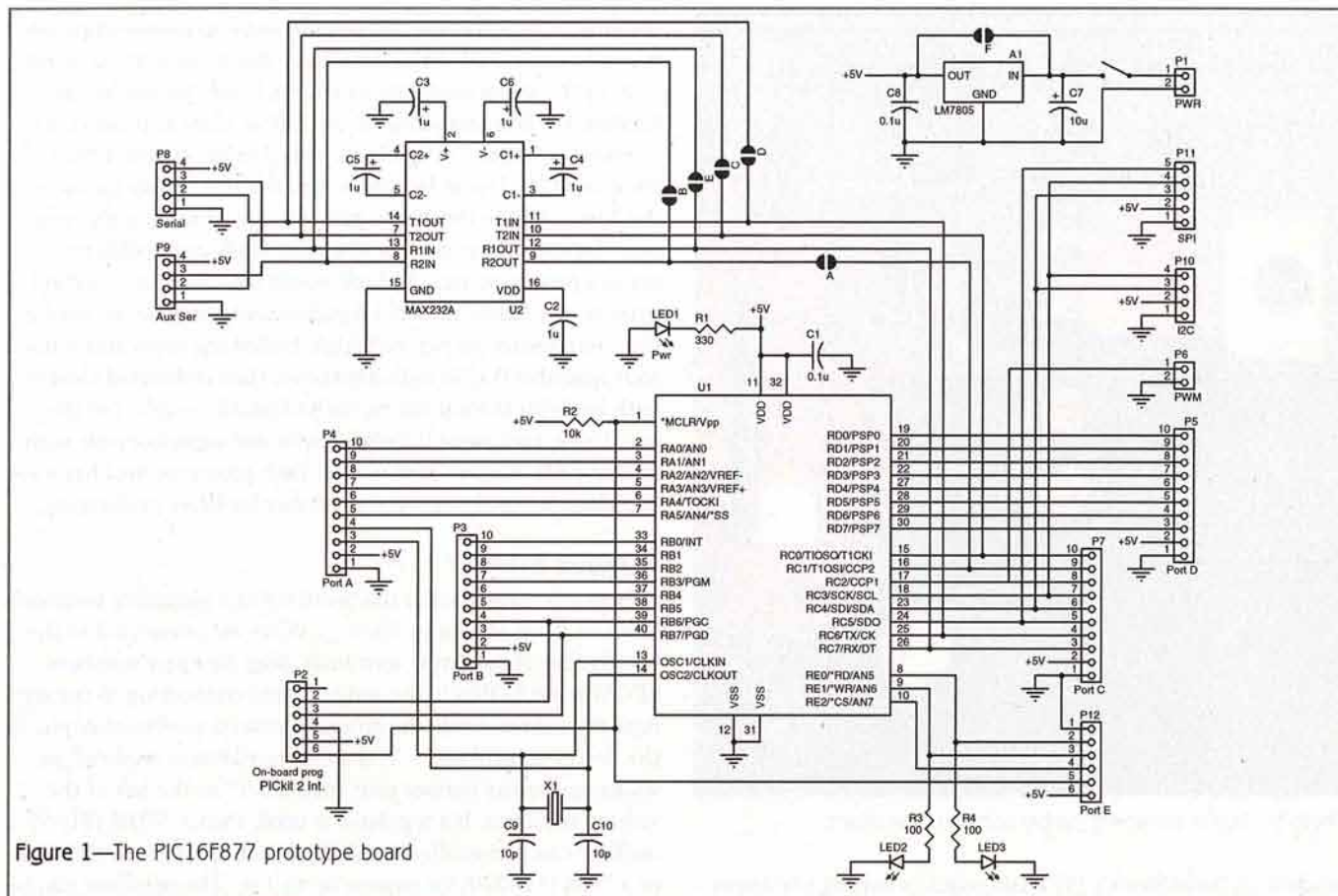


Figure 1—The PIC16F877 prototype board

program, compile it, and then program the device you are using on the development board.

To interface to external circuits, Mikro's development board uses 10-pin dual-inline headers with eight data bits, plus the ground and 5 V. Therefore, circuits built on a separate proto board can be easily plugged into the microprocessor and also have the required power and ground connection. Each port (A through E) has the same pinout. Usually, I build a circuit module and then test it out using short programs to test or exercise it. These exercisers usually develop into the calling procedures used in the main program. And RadioShack's PC board is ideal for prototyping most circuit modules with this system.

ADDITIONAL FEATURES

I chose other features as well. All connections to the board should be pluggable so the board can be quickly and easily removed for rework. There should be an on-board voltage regulator with a

solder jumper allowing either an unregulated DC voltage or 5 V to be connected via a screw terminal plug, plus a power switch and a "power on" indicator LED. It needs a single inline pin (SIP) header so Microchip's PicKit-2 in-circuit programmer can be connected, allowing the reprogramming of the microprocessor without removing it. You should be able to use either the 40- or 28-pin narrow (0.3" pin spacing) microprocessors with or without sockets. Port headers are connected to 5 V and ground, so power can be easily distributed to the remaining

prototype circuit boards.

The PC and SPI ports each connect to SIP headers and each also has 5 V and ground. The PWM output is connected to a two-pin SIP header, which includes ground. The serial ports (one hardware and one software driven) connect to Maxim Integrated Products's MAX232 level translator chip with solder jumpers, allowing either the standard RS-232 or TTL levels. The main serial port (hardware) goes to one four-pin SIP header and the auxiliary serial port goes to another. Both of these headers include

5 V and ground. A ground bar allows easy connection of test instrument grounds, while a "test point" output of the 5 V allows the easy connection of logic probes. It has a couple of test point outputs with LEDs that can be used in debugging and for triggering. Finally, an array of pads on any remaining blank board space allows some on-board prototyping of circuits.

The use of 10-pin dual headers with ribbon cables presented a drawback. Installing dual inline

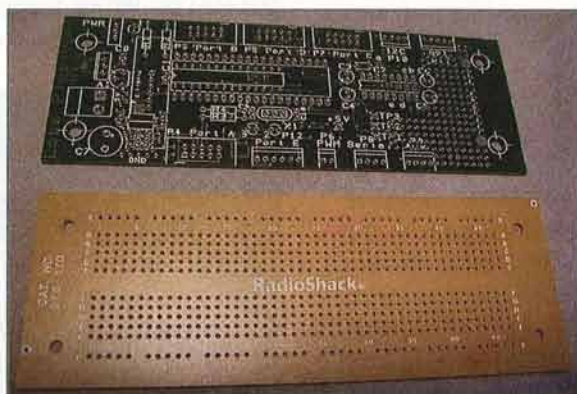


Photo 2—An outline of the RadioShack board

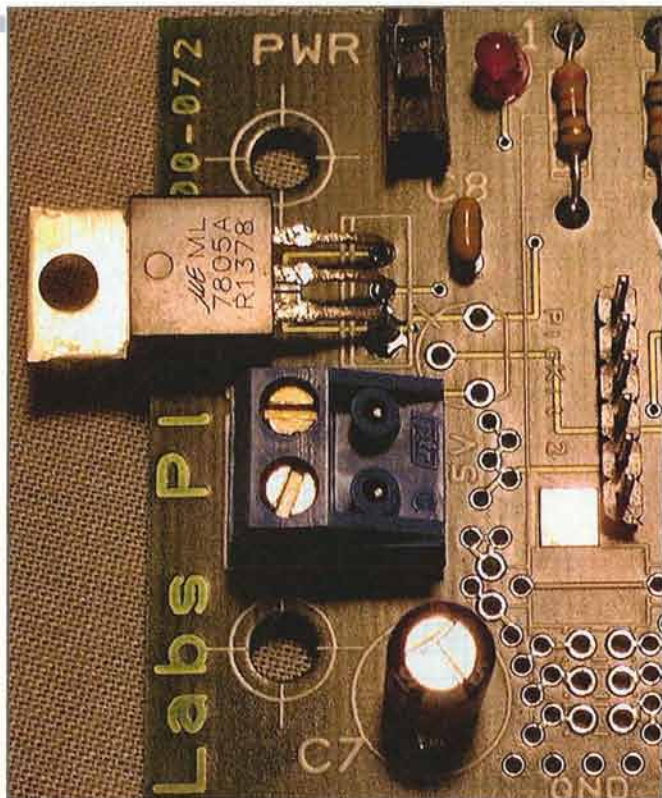


Photo 3—This is the power supply portion of the board.

headers on RadioShack's PC board requires cutting five traces in half—a rather tedious job with a razor knife. The alternative is to use a DIP ribbon cable header (Digi-Key part number HDP10S), which means soldering the cable to the proto board and having it flop around so it's always getting in the way when you're trying to do rework. Instead, I also designed a small circuit board to adapt a DIP header to the 0.3" spacing of the proto board. More about that later.

With the basic requirements now defined, I drew up the schematic (see Figure 1). Note that microprocessor pin numbers are for the 40-pin devices. Refer to the pinout diagram posted on the *Circuit Cellar* FTP site for the conversion of pin numbers for the 28-pin devices. Although designed for PIC16F8x7 devices (I have a bunch of PIC16F877 devices from past projects), I also designed it for PIC16F7x7 devices, which have an internal oscillator. The two pins used for a crystal or ceramic resonator (the board allows you to use either) are also used as I/O pins for port E.

I laid out the board with the same outline as RadioShack's board (see Photo 2) so it can be easily mounted on the same carrier as the prototype boards. More about that later, too. The microprocessor is placed in the approximate center with connectors around the board's perimeter so cables will not be in the way when probing with instruments. To allow mounting on the wooden carriers, each end of the board must have the first half inch free of components on the underside—that is, no through-hole components are allowed. Two additional features are pad layouts for using either a TO-220 or a TO-92 voltage regulator and pad layouts for using either a resonator or a crystal (including loading capacitors). Also, enough vertical space must be left for clearance of the PICkit 2 programmer. I placed

the ground bar off to the right end by itself so ground clips can be easily connected with a minimum obstruction of the board.

With the major components placed, I laid out the circuit, keeping the area inside the 40-pin DIP as clear as possible so the narrow 28-pin DIP could be placed in the center. I then completed the layout by connecting the appropriate pinout of the 28-pin DIP to the 40-pin pad. I also tried to keep the area near the ground bar as clear of circuit lands as possible to make a prototype area. As luck would have it, I had a second smaller area below the PICkit programmer that can be used if the components are not very high. I filled the main area with pads spaced at 0.1" in both directions, then connected clusters with lands on the top side so each cluster is visible. For the small area, I set some 0.25-W resistor and capacitor pads with joining pads to allow easy wiring. Each prototype area has a set of pads connected to ground to further facilitate prototyping.

POWER SUPPLY

Power is connected to the board using a pluggable terminal block at P1 as shown in Photo 3. Wires are connected to the board using these screw terminals (Digi-Key part numbers ED1613 and ED1682), the positive lead connecting to the pin near the center, while the ground connects to the other pin. If the power is regulated 5 V, then no regulator is required, so solder across the jumper pads marked "f" to the left of the voltage regulator. If a regulator is used, then a 78L05 (TO-92 outline) can be installed at A1 if current is less than 100 mA or a 7805 (TO-220) for current up to 1 A. The regulator can be installed with sufficient lead length to be bent over on its back and out of the way. In this position, a small heatsink can be installed. You can install a large filter capacitor before the regulator at C7 and a high-frequency suppression capacitor after the regulator at C8.

If you want a power switch (top center of Photo 3), install a PC-mount slide switch (Digi-Key part number EG1903) in S1; otherwise, solder a jumper wire between the center and top pads. For a power-on indicator, install an LED in LED1 (marked with just a 1) and a 330-Ω resistor in R1. This will give you a visual indicator that power to the prototype is on.

PROGRAMMER & PROCESSOR

A single inline header (center right of Photo 3) is installed at PICkit-2 using six pins from a breakaway header strip (Digi-Key part number S1022-36). To program the microprocessor, just plug the PICkit-2 programmer into the header with its white arrow adjacent to the white arrow on the circuit board.

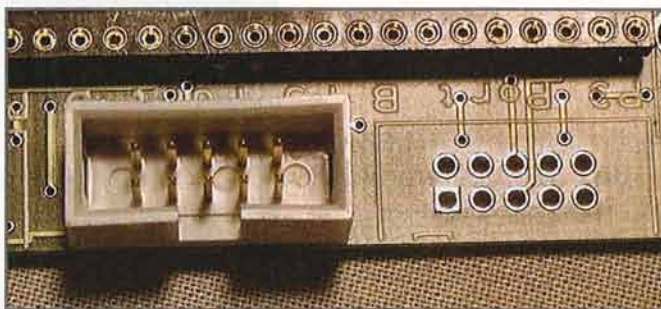


Photo 4—A typical 10-pin header used for ports

40 pins	PIC16F724	PIC16F727	PIC16F747	PIC16F777	PIC16F871
	PIC16F874A	PIC16F884	PIC16F887	PIC16F914	PIC16F917
	PIC16F977A				
28 pins	PIC16F722	PIC16F723	PIC16F726	PIC16F737	PIC16F767
	PIC16F870	PIC16F872	PIC16F873A	PIC16F876A	PIC16F882
	PIC16F883	PIC16F886	PIC16F913	PIC16F9PIC16	

Table 1—These devices will also work with the circuit board.

Note there is no key. The programmer can be plugged in either way, so make sure you get it right.

As previously stated, either a 40- or a 28-pin device can be used with this circuit board. While designed specifically for the PIC16F877, it can also be used with the devices listed in Table 1.

A 10-k Ω pull-up resistor is installed in R2 for MCLR and the programmer. A 0.1- μ F capacitor is installed at C1 for noise suppression of the microprocessor. I have found through bitter experience that, if at all possible when doing prototype work, always use sockets for ICs, because there is nothing worse than desoldering a chip only to find out that it wasn't the problem! For devices using an external clock, install a crystal or ceramic resonator in X1 and, if required, install loading capacitors in C9 and C10.

I/O PORTS

I use ribbon cable and 10-pin headers to connect the microprocessor's ports to outlying prototype boards (except for Port E). Each port has its full eight I/O bits, ground, and 5 V. Since the dual-inline headers will not directly install on RadioShack's proto board, I designed a small adapter board, which accepts a single 10-pin DIP header that conducts the signals to two single-inline header pins (same as used on PICkit 2 header) that are 0.3" apart, thereby allowing the pins to be inserted into RadioShack's board. Now, port ribbon cables are easily plugged into the adapter board, which is soldered on the outlying proto boards.

Where port pins are needed on more than one proto board, I designed a "daisy

chain" adapter board with two headers. They are electrically in parallel, so a second ribbon cable can be plugged in to connect a second proto board. The port pinouts on RadioShack's proto board are the same as on the microprocessor board—that is, the pads on the proto board match the pinout pattern of the microprocessor board. A short, bare jumper wire is then soldered from the ground pads under the adapter to the bus strip on the upper edge of the proto board. A second jumper wire connects the 5-V pad to the lower bus strip. The individual port pins are connected to the circuit using insulated solid wire soldered to the appropriate pads. I prefer AWG #26 wire and use different colors to better

navigate through the circuit.

I recommend using keyed headers and plugs for interconnecting port cables (see Photo 4) so there is only one way to plug in the cables. This feature can be a life saver. Imagine you're working on it again months later and rushing to put it back together, and when you try to insert a plug in backwards, it doesn't go in because of that key. And if you had put it in backwards, it would have blown a chip, which would have taken you two weeks to replace, because it's almost always a chip that you don't have a second one of.

The RadioShack proto boards are spaced at about 0.25" to allow cables to pass between them and run under the proto boards. This makes for a less-cluttered prototype and easier-to-connect test probes.

TEST POINTS & LEDs

I often add test points and LEDs to a microprocessor circuit to aid in debugging, especially at the systems level. Test points give you trigger signals for oscilloscopes, DSOs, and logic

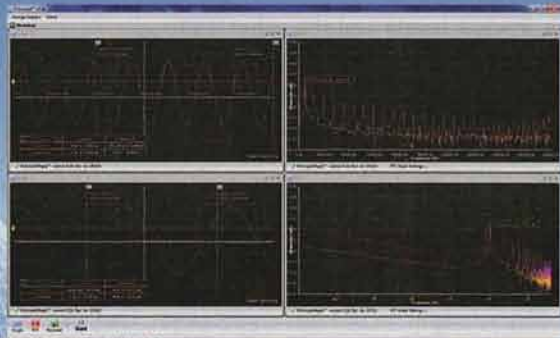
Function	Solder jumpers
Main serial port	d, e
Aux serial port	a, b, c
No A1 regulator	f

Table 2—Solder shorts

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analyzers that can be placed in the software exactly where you want them instead of trying to find just the right on-board signal. Test point 1 is bit 1 of port C, which is also the receive line for the auxiliary serial port, so you can easily check if the signal is present and of the right sense. Test point 2 is bit 0 of port D and test point 3 is bit 0 of port B.

Often, a simple visual indication is all that is needed to show that a process or function has started or finished, so I included two LEDs, driven by bit 0 and 1 of port E. Since 100- Ω limiting resistors (R3 and R4) are in series with the LEDs, each LED can be quickly and simply removed from the circuit by cutting either lead of the resistor. Of course, the LEDs and resistors are only installed if needed.

Finally, since port E has only two or four I/O pins (depending on the microprocessor version), a six-pin SIP header is used. Like the other ports, both the 5-V and ground lines are included.

SERIAL PORTS

The serial ports (main and auxiliary) may be used with or without a level driver by shorting or not shorting solder pads "a" through "e," as shown in Table 2. In addition to the hardware serial port built into the chip, I made provision for a software serial port to be used as the auxiliary. I find having an auxiliary serial port very useful in debugging, particularly at the systems level. However, if the driver chip (to give true RS-232 levels) U2 is used, then both serial ports are connected. You can't have one port with RS-232 levels and the other TTL.

I have some equipment that uses a noninverting TTL serial connection; therefore, I designed the circuit so the serial ports could be either TTL or RS-232 levels. If TTL is desired, then driver chip U2 and capacitors C2-C6 are left off the board. For the main serial port, solder across pads "d" and "e," and for the auxiliary serial port, solder across pads "a," "b," and "c." When using driver chip U2 with the auxiliary serial port, solder across pad "a" to connect the chip's output to the microprocessor. This pad is included so you can have the driver chip for the main serial port, but leave port RC1 open for use if the auxiliary port isn't being used.

Driver chip U2 is Maxim's MAX232, which provides inversion and level driving for two serial ports. The chip uses capacitors C3-C6 to create the positive and negative output voltage swings. This gives an RS-232-level output between ± 5 and ± 8 V. Connect the serial ports to the outside

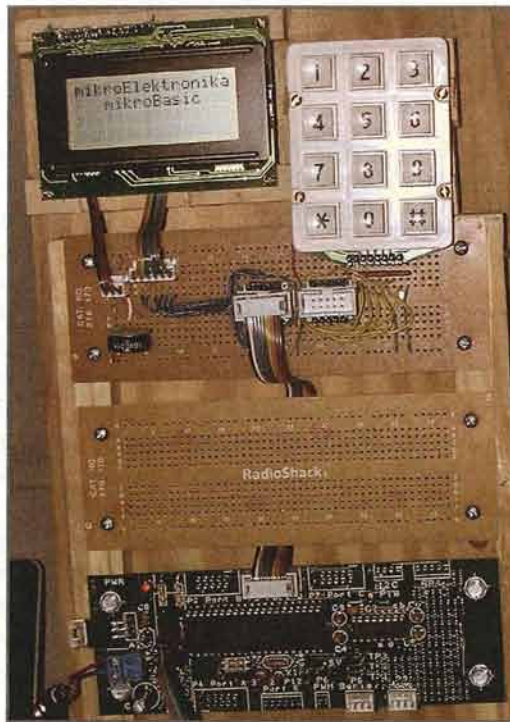


Photo 5—A prototype mounted on a wooden back plate.

world (DE9 or DB25 connectors) using single-inline header P8 for the main serial port or P9 for the auxiliary serial port.

SPI/I²C BUSES

Since the SPI and I²C synchronous serial buses use the same hardware resources in the microprocessors, you can use one or the other, but not both. Because of this dual function, both use the same I/O lines, and hence the headers are connected in parallel. And since you can only use one or the other, you need only install one header (or none if you aren't using either). Like the ports, the SPI/I²C headers also have ground and 5-V lines, so you can put synchronous serial devices on a proto board and connect them to the microprocessor board without any other ports having to be connected, too. But note that the I/O lines (port C) remain connected to both the serial

headers and the port C header, so if you connect port C to another proto board, you cannot connect those pins to other circuits without risking corruption of the serial functions.

Also note that none of the recommended resistor terminations are included on the microprocessor board, so you must put them on your proto board. Keep in mind that when using multiple boards with synchronous serial devices, the last board in the wiring chain should be the board with the termination resistors.

PULSE-WIDTH MODULATION

Another often-used special-function device of microprocessors is the PWM used to drive things such as DC motors. Since such devices often need high current or require voltages greater than 5 V, the positive power supply is not carried. This is considered as strictly a signal output line. Like the synchronous serial buses, it is connected to port C, so if used, then bit 2 cannot be used on the port C header.

MAKING THE BOARDS

I wanted to have about six boards made so I would have a ready supply waiting when I needed one, but when I checked with my usual circuit board maker, I found that six would cost me almost \$400. That was somewhat more than I wanted to spend, although I would have them in just a few days. I decided to check around with other board fabricators and see if I could find a better price. I quickly found that PCB-pool.com would make 10 boards for just \$160, much better at \$16 each instead of \$60 plus. The tradeoff was 10 days for production instead of two, but



Photo 6—The development setup

since I didn't have a project waiting for them, I could wait.

For those of you who haven't ordered your own circuit boards, you need something called Gerber plot files, which is the electronic artwork used by PCB fabricators to make your circuit boards. People are surprised to learn that Gerber plot files are just text files, which any editor or word processor can read and display just like any ASCII text file. This text is actually a set of data and codes that tells the plotter where to draw lines (X and Y positions), pad shapes, and their sizes. The drill file is another text file telling where to drill holes and what the hole sizes are.

Once you have designed your circuit board, you use your circuit board CAD program to generate the Gerber plot files for the top, the bottom, the silkscreen (white writing on circuit board), and the solder mask. This gives you a real professional circuit board just like you find in commercial equipment. With a set of plot files, it's just a matter of choosing a vender, making an order with your credit card, and sending the files as an email attachment. In as little as two days (premium price and overnight delivery), you have your circuit boards ready to stuff and solder.

To save money, I combined the artwork of the adapter boards with the main board and, having a shear, cut them apart to make separate circuit boards. But not everyone has a shear in their shop, so I'm including a file package with separate Gerber plots for each circuit board. It's more expensive this way, but then a shear will cost you hundreds of dollars. These file sets are available on *Circuit Cellar's* website. (The file names are COMBINED.zip for the one circuit board with all boards combined and SEPARATE.zip for individual board files.) Individuals may make and use as many of these circuit boards as desired, but may not sell or resell, either as an

individual or business, any or all of the circuit boards.

MOUNT & CONNECT

The one thing I really like about RadioShack's PC board is the ease of making a wooden carrier, which allows mounting several proto boards in line to prototype large, complex circuits. Photo 5 shows the mounting of RadioShack's proto boards with my Universal Pic prototype board (this is an alarm project I'm doing for my home shop). For a back plate, I cut a common 1" x 8' pine board to the length I thought I'd need. Then, using 0.5" square basswood strips (from Hobby-Lobby), I created two rails down the length of the pine board by gluing these wood strips onto the pine board, spaced apart by the width of the RadioShack proto board. That way, the proto boards can easily be mounted using #4 x 0.375" pan-head screws. Just lay the proto board across the wooden rails so the board's mounting holes on each end are on the wooden rails. Then put a screw through each hole into the soft wood. This is why we need the half inch on each end of the board free of any circuit devices; the solder bump underneath would keep the board from laying flat.

The nice thing is, when you need to do work on a proto board, you just unscrew the four screws and lift it up. That's why we want to use pluggable cables to interconnect multiple boards. The carrier, in addition to being cheap to make, lies flat on the workbench or you can put some cross pieces on each end so it can sit upright. It easily goes out in the field to connect to real equipment and lets you fully test your circuit before committing it to a printed circuit board.

Finally, Photo 6 shows the development setup using a cable to connect Mikro's EasyPIC4 development board to my project prototype. This is an easy way to program the universal board's microprocessor with Mikro's IDE. Cheap and easy to build and use—that's why I've used this method of prototyping for years. And now, with my universal microprocessor board, it's even easier to use. 📁

James Lyman (jclyman@pobox.com) owns Labs Plus (www.labsplusdesign.com); a Texas-based company that designs and builds custom electronic instrument systems for security applications and nondestructive testing. Previously, he worked for Cyltek, Y-COR, The Southwest Research Institute (San Antonio, TX), Datapoint Corp., and Bendix Corp. James holds a BS in Aerospace Engineering, a BS in Electrical Engineering, and an MS in System Management.

PROJECT FILES

To download the project files and pinout diagram, go to http://ftp.circuitcellar.com/pub/Circuit_Cellar/2010/243.

SOURCES

PIC16F877 Microcontroller and PICkit 2 programmer/debugger

Microchip Technology, Inc. | www.microchip.com

EasyPIC4 Development board

MikroElektronika | www.mikroe.com



A Tour of the Lab (Part 2)

The Frequency Domain

In the first part of this series, you learned about the time domain equipment a professional engineer needs to succeed in the ever-evolving embedded design industry. This article is about essential frequency domain equipment.

In the first part of this article series, I covered the topic of classical test equipment, from oscilloscopes to logic analyzers, frequency counters, and reflectometers. All such equipment has one thing in common: it works in the time domain. OK, I admit this is a complicated and probably pedantic way to say that such devices simply allow you to measure how a given signal evolves over time—which is usually what an engineer is looking for—but this enables me to introduce this second article. There is another kind of engineer who feels more comfortable in the frequency domain: the RF designer.

As you may know, frequency and time domains are basically two views of the same physical reality, thanks to the well-known Fourier transform. For example, a quick pulse in the time domain corresponds to a wide-band noise signal in the frequency domain. A sine wave in the time domain is a frequency “pulse” in the frequency domain. And any periodic signal in the time domain is a set of equally spaced harmonics in the frequency domain with given amplitudes and phases. So why aren’t oscilloscopes enough? The first answer could be that multi-gigahertz oscilloscopes are still quite expensive; but, as I’ll explain in this article, looking directly at the frequency domain could be a terrific tool for wireless designs and more. For example, a spectrum analyzer helps you to discover small perturbations buried in the noise and to obtain clues as to their root cause.

Now it’s time to wrap up my lab tour with a

presentation of the two most common frequency-domain instruments: the spectrum analyzer and the network analyzer. I hope to show you both their main characteristics and what they are used for.

SPECTRUM ANALYZERS?

A spectrum analyzer is nothing more than a radio receiver. Get an FM radio with a built-in reception level indicator (or connect an AC voltmeter somewhere before the FM demodulator), gently sweep the frequency button, plot the signal strength against frequency, and you’ve got a spectrum analyzer. Figure 1a shows the internal architecture of a classic swept RF spectrum analyzer. The input signal first passes through an attenuator in order to avoid any saturation in the initial stages, and then it’s low-pass-filtered to reject out-of-band signals. Then the signal is down-converted to a fixed intermediate frequency through several heterodyne mixing stages. (Remember that multiplying two signals enables you to get the sum and difference frequencies. Then one of the two can be filtered out.) These down converters must be driven by very low-noise local oscillators in order to get a clean measurement. That’s why spectrum analyzers are not as simple as they look. The first local oscillator is swept to get a plot around the frequency of interest and with a frequency span set by the user.

The next critical component of a spectrum analyzer is the resolution bandwidth filter (RBW). It

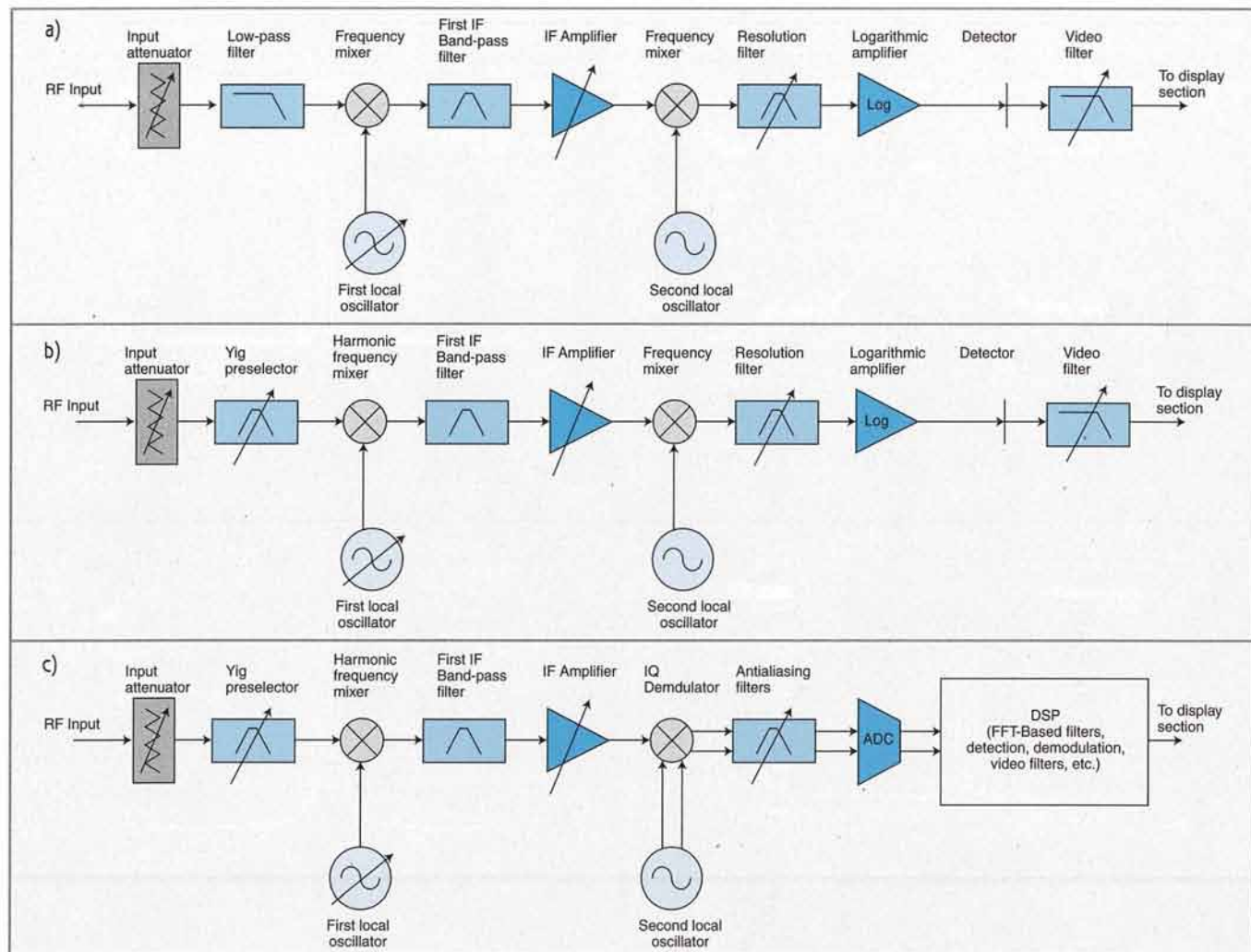


Figure 1a—The architecture of a typical RF spectrum analyzer is based on a flexible down-conversion chain. After passing through a narrow-resolution band-pass filter, the signal is detected and displayed, usually with a logarithmic vertical scale. **b**—Building a microwave spectrum analyzer requires only slight modifications in the first mixer stage, using usually harmonic mixing techniques and a Yig preselector. **c**—Modern spectrum analyzers are often based on DSP techniques for the low-frequency stages, but the principles are still the same.

enables you to set the frequency resolution of the instrument, and it's usually selectable from multiple megahertz down to 1 Hz or less for the best analyzers. Why not always use the best resolution? Simply, when the resolution gets finer, the sweep time must be increased to give enough time for the filters to stabilize their outputs. Spectrum analyzers can automatically select a reasonable RBW for a given frequency span, but you must understand what's going on in order to switch to manual when needed.

After the resolution bandwidth filter, the signal goes through a detector and a logarithmic amplifier before being displayed. A last filter, the video bandwidth filter (VBW), cleans up the displayed curve if needed.

The architecture I just described is used for "low-frequency" spectrum

analyzers up to a couple of gigahertz. Higher-frequency microwave spectrum analyzers are a variation of the former (see Figure 1b). Usually, this equipment replaces the first mixer with a harmonic mixer, which generates usable output signals for all the harmonics of the frequency of the first oscillator. This allows for a reasonably priced local oscillator while extending the frequency range, but it has a big disadvantage: even when the input signal is a clean sine wave, the displayed output spectrum is full of spurious responses



Photo 1—My latest spectrum analyzer is a high-end modular HP70000 system that allows measurements from 100 Hz to more than 22 GHz. Here it is displaying FM broadcast stations, separated from each other by 200 kHz. The modules on the right of the display are the IF filters (10 Hz to 3 MHz) and the main controller. In the bottom rack, from left to right, you'll find a 3-GHz tracking generator, oven-controlled reference oscillator, RF input section, and an external mixer interface.

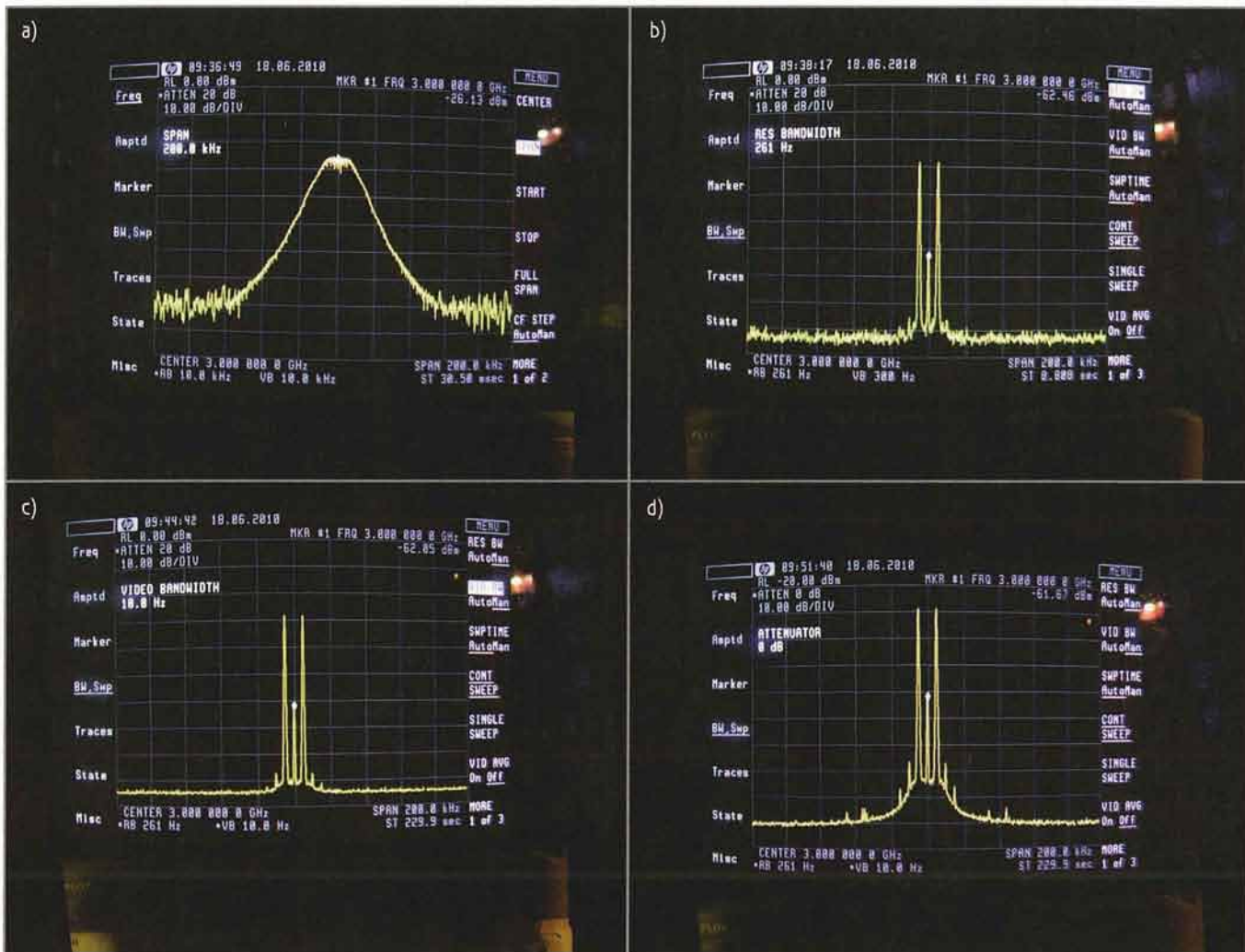


Photo 2a—Here is a classic spectrum analyzer display. The center frequency is 3 GHz, the frequency span is 200 kHz, and the resolution bandwidth is 10 kHz. b—Increasing the resolution bandwidth allows you to detect much finer details of the same input signal. The noise level is also drastically reduced, but the sweep time is far longer. c—Reducing the video bandwidth (here to 10 Hz) filters out the signal's noise. d—Lastly, reducing the input attenuation brings the signal level up, but with risks to the equipment's health.

due to the harmonic mixer. Experienced users are able to distinguish the real signal from the spurious, but this makes life more difficult.

Fortunately, there is a solution: high-end microwave analyzers include a front-end, high-performance, tunable

band-pass filter called a preselector, usually based on yttrium iron garnet (Yig) technology. Yig is one of the few technologies that enables you to build widely tunable band-pass filters (from 2 to 20 GHz is not uncommon) with a pass-band of only a couple of megahertz. This preselector is swept at the same time as the local oscillator to remove spurious signals from the display. This has a cost, but, in short, never buy a microwave spectrum analyzer without a built-in preselector or you may be disappointed.

Lastly, the most recent spectrum analyzers replace the analog RBW and VBW filter as well as the detectors with DSP-based digital processing (see Figure 1c). The principles are still the same, but one of the main advantages (in addition to a drastically simplified calibration) is that they allow significantly shorter

measurements. Basically, they are frequency-sweeping analyzers when the frequency span is large, but they configure themselves into fixed-frequency, wide-bandwidth receivers when the desired span is low enough. The signal is then digitized in the time domain and processed to get back a frequency domain representation through Fast Fourier transforms. Both modes can be mixed, too. Think of them as digital oscilloscopes with a built-in input RF down-converter. Note that some of these analyzers can't sweep at all and can only display quite narrow frequency spans. For example, the so-called transmitter analyzer often falls into this category.

SETTINGS

Enough theory. Let's turn to my spectrum analyzer. Photo 1 shows you my

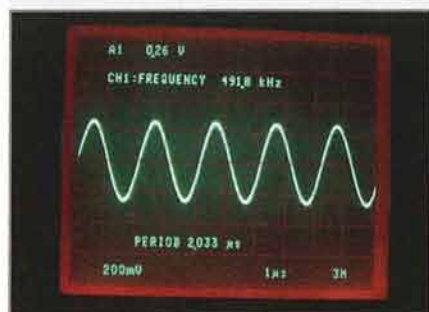
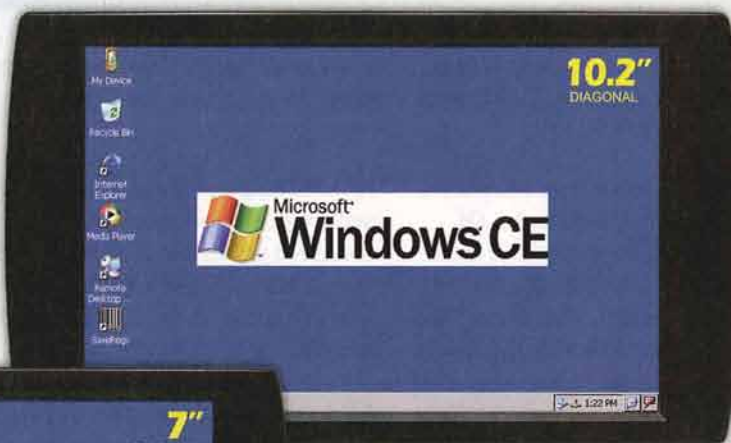


Photo 3—This is a clean 490-kHz sine signal, at least when measured on an oscilloscope, isn't it? Look for its spectrum analysis in Photo 4.

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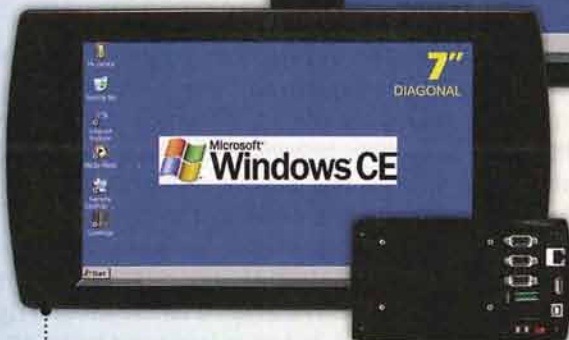
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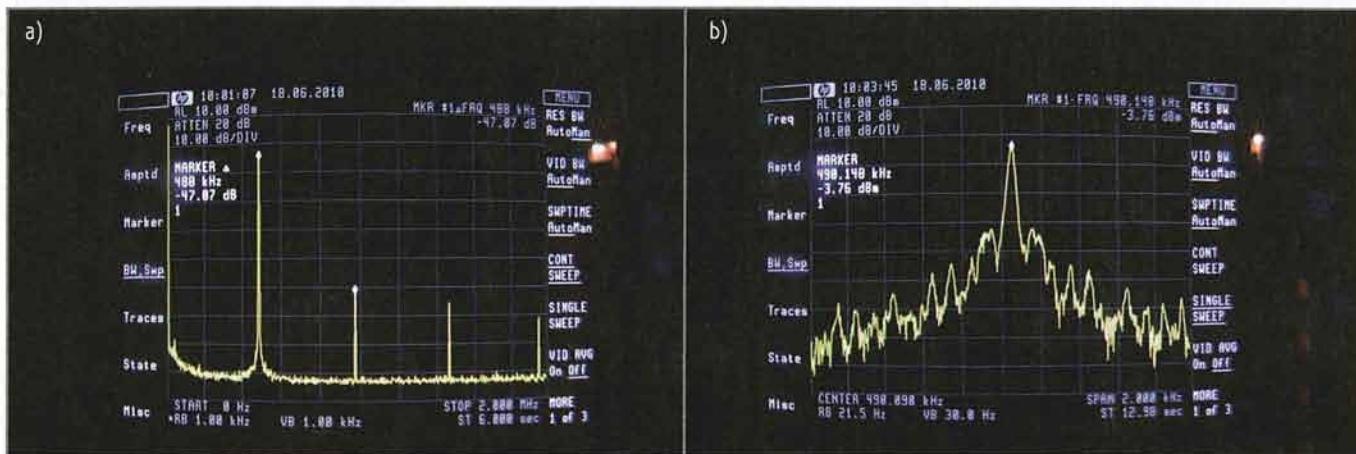


Photo 4a—Here is the sine signal depicted on Photo 3 measured with a spectrum analyzer. The first peak is at 490 kHz as expected, but the second, third, and fourth harmonics are clearly visible. The second harmonic is 47 dB lower than the carrier. This kind of measurement allows you to calculate the harmonic distortion of the source. b—Moreover, a close view of the 490-kHz signal shows that the source is far from clean, with a high level of 100-Hz frequency modulation visible on this plot (horizontal span is 2 kHz).

latest HP70000-series analyzer. I admit it is not an entry-level system, but I couldn't resist showing you this monster. Of course, cheaper systems are available on the Internet or from brokers from companies like HP/Agilent, Rhodes & Schwartz, Tektronix, Aeroflex, and a couple of others. A note of caution: spectrum analyzers are complex systems, and even old devices are still very useful, so, unfortunately, prices remain high. You might find a decent 20-year-old spectrum analyzer for \$1,000, but few are significantly cheaper. Some low-cost PC-based spectrum analyzers have appeared on the market in the last few years, but their performance has been, as far as I've tested, quite disappointing, even though they can be useful for applications like on-site RF surveys. Just never forget that old equipment is probably repairable if something fails (except, usually, the first mixer), but newer, fancy equipment full of high-speed ASICs may not be that easy to fix.

OK, imagine that you are now in front of a spectrum analyzer. What changes in the displayed signal when you play with the analyzer settings? I hooked up a 3-GHz signal to the

HP70000 input, set a span of 200 kHz and an RBW of 10 kHz, and *voilà*, the result is shown in Photo 2a. The signal power is measured on the top of the curve. Here, I found -26 dBm (corresponding to $1 \text{ mW} \times 10^{-26/10}$, or 2.5 μW). Is it a pure sine wave? It could be. But since the RBW is set to 10 kHz, any detail closer than 10 kHz is not visible.

With the same frequency span, I manually narrowed the RBW and got the plot shown in Photo 2b. As you can see, the signal power is still the same, but now you can see that the input signal was not a clean sine but two closely spaced carriers, with a smaller spurious frequency in between. For the full story, the input test signal was in fact generated by an Agilent E4438B digital signal generator configured in "multitone" mode. The middle signal is a leakage of the carrier frequency. Photos 2a and 2b show something important. When the RBW is narrowed, the noise floor (as measured on the left and right edges of the plot) is lowered. In fact, it is reduced by 10 dB each time you divide the RBW by 10. So, a fine RBW must be used whenever you are looking for signals of very small

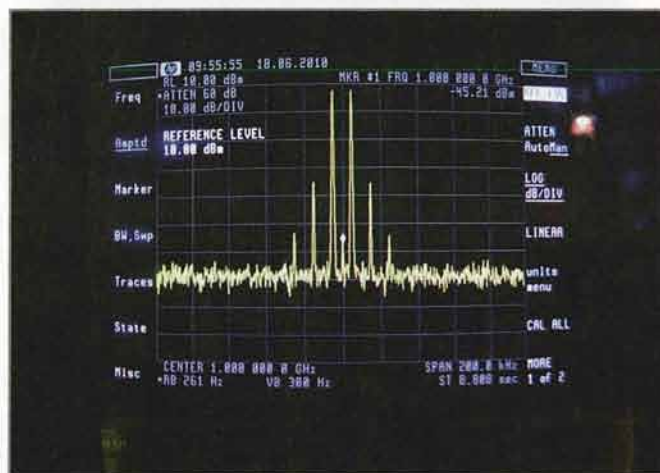


Photo 5—Inject two closely spaced sine signals at the input of a device like an amplifier and hook up a spectrum analyzer at its output. The output spectrum will show intermodulation results and allow you to calculate important parameters like the IP3 of the amplifier.



Photo 6—A spectrum analyzer with a built-in tracking generator allows you to measure the frequency response of active or passive devices (a 250-MHz band-pass filter in this example).



Photo 7—At the bottom is an old, but useful, HP8755C scalar network analyzer. It is paired with the HP8620C sweeper (at the top of the stack). It enables me to measure the frequency response of any device, with lower dynamic range and resolution than with a spectrum analyzer, but for a fraction of the cost. In addition, its frequency range is far higher, up to 18 GHz.

amplitude, even if they are wide in terms of frequency.

The video bandwidth filter (VBW) is simply a time-domain filter of the displayed curve. It cleans out noise from the measurement, but could also cause signals of interest to vanish, so it should be used carefully. Photo 2c shows a VBW in action.

The last important setting is the input attenuator. It has two functions: it protects the input stages of the analyzer against strong signals and also enables you to avoid any nonlinear effects in the input sections. As you can see in Photo 2d, reducing the input attenuation allows you to bring the signal level up relative to the analyzer's noise floor. However, doing so can generate artifacts on the display due to nonlinearities, or can even destroy your expensive analyzer (especially in the 0-dB attenuation position) if you are not careful enough. Practically speaking, try to avoid a 0-dB attenuation unless you are 100% sure of

the input signal. Each time you reduce the attenuation by 10 dB, the displayed signal must be unchanged and moved up by 10 dB. When spurious signals appear, or when the relative level of harmonics changes, you know that the attenuation is too low.

SPECTRUM ANALYZER USAGE

Spectrum analyzers are of course invaluable for radio designers. They are used to check the output power and occupied channel bandwidth of a transmitter, measure the power leaking into adjacent channels, or simply evaluate the ambient RF noise before installing a new radio site. Spectrum analyzers are also present anytime EMC is a concern. Refer back to my August 2007 column on EMC for more information ("Let's Play With EMI," *Circuit Cellar* 205).

What else could spectrum analyzers be used for? Imagine you have a sine signal, even a low-frequency one. For that experiment, I used a low-cost LF signal

Photo 8—A vector network analyzer—here a venerable and reasonably affordable HP8754A—allows you to measure the transmission and reflection characteristics of any device, as long as you get the associated measurement bridge (here a HP8502A, on the top of the stack), both in amplitude and phase.



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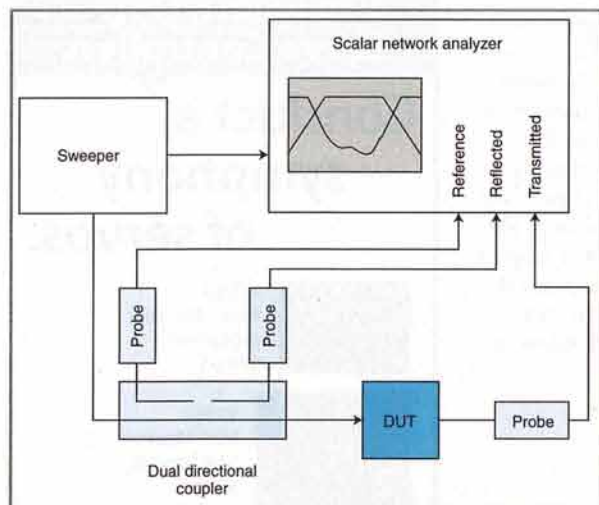


Figure 2—This is the classic test setup used for scalar network analyzers. A pair of directional couplers enables you to measure both the transmitted and reflected signals for a given DUT, as well as the reference input signal to establish power ratios while minimizing measurement errors. Vector network analyzers use basically the same setup, but the detecting probes are replaced by phase-sensitive receivers. The couplers can be external or integrated inside the analyzer.

generator set to 490 kHz. I connected it to my trusted Tek 2467A analog oscilloscope and got what you see in Photo 3. A very clean sine, isn't it? Are you sure? As you may imagine, a spectrum analyzer will enable you to obtain a much finer analysis. I then connected the same generator to the spectrum analyzer. The result is shown in Photo 4a. Yes, there is a sine carrier, but there are also clearly visible harmonics. Here the second harmonic is measured 47 dB lower than the carrier, and the third and fourth are 53 dB and 59 dB lower, respectively. This means the harmonic distortion of the input signal—assuming there aren't any other harmonics—is $10^{-47/10} + 10^{-53/10} + 10^{-59/10} = 0.0000262$ in terms of power. Since the voltage is the square root of the power, this is equivalent to a voltage harmonic distortion of the square root of 0.0000262, which is 0.0512, or 0.5%. Not so clean. Such harmonic distortion often comes from nonlinear amplifiers. So, if you wish to reduce it, you will know what to work on, thanks to the spectrum analyzer. Here, the output amplifier of the signal generator is probably the first suspect.

Moreover, a spectrum analyzer can show you some very interesting things. I've simply zoomed around the carrier frequency with the same LF generator and got what you see in Photo 4b. This plot shows you that the generator output signal was not only distorted, but also modulated. Here, the spectrum is typical of a frequency modulation. The modulation frequency is the gap between each successive peak, here measured as 100 Hz. Well, I live in Europe, so I bet

that this is a spurious 50-Hz leakage from the generator power supply.

Thanks to their wide dynamic range, spectrum analyzers can also show you extremely small signals. Imagine that you have a 0.1-mV signal—say, a 10-MHz modulated carrier—added to a 1-V white noise signal spanning from DC to 1 GHz. Looking at this signal in the time domain (i.e., on an oscilloscope) will show you just noise. But using a spectrum analyzer tuned to 10 MHz will allow you to see and measure the 0.1-mV signal without any problem. The 0.1-mV signal, with a 50-Ω impedance, is equivalent to a power $P = U^2/R = 200$ pW, or -67 dBm (as $\log_{10}(200 \text{ pW}/1 \text{ mW}) = -6.7$). Similarly, the noise power is $P = U^2/R = 20$ mW. As it is spanning from DC to 1 GHz, the noise power in a given 1-kHz window is $20 \text{ mW} \times 1 \text{ kHz}/1 \text{ GHz} = 20$ pW. So using a RBW of 1 kHz, the signal will be 10 times higher than the noise and clearly measurable.

A spectrum analyzer has millions of other applications, like the evaluation of nonlinear effects (see Photo 5), but I hope these examples will be enough to convince you. Let's now move on to network analysis.

TRACKING TO SCALAR

Some spectrum analyzers have a very useful added feature: a tracking generator. This is a sweeping RF generator, precisely locked on the sweeping measurement frequency of the analyzer. Its output amplitude is also leveled. So, if you connect the output of the tracking generator to the input of the analyzer, you will simply get a horizontal line on the

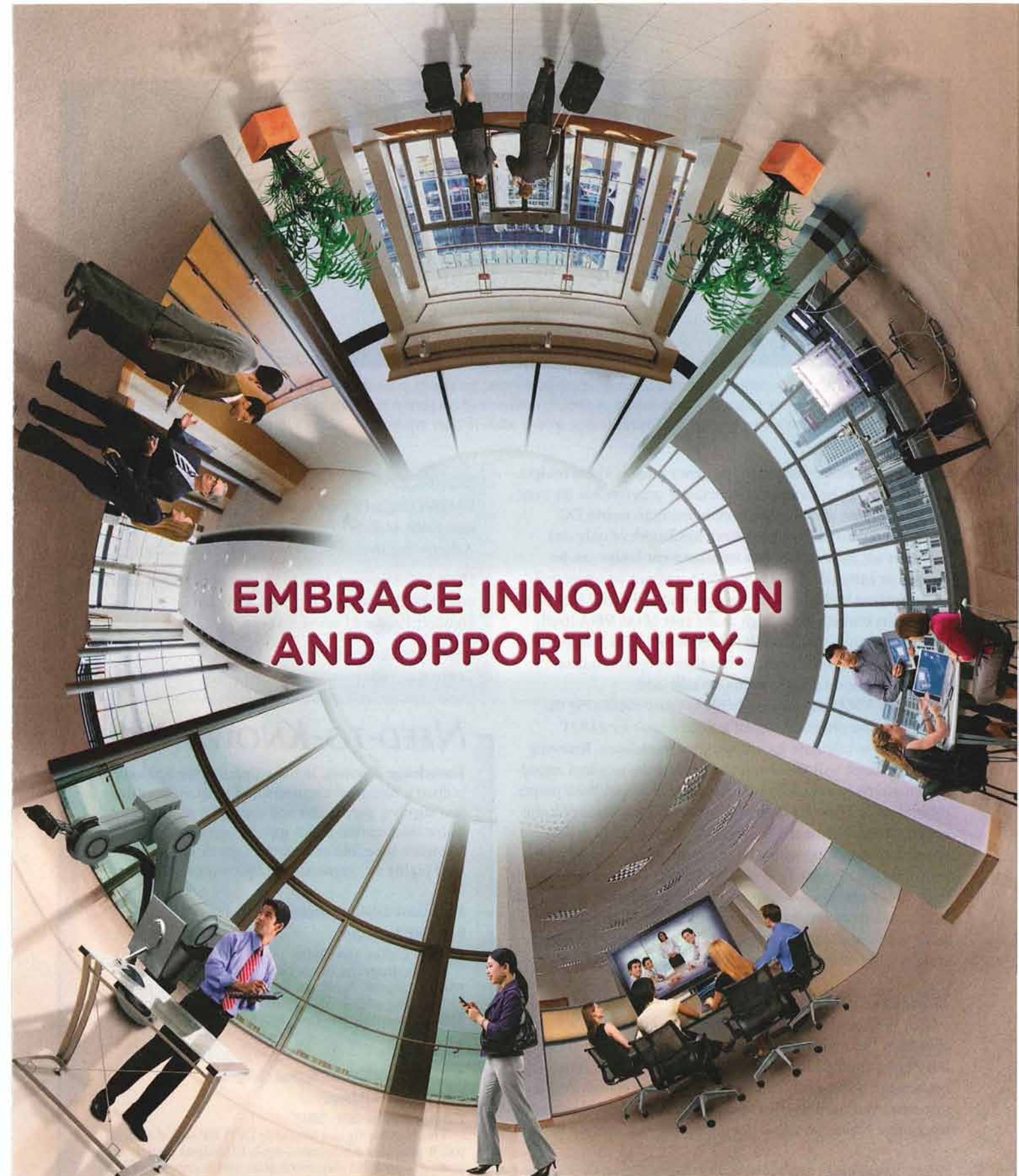
display. For each frequency, the analyzer will be tuned to the tracking generator's frequency (as both are locked) and the measured amplitude will be constant. But if you connect any device under test (DUT) in between, like a filter, you will get its frequency response curve directly, as you can see in Photo 6. Cool, isn't it? The advantage of this setup is the wide dynamic range of the measurement, as a spectrum analyzer is used as a receiver. Nothing forbids you from using an RBW as small as necessary to reduce the noise to very low levels. The downside is that tracking generators are expensive and usually limited to quite low frequencies.

Enter another test device: the scalar network analyzer and its companion, the microwave sweeper (see Photo 7). Here the sweeper is an autonomous sweeping generator and sends to the DUT a frequency sweeping through the frequency band of interest. The scalar network analyzer detects the DUT output signal amplitude with a simple diode detector and plots it against frequency. The dynamic range is far more limited than using a spectrum analyzer due to the wideband diode detector. However, the good news is that you will easily find them from brokers or on the Internet with a complete setup going to several gigahertz for a few hundred dollars.

The other good news is that the frequency range is only limited by the sweeper and detectors, so going up to 10 or 20 GHz is not that difficult. In addition, you can use a scalar network analyzer to measure not only the signal transmitted through the DUT, but also the signal reflected back from it, which enables you to evaluate its impedance-matching performance. This is usually done with a pair of external directional detectors connected to several inputs of the analyzer (see Figure 2).

VNAs

Scalar network analyzers are useful, but vector network analyzers (VNAs) are even more useful, and that's why they are so expensive. A VNA includes a sweeper generator, but in place of simple diode detectors the VNA uses phase-sensitive receivers (usually built using a down-converting receiver chain). They also include a phase-calibrated measurement bridge to measure



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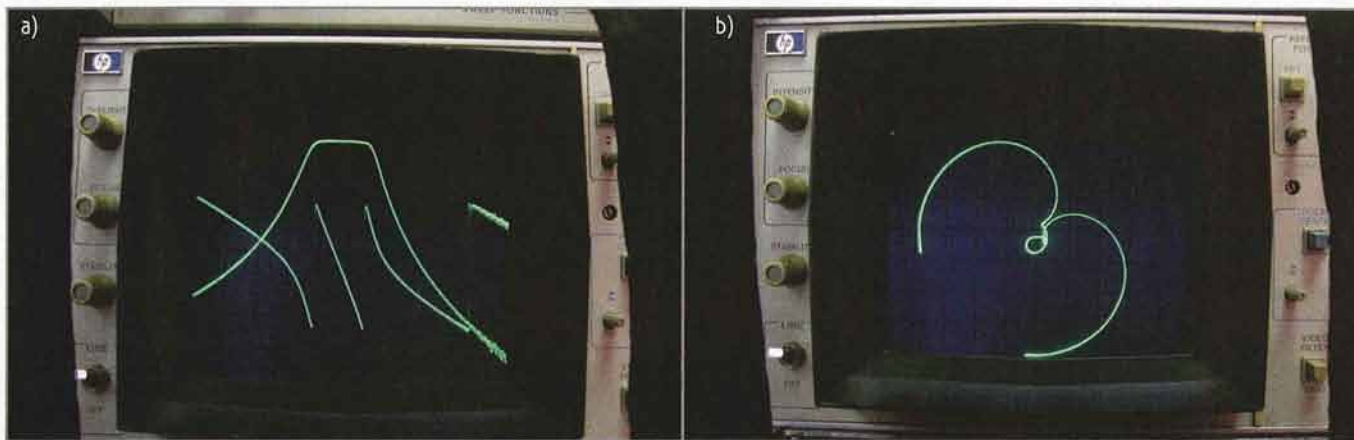


Photo 9a—With a VNA, you can display not only the amplitude response of a filter, but also its phase response. b—The reflected energy is often displayed in a polar format, generating the very useful Smith diagram. A perfectly matched load is a point in the center of the screen. Such a plot allows you to evaluate the required matching network graphically, but I'd need to write another article to cover that topic.

reflected signals for very wide frequency ranges. These bridges are functionally equivalent to directional couplers but are very wide band, thus allowing measurements from nearly DC (common directional couplers have bandwidth of only one octave or so). By the way, this measurement bridge can be built-in or external. If you buy a VNA without an integrated measurement bridge, be sure you can find and afford the bridge because its cost can be as high as the cost of the VNA itself. One last caution: there are 50- Ω bridges and 75- Ω bridges. The latter are significantly cheaper, but they're useless unless you're working on 75- Ω systems, so take care.

Why are VNAs so useful? Mainly because measuring the amplitude and phase of a signal reflected back by a DUT allows you to calculate its full complex impedance. Knowing this impedance will allow you to calculate the required impedance-matching network (see Photo 8 and Photo 9). With proper calibration, a VNA, for example, will enable you to match the impedance of an antenna or amplifier input to get a perfect impedance matching with a 50- Ω source, which means best performance. Without it, it would be a very long and painful task. VNAs are expensive and need a little expertise to be used with satisfactory results; but, as an example, I don't think it is really possible to seriously optimize any UHF antenna-based system without them—unless you have plenty of time.

TESTING MATTERS

This two-part series about lab test equipment was a digression from the topics I usually cover in "The Darker Side." But I hope you still found it useful and refreshing. Test equipment, and especially frequency-domain equipment, is just what you need to shed some light the darkest electronics issues like noise and nasty nonlinear spurious signals. ☒

Robert Lacoste lives near Paris, France. He has 20 years of experience working on embedded systems, analog designs, and wireless telecommunications. He has won prizes in more than 15 international design contests. In 2003, Robert started a consulting company, ALCIOM, to share his passion for innovative mixed-signal designs. You can reach him at rlacoste@alciom.com. Don't forget to write "Darker Side" in the subject line to bypass his spam filters.

SOURCES

E4438B Digital signal generator and HP70000 MMS spectrum analyzer

Agilent Technologies | www.home.agilent.com

HP8620C Sweeper, HP8754A vector network analyzer, and HP8755C scalar network analyzer

Hewlett Packard | www.hp.com

2467A Oscilloscope

Tektronix | www.tek.com

NEED-TO-KNOW INFO

Knowledge is power. In the computer applications industry, informed engineers and programmers don't just survive, they *thrive* and *excel*. For more need-to-know information about topics covered in Robert Lacoste's Issue 243 article, the *Circuit Cellar* editorial staff highly recommends the following content:

Low-Cost 2.4-GHz Spectrum Analyzer

by Scott Armitage

Circuit Cellar 189, 2006

Forget dropping big bucks on a microwave spectrum analyzer. Scott walks you through the process of building an 2.4-GHz spectrum analyzer. Topics: Spectrum Analyzer, Frequency Domain, RF

NimbleSig

A Compact DDS RF Signal Generator

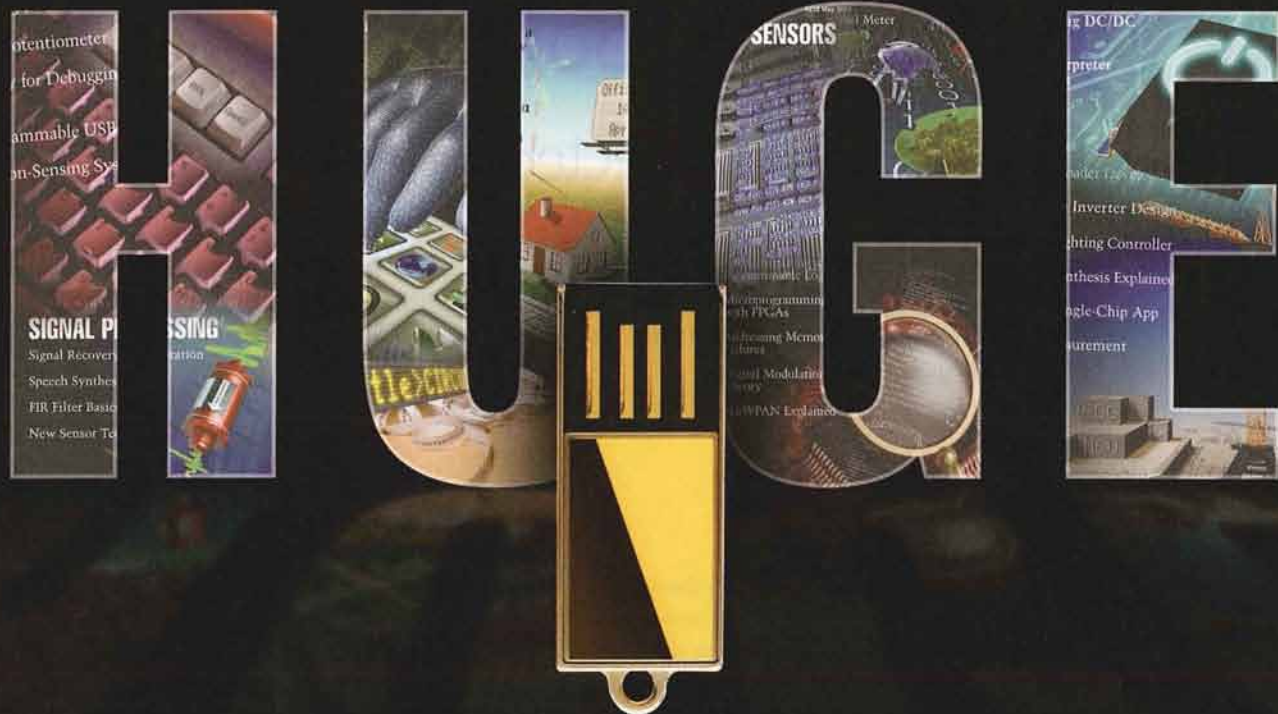
by Thomas Alldread

Circuit Cellar 208, 2007

The NimbleSig is a versatile DDS RF signal generator. It provides a frequency-agile RF output signal source with 1-Hz step resolution and is capable of low-level RF power measurement. Topics: Signal Generator, RF, DDS, Filter

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Avoiding Robotic FAIL

Expect the Unexpected

You're building a robot. Want to prevent failure? Plan for the unexpected. As you'll see, good engineering involves incorporating large safety margins, adequate redundancy, and comprehensive error-handling—and doing so under budget, of course.

More than 100 teams of roboticists from around the world converge on Hartford, Connecticut each April at the Trinity College Fire-Fighting Home Robot Contest. For many teams, this contest culminates a year of academic instruction and hands-on learning to create a robot able to find and extinguish a small fire in a simulated house.

Unlike many "robot" competitions involving tele-operated devices containing little more than motors and actuators, each firefighting robot must operate autonomously. The contest requires three different capabilities: arena navigation, fire detection, and flame extinguishing. Building a robot to accomplish any one of those tasks seems straightforward, but the combination frequently stumps even adult engineers.

Jake Mendelssohn, the contest's founder, put it this way: "The only people who think this is easy haven't tried it."

In this column I'll describe some of the

hard-learned lessons the teams take home each year. Although you may not build fire-fighting robots, your projects certainly face similar obstacles and you can learn from the unexpected problems these teams encountered.

THE CHALLENGE

The Trinity Contest consists of several different competitions with challenges appropriate for teams ranging from middle-school students to practicing engineers. The contest arena shown in [Photo 1](#) simulates a four-room house with intersecting hallways; robots may (attempt to!) use dead reckoning because the teams know the layout. An ordinary candle in one of the rooms serves as the fire.

The Basic arena has a solid black floor, white walls with painted or wallpapered areas, and white lines across the room doorways. The Standard arena adds carpeting, 3-D wall hangings, and mirrors. Teams may select additional challenges that can dramatically improve their robot's final score, including sound-activated starting, uneven floors, and variable door locations.

Each robot must complete three timed trials during the contest. Each trial lasts, at most, five minutes: the robot must start on command, search the arena until it finds the room with the candle, and extinguish the flame using any of several methods. The robot may then return to its starting location for an even better score.

The judges record the time required to extinguish the flame: smaller times (and, thus, scores) are better. Successfully handling additional challenges reduces the trial's score and



Photo 1—The contest arenas simulate a four-room house with intersecting hallways. I took this photo with an IR-sensitive camera through a visible-light blocking filter that highlights the IR distance sensor emissions on and near the robot.

Rank	Unique	Kit
1	6.18	4.71
2	8.05	16.89
3	8.79	603.97
4	11.34	656.37
5	608.75	1226.9
6	618	1320.28
7	604.38	1800
8	614.59	1800
9	1202.76	1800
10	1205.47	1800
11	1232.88	1800
12	1800	1800
13	1800	1800
14	1800	1800
15	1800	1800
16	1800	
17	1800	
18	1800	
19	1800	

Figure 1—Results from the High School Division competition. Although kit-built robots can be very fast, they have much lower reliability.

incurring penalties increases it, so the trial's final score has little relation to the actual elapsed time. A robot's overall contest score is the sum of the scores for each of the three trials.

Because each trial can last up to five minutes, the elapsed time for a successful trial could be as large as 300 seconds. If the robot fails to extinguish the flame, however, the judges will assign a score of 600. As a result, contest scores cluster around four values: near zero for robots that successfully extinguished the flame on all three trials and near multiples of 600 for robots that failed on one, two, or all three of their trials.

Teams may enter a Unique robot constructed according to their own design or a Kit robot (affectionately known as a Kitbot) built from a commercially available kit. Both types must have custom programming, although recent kits come with prewritten library functions implementing large parts of the Trinity contest rules.

Figure 1 summarizes the results for this year's High School Division. You can see that both Unique robots and Kitbots have difficulty completing the contest. Although four of 19 Unique robots succeeded, only two of 15 Kitbots completed all three trials. The overall success rate is painfully low: 21% and 13%, respectively.

Although building a Kitbot may appear a quick way to get into the contest, I've noticed that many similar

Kitbots fail in essentially the same way. Perhaps depending on Other People's Designs isn't such a good idea?

Figure 2 shows the results of the Senior Division, generally featuring robots constructed by college and adult teams. These robots are significantly more complex and run in arenas festooned with challenges. Unfortunately, they have worse reliability than simpler robots: only two of the Unique robots (4.6%) completed all three trials, while none of the three Kitbots accomplished that task.

While you may think you could do better, robots in the Trinity Contest seem to encounter a more hostile environment than Mars, known as the Death Planet for autonomous robots. Fortunately, you can retrieve your hardware from the arena, fix what didn't work, and try again.

MECHANICAL PROBLEMS

The Trinity contest rules specify the maximum size for each robot and, in fact, the judges use a "bounding box" to verify the dimensions. Photo 2 shows that some robots expand to fill the available space. Conversely, the contender for the Tiny Robot Prize in Photo 3 packs all the required functions into a much smaller package.

The robot in Photo 4 demonstrates that the rules do not impose a weight limit. Some robot teams apparently begin with a solid aluminum ingot and fit motors and circuit boards into carefully machined openings.

Unfortunately, all three of those robots share a common design flaw: any projecting part will cause trouble. The navigation algorithms generally assume the robot is a point moving in an ideal world and cannot recover after a high-traction tire touches a wall, a projecting sensor snags on a door opening, or a contact switch clobbers the candle.

It's heartbreaking to watch a middle-schooler's carefully constructed Lego Mindstorms robot undergo what we call *autonomous self-disassembly* as the control program doggedly forces the chassis through the maze, completely unaware of components torn off along the way. While the crowd loves it, that's a hard way to learn a lesson.

Even when a robot doesn't hit the

wall, the jolts encountered during ordinary transportation and numerous trial runs expose another common failing: intermittent electrical connections. Some teams bring their hardware halfway around the planet, but moving a robot even a few miles can render it dead on arrival in Hartford.

Robots competing in the Unique category are, by definition, one-off designs. Photo 5 shows what happens when designers place high priorities on easy access and rapid modification, rather than rugged durability and secure connections. To their credit, some of the cables terminating on that solderless breadboard do have heat-shrink strain relief tips, but I'm sure those appeared

Rank	Unique	Kit
1	33.76	606.08
2	40.88	606.21
3	621.23	1800
4	720.38	
5	1202.41	
6	1213.88	
7	1232.14	
8	1234.86	
9	1241.74	
10	1244.76	
11	1263.05	
12	1800	
13	1800	
14	1800	
15	1800	
16	1800	
17	1800	
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32	1800	
33	1800	
34	1800	
35	1800	
36	1800	
37	1800	
38	1800	
39	1800	
40	1800	
41	1800	
42	1800	
43	1800	

Figure 2—Results from the Senior Division competition for college and adults. These overwhelmingly custom-built robots have surprisingly poor reliability.

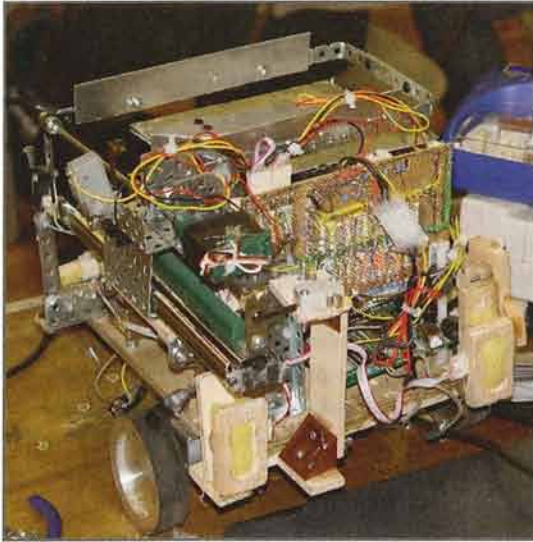


Photo 2—Some robot designs expand into every cubic centimeter of the allowed space. The projections and overhanging bits of this robot can snag on arena walls and doorways.

after the first few wires snapped off.

An adult engineer built the robot in Photo 6: all the components have firm connections to the chassis, the circuitry uses custom PCBs, and the cables terminate in actual connectors. Somehow, you know his experience includes dealing with flaky hardware and that he's willing to devote considerable effort to eliminating those problems.

Although you may think you don't have time for so many details, ask yourself some simple questions about your design: Can anything shake apart? Can you find the loose wire? Can you put it in the right spot? In the contest arena? In five seconds?

If you'd have trouble doing that, then your design needs more work!

SOFTWARE IS HARD

Most robots use frame-mounted flame sensors that require turning the entire chassis to locate the candle within a room. Typically, the robot will successfully navigate the maze, often at high speed, enter the room containing the candle, and begin rotating to scan for the exact flame location. The entire team tenses as the sensor's focus approaches the candle.

The robot rotates until the sensor aims directly at the candle, but it doesn't stop turning and the team shouts "Noooo!" in unison. The robot whirls continuously as their software

wizard stares at the ceiling and, within seconds, says "I know what's wrong! I can fix that!"

After some quick reprogramming, the robot starts its next trial at high speed, crashes into a wall, and fails that trial, too.

The process of writing complex software involves careful design and extensive testing. The process of *changing* complex software requires even more care and testing, neither of which seems possible in the heat of competition.

You already know, from personal experience, that changing a few lines of code in one function can elicit completely unexpected behavior

from another function. Robot control programs often use global variables, intricate data structures, and programming techniques that invite problems, generally because their programmers are new at their tasks and haven't yet learned to convert clever ideas into robust designs.

Programmers, at least good programmers, eventually learn how to write robust code and make thoughtful changes. Traveling halfway around the world to watch their techniques fail in action seems a brutal way to get that point across, though.

Some teams manage to destroy the only working copy of their robot's control program. Their robot *almost* worked on its first trial, but a code change triggered a crash on the second trial. It's only then that the team discovers they can neither restore the program that almost worked in the first trial nor undo the changes causing the crash in the second trial. Their non-functional robot must forfeit its third and last trial.

The only way to avoid such problems is by rigid discipline: use a source-code control system, create a new version for each change,

and maintain a backup of every version so you can roll back any changes. That's easy to say and difficult to do, particularly as your robot approaches the top of the "up next" list on the scoreboard displays.

SENSOR SNAFUS

Navigating the arena shown in Photo 1 seems simple, but that's because you're seeing the entire layout from above. The contest rules keep the maximum robot height below the top edge of the walls: it must navigate using only information gathered from its path inside the arena.

Over the years, several teams have attempted to work around that rule with magnetic compasses, generally based on flux-gate sensors, to determine the robot's absolute orientation and direction. While magnetic fields from high-current traction motors pose an obvious problem, they've generally solved that problem in the lab.

The contest takes place in an ordinary gymnasium, with a hardwood floor below an arched ceiling supported by steel I-beams. What the teams don't realize, alas, is that below every gym-sized hardwood floor lies a concrete slab reinforced with tons of steel: 12-mm bars linked by 4-mm wire mesh.

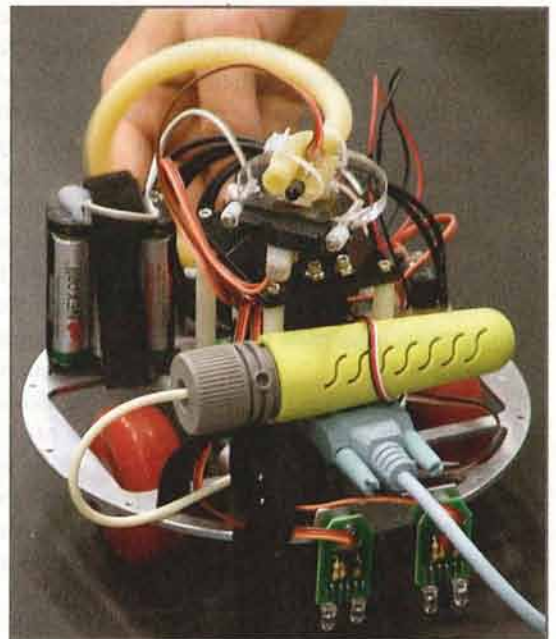


Photo 3—Other robots pack all the required functions into a surprisingly small footprint. The Tiny Robot prize rewards the smallest robot that successfully completes all three trials.



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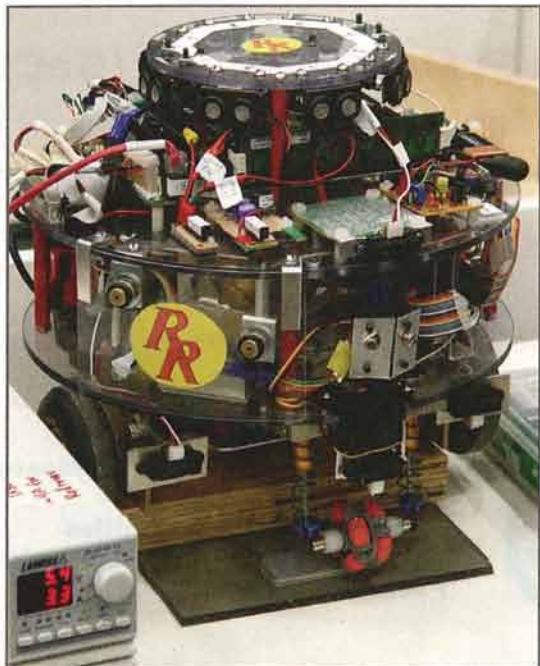


Photo 4—The rules place no upper limit on a robot's maximum weight!

That mild steel retains remnant magnetization from the electric arc welding used during its construction, as well as magnetization induced by nearby lightning strikes. Some years ago, a lightning strike in our driveway magnetized all my lathe and milling machine tooling, even though my shop is in the far corner of the basement. I'm still demagnetizing rarely used tools when I take them from a steel storage cabinet that provided no shielding whatsoever.

The local magnetic field in the Trinity gym thus varies widely over each arena, with complete polarity reversals matching the 150-mm mesh grid. This generally baffles robot navigation programs designed for a uniform magnetic field aimed generally north-south. If the robot doesn't have alternative navigation sensor inputs, it's out of the contest.

Some teams depend on ultrasonic distance sensors, as seen in the ring around the top of the robot in Photo 4. The wavelength of a 40 kHz audio signal is about 8 mm, which means the arena walls act as nearly perfect acoustic mirrors. Detecting a first-incidence reflected pulse seems easy enough, but reflections from right-angle corners require careful attention to detail. Those pesky wall hangings, particularly squares of highly absorbent carpeting, complicate the challenge.

Most teams use infrared sensors, with the Sharp GP2D family of distance sensors becoming a favorite. Other teams build their own IR sensors, which generally produce baffling results. I've written extensively about IR sensing in the past, so I'll just cover the high points here.

The weird ring in Photo 7 shows the beam pattern of an ordinary red LED used to mark the table in the Trinity RoboWaiter contest arena, as seen by an IR-sensitive camera through a visible-light blocking filter. Two things are of interest: a red LED emits plenty of IR and the beam doesn't have the nice Gaussian pattern you might expect. I've seen similar beam patterns from IR LEDs.

Putting such an LED in a triangulating distance sensor will cause problems, because the maximum intensity isn't directly on the LED's central axis. Worse, the reflected intensity will vary unexpectedly with distance, because it's definitely not a point source.

After a team has resolved the geometric issues, they will discover that an "IR photodiode" responds quite nicely to many different wavelengths. They should discover that problem before they arrive in Hartford, but experience shows that's not always the case.

The brown arch labeled *Photodiode*

in Figure 3 shows the response of an ordinary silicon photodiode. Although the peak of that curve doesn't quite match up with the peak of the IR curve showing the emission spectrum of an IR LED, it's reasonably close.

Several years ago, the gym's illumination came from banks of high-pressure sodium lamps. The *HP-Na* curve shows that the peak emission from those lamps occurs exactly at the peak of the photodiode response and the lamps completely jammed most IR sensors. If you're building robots for industrial environments, make sure you understand the ambient lighting.

Many teams discovered a mysterious 120-Hz modulation on their IR sensor output, with an amplitude that swamped the DC response they expected from their IR LED emitters. The typical symptom is a completely random voltage reading at that microcontroller's ADC channel, because the measurement isn't synchronized to the power-line modulation.

Silicon photodiodes respond to energy from many sources, including the fluorescent lights now used in the gym. Optical filters that reject the visible spectrum, as shown by the *87C Filter* curve, can help, but your circuitry must suppress unwanted modulation and your firmware must ignore any glitches that sneak through.

Other teams have used laser rangefinders, stereo triangulation through video images, and even more exotic techniques. Given the overall

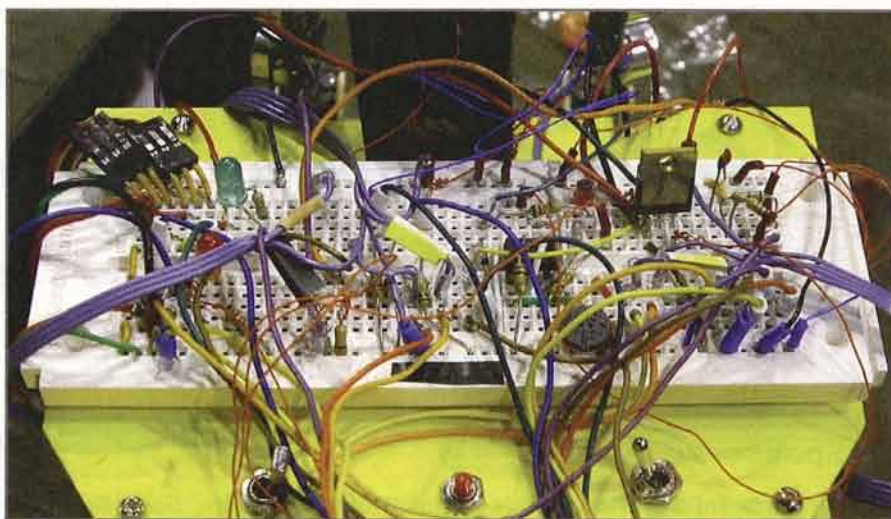


Photo 5—A solderless breadboard may handle low-speed digital logic on a workbench, but it's definitely not appropriate for mobile analog electronics!

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Display	3.2 inch QVGA TFT Color LCD Touch Screen	240 x 320 24-bit Color Touch Screen	320 x 240 24-bit Color LCD Touch Screen
ROHS	YES	YES	YES
Software Included	Sample Applications, uCLinux Distribution, SDRAM Initialization Code, Pre-emptive RTOS, GCC QuickStart Build	C/C++ IDE, Debug, RTOS, Visual State	C/C++ IDE, Debug, RTOS, Runtime Library
External RAM	32KB	64KB	32KB
External Flash	128MB NAND & 4MB NOR		128MB NAND & 4MB NOR
Add. HW Included	256Kbit FC EEPROM, Modem, 5-Key Joystick, 3-Axis Accelerometer	J-Link ARM Debug Probe, MP3 Decoder, Accelerometer	Prototyping Area
Price (\$)	\$345	\$495	\$370
Tools Xpress Avail.	RFO	In Stock	In Stock

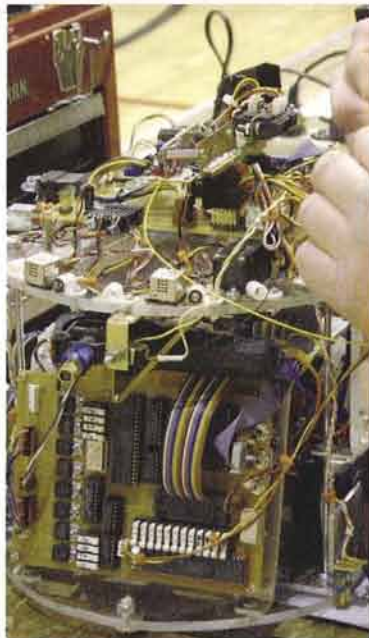


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Photo 6—Custom PCBs, secure connectors, and rigid mounts dramatically reduce the number of intermittent problems, but require attention to detail and plenty of design and construction time.



unreliability of most robots, it's not clear those methods provide a compelling advantage over simple sensors. The audience really likes scanning green laser pointers, though.

CONTACT RELEASE

Even projects produced by an experienced engineer can fail in an unexpected situation. A good engineer will incorporate large safety margins, adequate redundancy, and comprehensive error handling cope with those problems. An excellent engineer can do that without blowing the project's budget or schedule.

Constructing a robot that can bring back a prize from the Trinity contest presents a major challenge. If you think you can succeed, meet me at Trinity next year! 📧

Ed Nisley is an EE and author in Poughkeepsie, NY. Contact him at ed.nisley@ieee.org with "Circuit Cellar" in the subject to avoid spam filters.

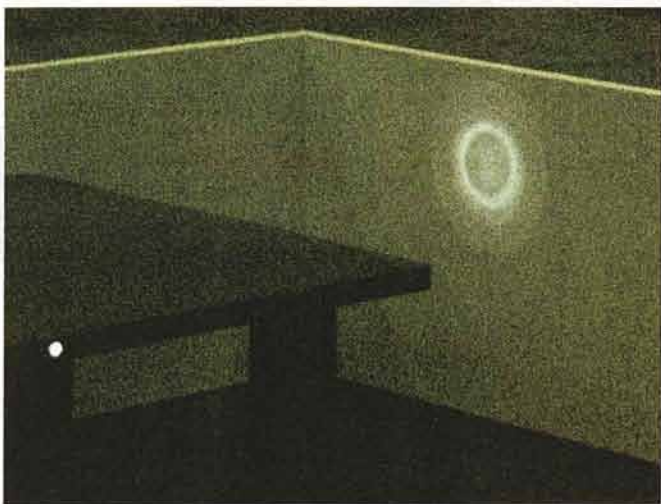


Photo 7—The beam from an ordinary red LED isn't the nice Gaussian pattern you might expect. IR LEDs behave similarly, much to the surprise of some teams.

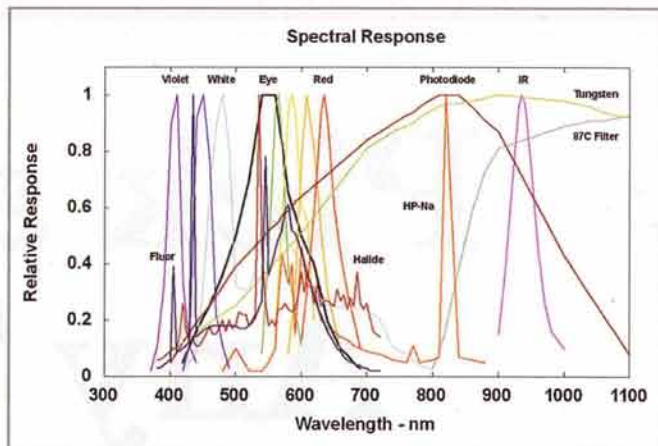


Figure 3—Many robots use Infrared distance sensors, but their silicon photodiodes can respond to energy from many sources.

RESOURCE

Trinity College Firefighting Home Robot Contest, www.trincoll.edu/events/robot/.

NEED-TO-KNOW INFO

Knowledge is power. In the computer applications industry, informed engineers and programmers don't just survive, they *thrive* and *excel*.

For more need-to-know information about topics covered in Ed Nisley's Issue 243 article, the *Circuit Cellar* editorial staff highly recommends the following content:

Robot Navigation and Control (Part 1)

Construct a Navigation Control Subsystem

by Guido Ottaviani

Circuit Cellar 224, 2009

This project is a navigation control subsystem for an autonomous differential steering explorer robot. A well-designed communications system remotely manages the robot. Topics: Robotics, Navigation, Dead Reckoning, Telemetry

Vision-Guided Robotics

by Hanno Sander

Circuit Cellar 224, 2009

You can build a vision-guided balancing robot that can interact with its environment. All you need is a handy design kit, an inexpensive camera, and a little guidance. Topics: Robotics, Vision, Balancing, PID, Frame Grabber, Tracking

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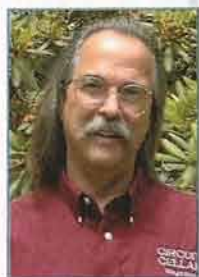
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Real-Time Feedback

A Versatile LCD Character Display Module

LEDs are efficient and serve an important role in many embedded design projects. But let's face it, a character-based LCD module can really bring a design to the next level. When you're looking for real-time feedback, a versatile LCD module is the way to go.

All of you who have built a hardware device that doesn't have some kind of status output, raise your hand. Ah, just as I thought. No hands. You'll have to search hard to find some piece of equipment without at least a power light. The first thing I want to know is: "Is this thing on?" I quickly follow that question with: "Is this thing running?" Is it just me, or do you too look for reassurance that all is well? One of the things that still bothers me about driving my wife's hybrid vehicle is the fact that the electric motor does not make a normal engine noise. Even when I can see the car is moving, I'm still looking for some other status indicator, like the speedometer to assure me all is well. It's spooky.

I doubt I've ever built a circuit without at least one LED. I use that blinky thing for all kinds of status indication while I'm debugging software. If I have the luxury, I'll add an LCD. While the code necessary to support an LCD is much greater than that necessary to use an LED, the ability to have verbose output outweighs the extra code that must be written to support it.

Most LCD modules use a parallel interface of 14 pins in a single or double row format. While the display is made up of rows and columns of dots or pixels, these are grouped together into character blocks of (nominally) 5 (columns) $\times$ 7 (rows). Each block is treated as its own distinct ASCII character display. You simply send a single ASCII byte to a memory address associated with a particular block on the display. The display figures out what specific 5 $\times$ 7 dot pattern to place into that associated block on the display.

Character LCDs come in a number of different formats from 1 $\times$ 8 (that's one row of eight characters) up to multiple rows of many character. The fact that any ASCII character can be displayed means that you can display text messages and also numeric values. There is nothing like seeing actual register values displayed while your application is running. This is most handy for real-time debugging.

Once you've had your first real-time feedback, you'll wonder how you ever got along without it. As with any good addiction, you'll find yourself craving more. While these displays are considered character, as opposed to graphics, there are some tricks you can play to make them just a bit

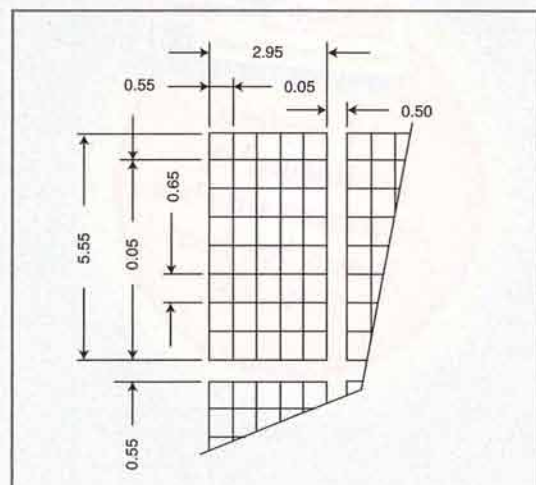


Figure 1—Character LCD modules are made up of individual 5 $\times$ 7 dot (character) matrices separated from one another both vertically and horizontally.

Figure 2—The Character Generator table uses 8-byte groups of predefined data that will control the status of each dot within the character matrices.

more useful. Let's begin with a quick look at how these function and you may begin to see how they might be used for more than just displaying text.

GENERIC CHARACTER LCD

One of the most obvious ways you can identify an LCD character display is by the blank areas that can be seen between each individual 5 × 8 character block. Figure 1 shows this in detail. Since there are no pixels in between each character block, there will always be this small frame of emptiness that gives the display a kind of window screen appearance. While this may not be optimum, it can practically disappear if you are creative.

The parallel interface for the LCD display consists of an 8-bit data path and three control signals: RS, RW, and E. Two registers are associated with the transfer of data: the Instruction Register (IR), when RS = 0, and the Data Register (DR), when RS = 1. Data is written to the IR or DR when RW = 0 or read from the IR or DR when RW = 1. Raising and lowering E (strobe) will complete the data transfer after the control signals have been set appropriately.

Writing to the IR register sets functions and pointers. Reading the IR

returns the status of the display (busy). Data is transferred through the DR to or from the Display Data (DD) or the Character Generator (CG) areas. The Address Counter (AC)—a pointer accessed via the IR—determines where in the DD or CG the DR's data is written to or read from. The AC is automatically incremented or decremented after each DD transfer.

DD RAM uses 80 bytes of RAM for line buffers. Differently sized displays (and biases) map this buffer differently; however, it is fairly straight forward. For the most part, the buffer is split in half, with the first characters of the first row addressed from 0x00 up to 0x27 and any second row addressed from 0x40 up to 0x67. With displays having four rows of less than 20 characters each, the third and fourth rows look like extensions of rows one and two, as if they were broken off the ends of rows 1 and 2 and stuck below them. For instance a 4 × 16 character display would be addressed as follows: row 1 0x00–0x0F, row 2 0x40–0x4F, row 3 0x10–0x1F, and row 4 0x50–0x5F. When the data byte 0x31 is stored at one of these locations, how does that translate into the 5 × 8 matrix pattern that represents an ASCII character?

Every character display module has a built-in CG table that contains predefined bytes that make up matrix patterns in ROM. Refer to the typical character table in Figure 2 as I point out some facts about it. Each table entry consists of 8 bytes (8 rows, top to bottom) for each character. With a byte's least significant bit (LSB) in the rightmost column, the bits signify which pixels will be turned on with a "1" in that bit position to represent a particular ASCII character in the 5 × 8 character block. Note that bits 7 through 5 are not used.

At first glance you will recognize the printable ASCII character set, which includes all of the numbers 0 through 9 and the uppercase and lowercase letters A through Z. Next, you will find most of the remaining blocks containing punctuation and miscellaneous symbols that you might choose to use in your text messages. Finally, take a look at the first column. There you will find these blocks labeled as CG RAM (x).

These are the often overlooked, user-programmable characters, where we can create some magic.

Let's get back to that character 0x31. The ASCII value of the digit "1" that I stored into an address in the DD. Using its value as an offset into the CG table, the display processor will find the entry (in Figure 2 at the fourth row from the left 0.1.2.3 and the second row down 0.1). Eight data bytes make up this image (a number 1), 0x04, 0x0C, 0x04, 0x04, 0x04, 0x0E, and 0x00. The display processor uses each DD RAM value as a pointer into the CG where it will find the 8 data bytes it needs to create the appropriate segment and common interface waveforms, which drive the row and column bits.

Once the you have initialized the LCD module (set up the IR), you only need to position the AC appropriately (usually to the address of the first character on the line) before transferring the display data to the DD RAM for each line.

ENHANCING TEXT DISPLAYS

There are a few tricks you can use to make a static display of text more attention grabbing. The simplest is to use the display On/Off control to blink the entire screen. By alternately writing the values 0xC0 and 0x40 to the IR, the display will appear to blink your message. You can also use the Clear Display command (0x01 to the IR) to remove all text from the display and then simply rewrite your message back to the display. Writing your message to the display using a short delay between characters is also an effective way to display it, as if it was being typed in by a user.

The LCD module has two optional cursors that can indicate the AC's location when the display is used to display text entered by a user, underline and block. The AC positions the cursor at the next address that data will be written to in the line buffer. Either cursor can be set to a static or blinking mode. In addition, you get to set the mode to automatically increment/decrement the cursor (move it to the next/previous address) or automatically increment/decrement the display (move the whole text line right/left). These are

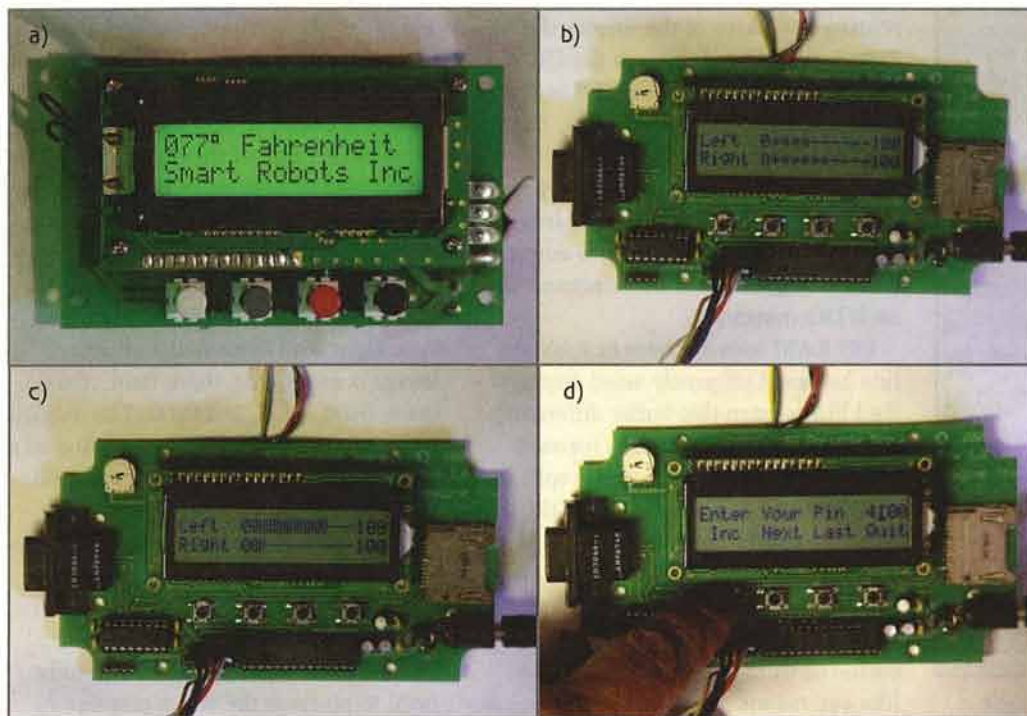


Photo 1a—This 2 x 20 character display uses the top line to display a list of status messages. The bottom line displays a continuously scrolling message. **b**—Bar graphs are a dynamic use of a character display. Here two active bar graphs are produced using standard graphic characters as bar glyphs. **c**—User characters give you the ability to define a special set of characters to enhance the look of your display. **d**—This application uses the bottom line of the display to label the external push buttons. This allows their function to be changed at any time. The top line is used to request or display data to the user.

great features when using the display in conjunction with user input—to give you feedback about what's being entered—but they are not too useful for simple text displays, unless you want to use the blinking cursor to attract attention. In some cases, the internal scrolling features can cause unwanted confusion. If the display line is shifted, it can begin displaying text from another line at the end, and not just the next line. (As you will remember, the first and third lines are mapped as continuous!)

So, how can you scroll a message without dragging in unwanted characters from another line? In some cases, you can take advantage of the 80-character line buffer on one- and two-line displays. But for the most flexibility, this must be done using external buffers in your application. Let's say you have a 20-character display and want to scroll a 100-character message. Give yourself 40 extra characters of blank space and use a buffer of 140 characters in length. If you put your message into this buffer starting at address 0x20, the preceding blank characters (and last 20 blank characters) will let your message appear to scroll onto the LCD line as if entering from the right side of the display and exiting off the left side. To accomplish this, set up a timer to signal every 0.1 second (or any other time for an appropriate scrolling speed). Every timer overflow, you will move 20 characters from this external buffer to a line in the LCD module. The first time, move the first 20 characters (all blanks); the second time, move characters 1–21 (blanks plus the first message character); the third 2–22, etc. Keep incrementing the address of the first character moved until you reach 120 and then continue to repeat the process over and over. No fancy footwork is done on the LCD. The 20 characters you move to the LCD each timer overflow is like a moving window into the external 140 character buffer. There is no reason you can't decrement the address and scroll the message from left to right, but

this is not easy to read!

For a truly interesting display you can combine scrolling, static, and blinking on multi line LCDs. I like to use the top line for a static or blinking short text message and a scrolling second line that gives verbose information.

Photo 1a shows a display that offers a list of status messages on the first line and a scrolling message on the second.

DISPLAYING QUANTITY

Many displays are more than just static text. Often what you want to display is the value of something. How that value is displayed is as important as the value itself. For instance, if you are displaying the level of a port's pins, a binary display of the data would be more helpful than a decimal number. If you are using an incremental encoder to show position, displaying the count with a polarity sign, or even converting the count to degrees or inches may make more sense. While a single line display doesn't seem to give you much to work with, it does have a lot of potential. Besides scrolling extended messages you might choose to cycle through a number of important data items. Whenever possible, include a text tag along with each piece of data (i.e., "Temperature = 60°", "Temp = 60°", or even "T = 60°"). You'll be surprised at the amount of data that can be displayed by using this cycling technique. It's simple to compose small text strings on the fly and eliminate using any external buffers.

Bar graphs are an excellent way to show relative amounts. You can use any character for the graph, but a non-alphanumeric is best. The asterisk (*) is good choice. The graph's total length can be indicated by the number of blank characters displayed. When room allows, I like to give boundaries to the graph with labels. You might use Max/Min, 0/100, Off/On, or some other text to give your graph more meaning. Try to choose a graph length (number of characters

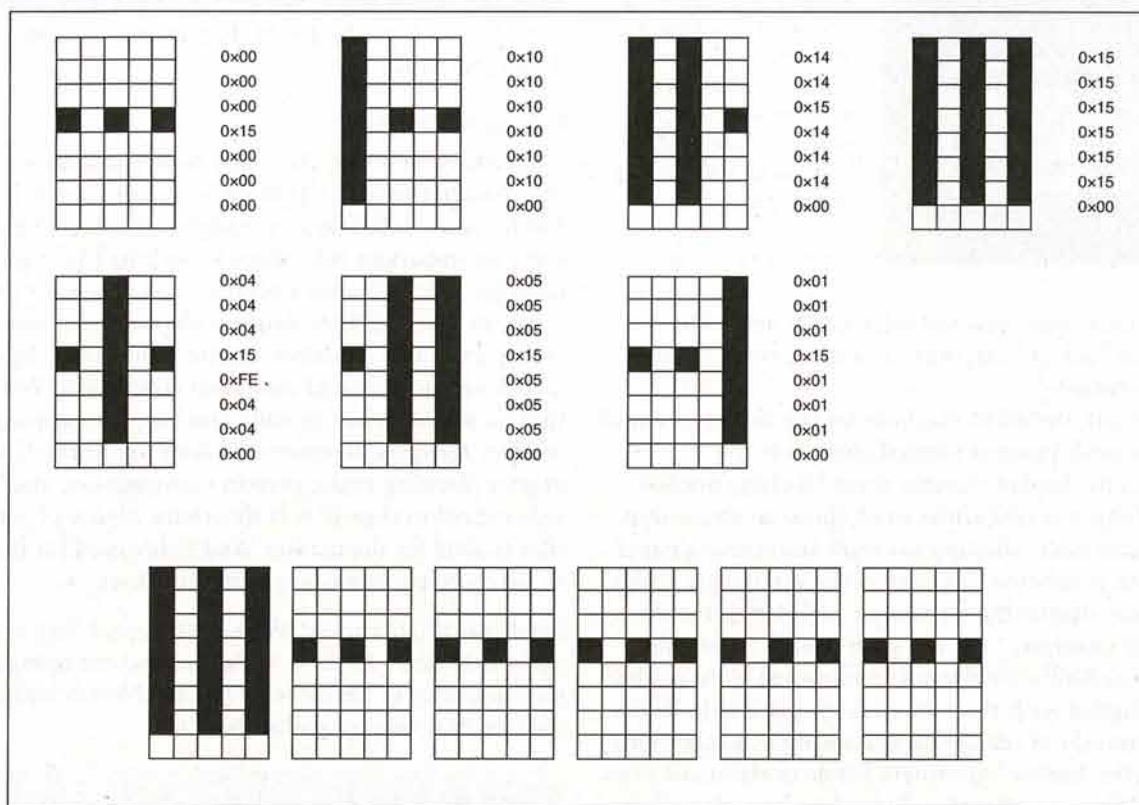


Figure 3—Here are some user-created bar graph characters that can be placed into Character Generator RAM locations CG RAM (0) – CG RAM (6). The lower group shows how these might be used to indicate an 18-bar graph using only six characters!

used for bar] that makes sense for the value you are trying to display (like 10 for percent), '0 ** 100'. Using the minus sign in place of the blank characters gives the bar graph a little more meat, "0 ** ——— 100" (see Photo 1b) as you can easily see the relationship between the bar and the graph length.

An issue with this bar graph is its resolution. Since the display is character-oriented, resolution is limited to the

character count. Or is it? Remember those CG RAM (x) locations in the CG table. We can use these to define new characters used especially for bar graphs. See Figure 3 for the character glyphs along with the 8 bytes of data defining each glyph. While it takes only the top four glyphs to build a bar graph that grows from left to right, the additional three glyphs increase the possible graphs that grow from the right as well as balance type graphs that use a central reference and can build to the left and/or the right.

Using these new glyphs you can indicate three different levels within a single character space. I chose this pattern because each character has a blank column between it (refer back to Figure 1) and your eye is fooled into thinking that this not a blank column but simply part of the overall bar graph. If you can get by this unusable blank column issue, you could design the glyphs using all five columns and have each character represent five different levels, but I prefer the three column approach as in Photo 1c.

USER INPUT

With small displays, it often makes more sense to use push buttons that have permanent functions. The use of lists, that is,

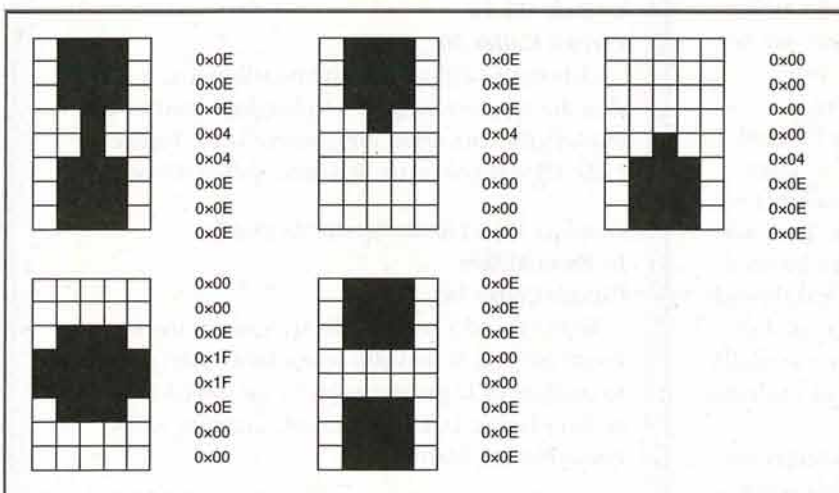


Figure 4—These user numeric character pieces are placed in Character Generator RAM locations CG RAM (0) – CG RAM (4). Copies of the first four are assembled into a 3 x 3 character matrix to form the numerals 0–9, the last is a large format colon glyph.



Photo 2—It is difficult to find character displays that have large format characters. With this user-defined character set, large format characters can be simulated as in this real-time clock.

choices that are displayed and selected by using “up,” “down,” and “select” can make a single line LCD functionally acceptable.

We can thank the ATM machine for the introduction of re-definable push buttons located along side the CRT/LCD. The display changes these labels as needed. The same button might allow us to choose an account at one point, and later, whether we want to receive a paper receipt. Even a one-line LCD can make use of this design by alternately displaying a question with labels for the buttons. For example, “Do you understand?” and “Yes No.” With pushbuttons physically mounted close to the LCD and aligned with the text areas, you are only limited by the amount of text space you need for labels. With a 20-character display four 4-byte labels is about the practical limit. This is perfect for things like “up down left right” or “+ – next back.”

A 2 × 20 display and four push buttons really make a versatile display. When the top line is used for user interactivity and the bottom line defining the push buttons, it will handle most of the user I/O you need for many of your projects (see Photo 1d).

LARGER DISPLAYS

When larger displays are necessary, don’t overlook multiple-line character LCDs. While larger displays generally mean more lines of small characters and not larger characters, you can simulate larger characters by using the CG RAM characters available to the user. But you need to keep things simple because there is room for only eight CG RAM characters (at a time). Remember: these are easily replaceable, so you can change them on the run according to what your application needs displayed.

The character set in Figure 4 was designed to be used on three lines of a display to form 3 × 3 blocks of large format numerals. This leaves the fourth line available for a text message using the standard character set. This was accomplished by defining 3 byte strings that can be used to build each line of characters. The 10 characters, 0 through 9, are each made up of three 3-byte strings for a total of 30 strings. However, only about half of these are actually needed because many are not unique and used in multiple places.

You can build the display on the fly, making decisions and filling in each line as required, but I find this often leads to problems when there are other activities that can take precedence over the display routine. Therefore, I find it better to use RAM buffers in the micro for each line,

build the screen there, and transfer each new screen all at once. That’s how the 4 × 24 display was used in the clock display in Photo 2.

NO ALTERNATIVE

For many a project, there just is no good alternative to the character-based LCD module. Prices start at less than \$10 for some small display modules. While an LED can serve an important role, there is nothing like a good text message to indicate the operating status of your project. I guess we can thank the original display controller designers for providing a flexible system. Since then, many manufacturers have created their own controllers. You’ll find that no matter who’s module you buy, they remain compatible. Today’s differences are more about the look of the display (viewing angle, current consumption, and back-lighting color) than how it functions. Plenty of competition is good for the market. And that’s good for the designer. So show me some creativity out there! 📺

Jeff Bachiochi (pronounced BAH-key-AH-key) has been writing for Circuit Cellar since 1988. His background includes product design and manufacturing. You can reach him at jeff.bachiochi@imaginethatnow.com or at www.imaginethatnow.com.

PROJECT FILES

To download the videos, go to ftp://ftp.circuitcellar.com/pub/Circuit_Cellar/2010/243.

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Knowledge is power. In the computer applications industry, informed engineers and programmers don’t just survive, they *thrive* and *excel*. For more need-to-know information about topics covered in Jeff Bachiochi’s Issue 243 article, the *Circuit Cellar* editorial staff highly recommends the following content:

LCD Digital Voltage Meter

by Dale Wheat

Circuit Cellar 209, 2007

Dale built a lightweight digital voltmeter. It measures the supply voltage of a rechargeable battery and displays the data on an inexpensive LCD. Topics: LCD, Digital Voltmeter, Resistor, Voltage Divider

Graphics LCD Library for the Z8 Encore!

by Brian Millier

Circuit Cellar 168, 2004

Brian created a graphics library you can use for your future projects. It provides access for Encore! programs to graphics LCD panels driven by the T6963 LCD driver chip. Topics: LCD, Z8 Encore!, Graphics, LCD, Fonts, Bitmap, Memory

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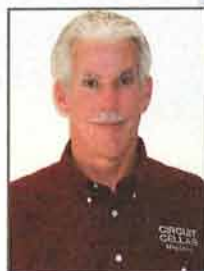
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Live for Today

The 8-Bit MCU Still Matters

"The 8-bit market is dead." Many years have passed and billions of 8-bit MCUs have hit the market since Tom first heard this statement. And in today's era of 32-bit wonderchips, it's hard for our little friends to get any respect. You may not notice them, but they're everywhere.

OK, I'll concede that after some 30-plus years the 8-bit market is "mature." But, with billions of units still shipping each year, it's hardly on death's door. An interesting question to contemplate: When do you think the last AVR, PIC, '51, '68, etc. will get shipped? Ten years? Twenty years? Fifty years? Ever? It's kind of like asking when nails and screws will disappear. I doubt I'll be around to see the final curtain call.

Don't get me wrong. The latest generation of practical 32-bit MCUs will surely be the engines that enable new categories of embedded

gadgets with fancy software and interfaces. But mini-me MCUs still have a role to play.

BYTE ME

What's so magic about 8 bits? You'd think 4 bits might be satisfactory since that's enough bits to count to 10, just like your fingers. But what about your toes? Not to mention 4 bits isn't enough bits to encode the alphabet. By contrast, 8 bits can count to 100 (both plus and minus, thank you), and handle ASCII to boot. That's more like it.

Bit creep has taken us from 4 to 64 bits and beyond. But just what "bits" are you talking about? ALU, registers, opcodes, address space, physical bus width on- or off-chip?

To my mind, there are really just two classes of MCUs. I mainly look to the register width, or "programmer's model" if you will, as the truest measure of "bitness." Using that metric, I combine typical 8- and 16-bit MCUs in one category and 32-bit chips in another, the difference mainly reflected in software aspirations. The little chips can handle dedicated applications while the big ones do the heavy lifting when it comes to running an OS, driving a fancy display,

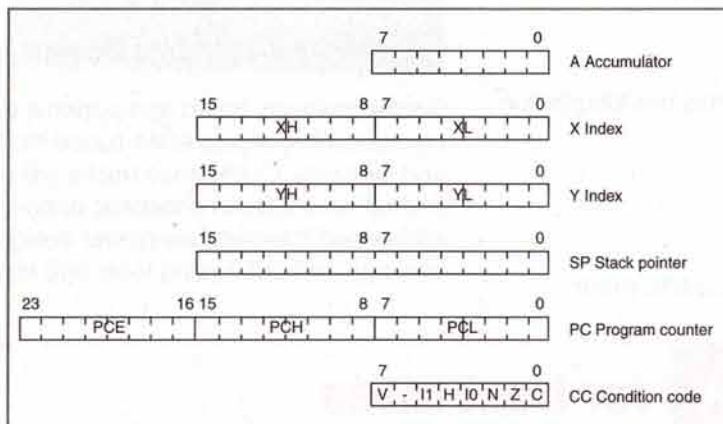


Figure 1—The STM8 harkens back to one of the very first microprocessors (the MC6800). But, thanks to the march of silicon, it delivers a lot more (MIPS and I/O) for a lot less (power, board space, price).

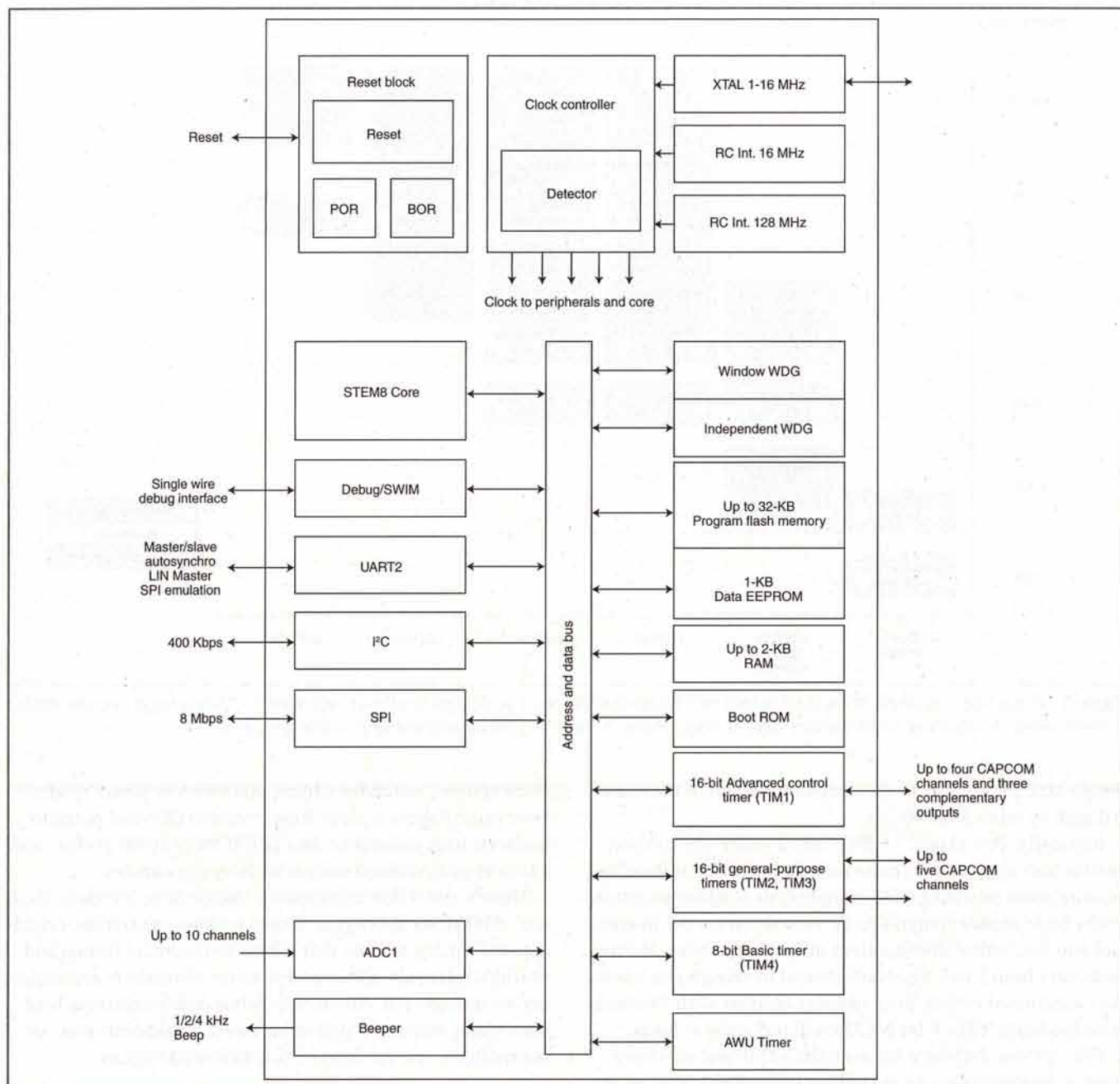


Figure 2—Small and simple they may be, but STM8 MCUs still have a lot to offer a world clamoring for ever more gadgets.

streaming a torrent of data, or crunching numbers.

Enter the “new” 8-bit STM8 line from STMicroelectronics. I put the word “new” in quotes because the architecture is a freshening of the earlier ST7, both branches of a family tree that clearly has roots in the dawn-of-silicon Motorola 6800 (see Figure 1). But look a little closer and you’ll find modern hardware including a three-stage pipeline, 32-bit-wide instruction bus, and large (16-MB) address space.

ST is on record citing favorable expectations for 8-bit, but talk can be

cheap.^[1] STMicro puts their chips where their mouth is, backing their hand with a full catalog of parts covering a spectrum of cost and performance (STM8S), power consumption (STM8L low-voltage and power), and temperature range (STM8A automotive to 145°C).

This month’s chip du jour is an STM8S105C6 (see Figure 2). There’s a method to the part number madness, as shown in Figure 3, where you can see the ‘8S line comprises “Access” (small, and cheap, is beautiful) and “Performance” (faster clock rate, more

memory and pins, fancier I/O) parts.

Admittedly, using the terms “performance” and “8-bit” in the same sentence is pushing it. Thanks to the pipelined Harvard architecture and 32-bit flash bus, STMicro can rightfully claim theoretical peak throughput approaching one instruction per clock. However, as usual, there are many instructions that require multiple clocks, such as branches, calls, returns, and 16-bit operations. I’d say a more realistic estimate of a typical program mix might be on the order of two to three clocks per instruction.

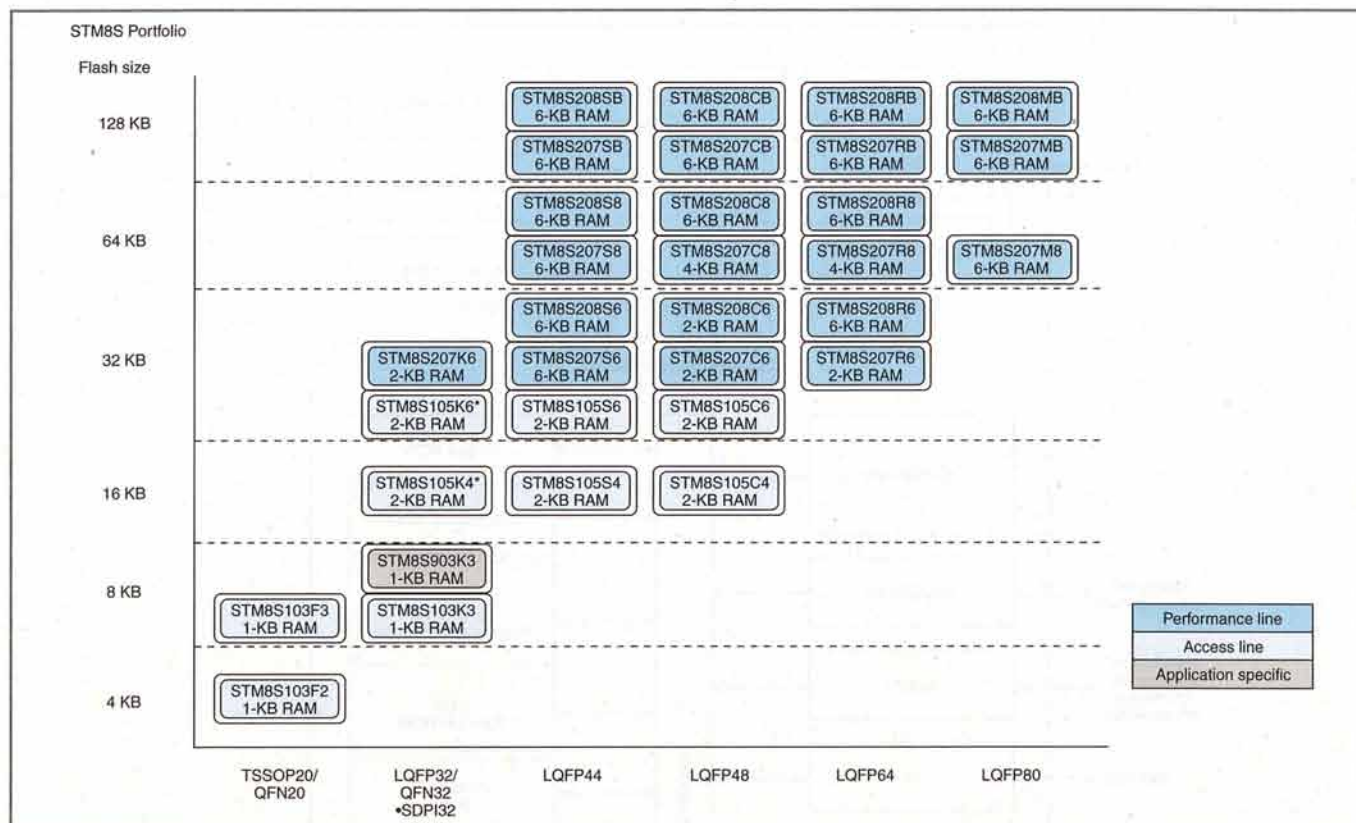


Figure 3—Being a serious player in the 8-bit market isn't for lightweights since you've got to offer enough parts to cover a range of applications. STMicro antes up with three STM8 families (the "S" shown here, "L," and "A") comprising nearly 100 different parts.

That's still plenty fast to do useful things and in the same ballpark as other 8-bit MCUs.

Ironically, this classic “CISC” has a relatively concise instruction set of just 80 basic instructions. The architecture is more about providing a full complement of addressing modes (eight basic modes comprising 20 variations) for the instructions to use, rather than a zillion different op-codes. Instructions vary from 1 to 5 bytes and are said to average just 2 bytes. As I mentioned earlier, programmers familiar with Motorola-now-Freescale ‘68xx 8-bit MCUs will feel right at home.

One obvious difference between the STM8 and old-timey chips is provision for a 24-bit address space. Before you get too excited note that the further reaches are only accessible with a limited repertoire of instructions, namely “far” jump (JPF), call/return (CALLF/RETF), and load/store (LDF). Since none of the STM8 parts have an expansion bus or giant on-chip memories, the larger address space is rather a moot point. While there are plenty of things an 8-bit chip can do, it’s clear a 32-bit MCU is likely to be a better choice for applications that truly need “beyond 64K” headroom.

The STM8 has all the usual suspect peripherals, such as robust GPIO (pins can source/sink up to 20 mA), serial (SPI, I²C, UART with IRDA, and LIN support), timer/counter (3 × 16-bit, 1 × 8-bit with 8-bit prescaler), up to 10 channels of 10-bit ADC, and even CAN on some models. There's also built-in glue logic including high- and low-speed clocks with failsafe switchover, power-on and brownout reset, two voltage regulators (main and low-power) for 2.95- to 5.5-V operation, two completely independent (i.e., different

clock source), watchdog timers, and four low-power modes. Noteworthy specs include long retention (20-year) program memory, high-endurance data EEPROM (300,000 cycles), and a factory-programmed unique 96-bit serial number.

There's also a decently capable "Single Wire Interface Module" (SWIM) for debugging. It uses a clever arbitration, encoding, and timing scheme that adapts to the MCU timing and provides relatively nonintrusive access to registers and memory via a single pin. An on-chip debug module features hardware single step and a pair of hardware breakpoints (one for instructions, one for data) with conditional triggers.

DISCOVERY CHANNEL

ST certainly makes it easy to kick the tires with the STM8S "Discovery" evaluation board (see [Photo 1](#)). It's

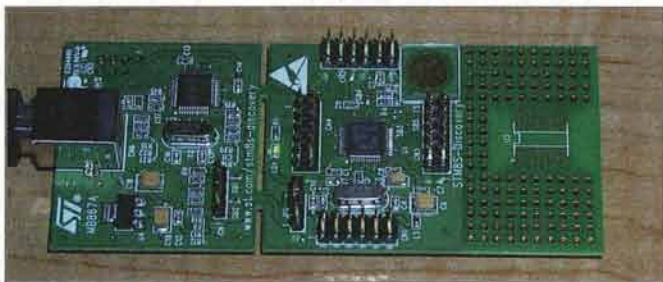


Photo 1—See for yourself what STMicro brings to the 8-bit party with the STM85 Discovery board. The resemblance between the STM85 chip (on the right) and STM32 (on the left) is more than package deep since I/O functions are being standardized across both lines.

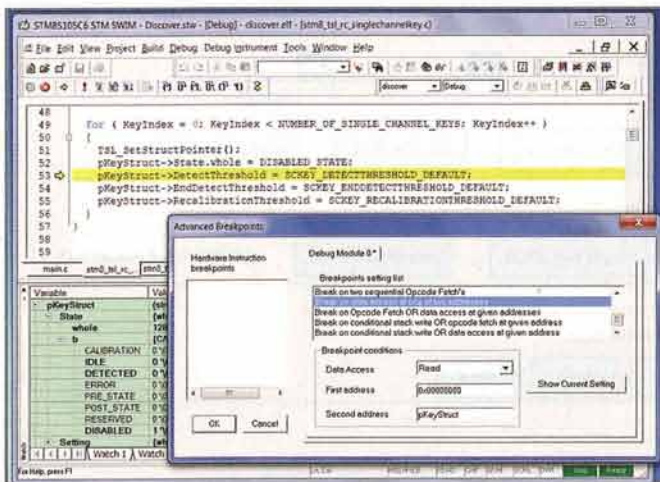


Photo 2—The ST Visual Developer (STVD) is a multi-window IDE that takes advantage of the STM8 built-in debug hardware. For example, you can set conditional breakpoints that trigger when a particular variable is accessed, something a purely software debugger can't do.

only \$10, all the more a bargain since it's actually two boards in one, an STM8S board and the PCB-equivalent of a USB debug pod (i.e., SWIM adapter). I had to smile at the tail-wagging-the-dog irony when I noticed the debug pod PCB uses a 32-bit STM32 Cortex-M3 MCU.

Two skinny PCB "bridges" (one for power and one for SWIM) connect the STM8S and debug boards so you have the option of snapping them apart. The debug pod PCB has a four-pin SWIM connector (power, ground, RESET,

SWIM) so you could use it for another project.

The STM8S board provides headers to access the pins and a small prototyping area. Experimenters will appreciate the use of standard (i.e., 0.1") headers rather than some fine pitch oddball connector. I'm less enamored of the decision to dedicate prototyping area to a particular surface-mount package (SOIC-16), but it's there if you can use it.

All the tools you need, including ST Visual Developer ("STVD," see Photo 2) and C compilers from Raisonance and Cosmic, are just a download away. As well, IAR recently introduced a version of their popular "Embedded Workbench" for the STM8.

To get you started "out of the box," the Discovery board includes a touch-sense electrode and LED and comes preprogrammed with a demo program that changes the LED blink rate when you touch the sensor. Besides being useful as a quick test, the program demonstrates a library of touch-sense software that STMicro has written for the STM8 family.

The touch capability is based on the classic RC discharge scheme that, with the addition of a resistor (the R) and electrode (the C), allows any GPIO pin to be used for touch sense (see Figure 4). A second resistor in series is optional for noise reduction. The STMicro library can handle up to 24 single-electrode "keys" and two multi-electrode (five- or eight-electrode) "sliders" or "wheels." STMicro embellishes the basic acquisition cycle with oversampling (see Figure 5), glitch filtering and calibration. As usual for GPIO-plus-software schemes, the burden grows quickly with the number of touch keys and the library must be called frequently enough to avoid latency issues (i.e., sticky keys). Even if you have the cycles to spare, the fact interrupts are disabled during portions of the acquisition cycle can crimp your application's real-time style.

If you find yourself getting bogged down trying to juggle things, an easy answer is just to throw another MCU into the mix (i.e., one to run the application and one for the touch interface). Thanks to ever-smaller prices, power, and packages, 8-bit chips are getting to be like their potato chip cousins in the snack aisle: you can't eat just one.

MORE THE MERRIER

The STM8 is a worthy contender in a competitive 8-bit MCU market. But maybe the real story isn't so much about STMicro standing out from the crowd as it is their testimony, in silicon, that there's still a crowd to stand in.

Think of how many 8-bit MCUs you bump into every day? Practically everything with an electron moving has one or more buried inside, you just don't see them. Now consider yet-to-be-served demand in developing economies on a global scale. Billions of people playing gizmo-and-gadget catch-up will keep the fabs running night and day.

Here's another way of looking at it. It's hard to reconcile

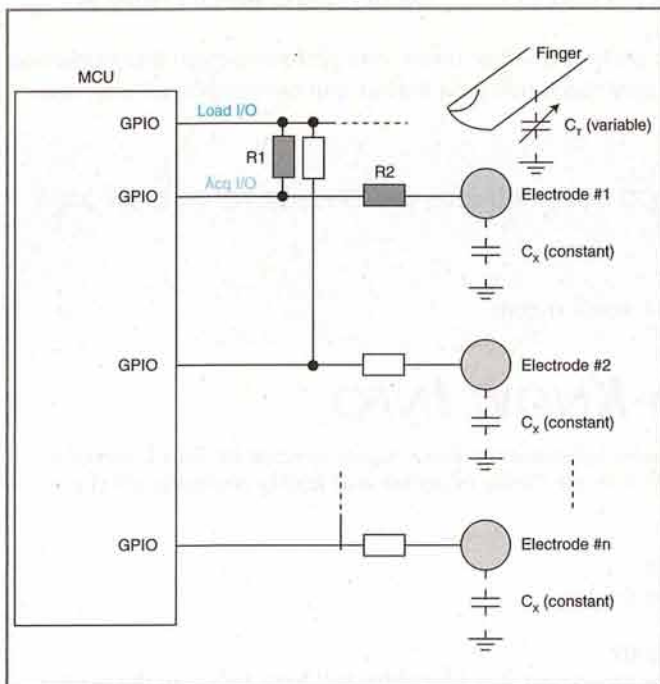


Figure 4—The hardware to implement touch sensing with the STM8 is minimal, just the touch key and a resistor or two (the series resistor is optional for noise reduction) connected to a GPIO pin. The trick is to detect a tiny change (e.g., 5 pF) in capacitance by measuring how long it takes to charge and discharge the RC network.

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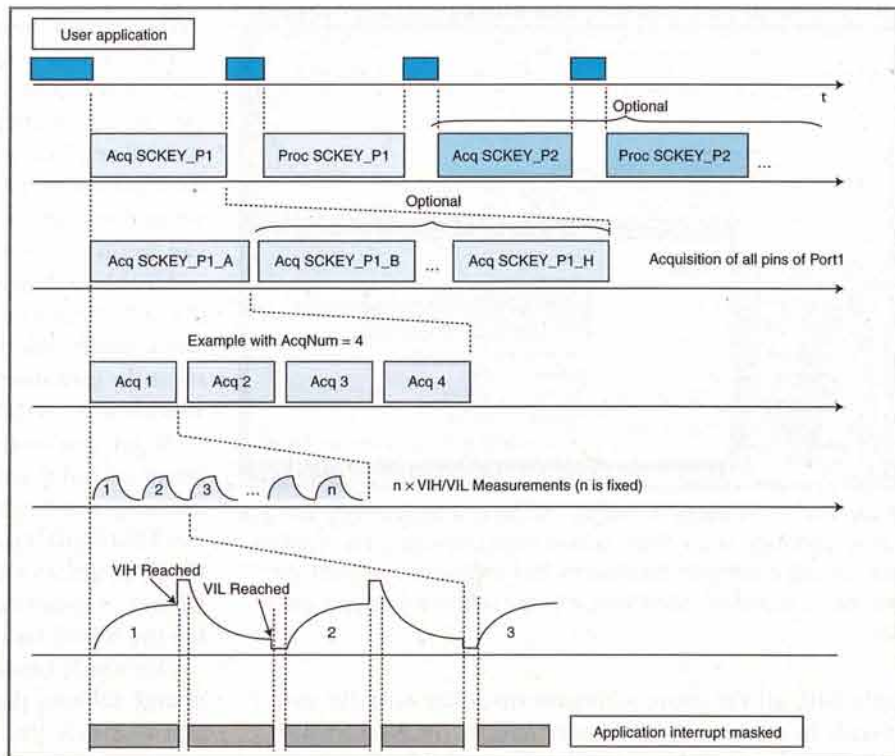


Figure 5—The ST touch-sense library software is where the action is since it handles the gory details of low-level capacitance measurement and higher-level glitch filtering. Just remember more cycles devoted to touch sensing (i.e., more and faster sampling of more keys) means less available for your application or responding to interrupts.

the premise that the 8-bit party is over with the fact major players keep introducing new parts. You can start to

think about writing the eulogy when the new chips stop. But until then, I say live, and design, for today. ☹

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.

REFERENCE

- [1] A. Pele, "8-bit MCU market still alive, says ST executive," *EE Times*, 2009.

SOURCE

STM8 8-bit MCU

STMicroelectronics | www.st.com

NEED-TO-KNOW INFO

For more need-to-know information about topics covered in Tom Cantrell's Issue 243 article, the *Circuit Cellar* editorial staff highly recommends the following content:

A Really Simple Plan

The "8-Bits" Saga Continues

by Tom Cantrell

Circuit Cellar 224, 2009

Sure, 32-bit micros are popular, but 8-bit chips still have a place in the market. Tom says major companies will be finding uses for the simple and inexpensive chips for years to come. Topics: 8 Bits, Microcontroller, Registers, Memory

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CROSSWORD



Down

1. Same-to-same
2. Finite impulse response, infinite impulse response, fast Fourier transform
4. Technology behind "e-tolling"
5. Computed by an adder
7. Content added to the end of a datasheet
8. Fast diode, electron tunneling
9. Sampling theory, Harry
11. A robot that looks and moves like a human
12. Signal reduction
15. Fathom [two words]
18. An error-finding app

Across

3. 5 MB to 3 MB
6. Yig [three words]
10. Disengage or complete a circuit
13. Embedded computing language developed by the DOD
14. Damping decreases a vibration's _____
16. μm
17. Trace line on a PCB
19. A different arrangement, but same result; $6 + 5 = 5 + 6$

The answers will be available in the next issue and at www.circuitcellar.com/crossword.

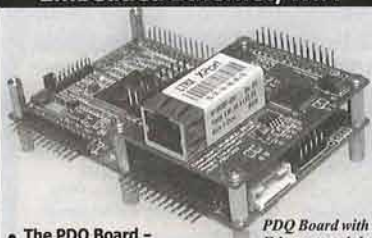
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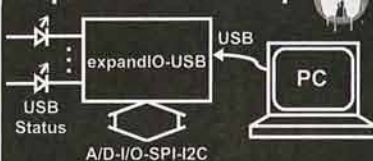
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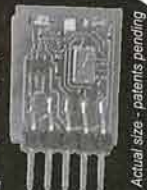
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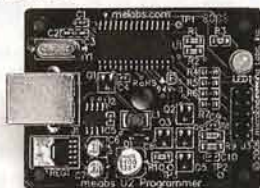
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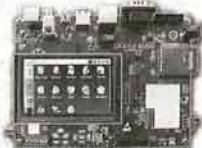
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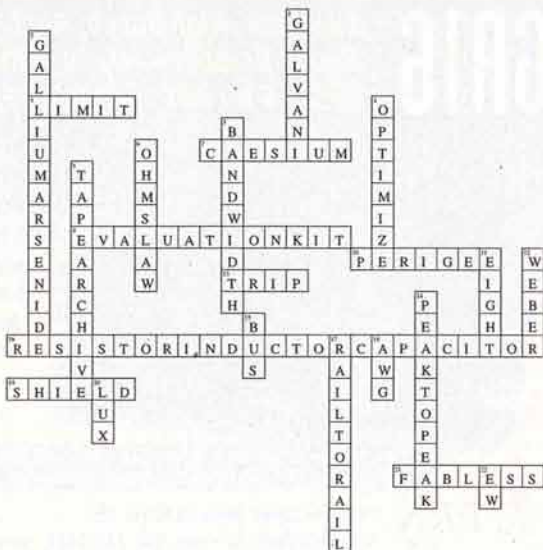
CROSSWORD ANSWERS from Issue 242

Across

3. LIMIT—Lim
7. CAESIUM—Cs
9. EVALUATIONKIT—EVKIT [two words]
10. PERIGEE—An antonym for a satellite's apogee
13. TRIP—Mechanical catch, switch
16. RESISTORINDUCTOR-CAPACITOR—RLC [three words]
19. SHIELD—To impede RF radiation
21. FABLESS—Wafer-less development company

Down

1. GALVANI—Performed experiments involving electricity and frog legs in the late-18th century
2. GALLIUMARSENIDE—GaAs [two words]
4. OPTIMIZE—Increase software's effectiveness
5. BANDWIDTH—Bigger pipe = more what?
6. OHMSLAW— $R = V/I$ [two words]
8. TAPEARCHIVE—.tar [two words]
11. EIGHT—The absolute value of -8 and 8
12. WEBER—Magnetic flux
14. PEAKTOPEAK—"PP" in VPP [three words]
15. BUS—A LAN's principal cable
17. RAILTORAIL—R-2R [three words]
18. AWG—Brown, Sharpe, wire, standards
20. LUX—Lx, light intensity
22. EW—Exawatt



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PRIORITY INTERRUPT



by Steve Ciarcia, Founder and Editorial Director

Sci-Fi Inspirations

If I were to poll *Circuit Cellar* readers, I'm sure I'd find that many of you are science fiction fans like I am. Speaking for myself, I've always viewed sci-fi as a kind of wish list for the future. I've also challenged myself to consider what it would take to turn some of the fictional ideas into real products. We don't have time machines yet, but we certainly have a myriad of other great products that were once merely fiction. Think about the 1850s, when science fiction included concepts like voice telephones, self-powered cars, solar electricity, and manned rockets. (Heck, I think even the modern flush toilet was still sci-fi.) My hat is off to the thinkers and writers who conceived ideas that were decades ahead of their time but still plausible enough to inspire others to make them a future reality.

Certainly one of the best sci-fi idea producers for my generation was the original *Star Trek* series in the late 1960s. While not properly appreciated by the mass TV audience and canceled after three years, it eventually became a cult classic among the techie crowd and inspired 10 movies and four spin-off TV series in subsequent years. In my opinion, perhaps we can thank *Star Trek* for inspiring some of the following:

Cell Phones: Originally called "communicators" in the series, these miniature flip-top, voice-activated speaker phones provided both communication and physical location data to users. Even Martin Cooper, the original inventor of the cell phone at Motorola, said his inspiration was the *Star Trek* communicator.

Large-View Screen: While it seems that displays on ship consoles were still bulky CRTs, the main viewing port of the Enterprise was a very large screen with surprisingly high definition. Perhaps the precursor to HDTV?

Bluetooth Earpiece: While not presented as a universal communication connection concept, Lt. Uhura noticeably wore a wireless earpiece in many episodes that perhaps inspired today's Bluetooth earpiece.

Tricorder: The original tricorder is probably equivalent to today's personal data assistant (PDA) with a variety of additional monitoring sensors. While many environmental attributes like light, sound, and EMF sensing are a current reality, true noncontact biometric sensing has a way to go, but we're well on the path to an authentic tricorder.

Automatic Doors: Doors that slide open and closed as people pass through them isn't necessarily something we want at home, but with an arm full of groceries or boxes, they are welcome additions to commercial establishments. They weren't invented for *Star Trek*, but their frequent use on the show surely popularized the concept.

Phasers: Handheld, directed energy weapons aren't real yet, but larger high-energy lasers and ion beam weapons definitely are. Of course, it's yet to be seen if a handheld, megawatt ion blaster can really ever have just a "stun" setting. :-)

PC Tablets: It seems like everyone on the Enterprise was always referring to and using graphics tablets that looked a lot like today's mobile touch-screen computing devices. Of course, back then, they probably used TrekDOS.

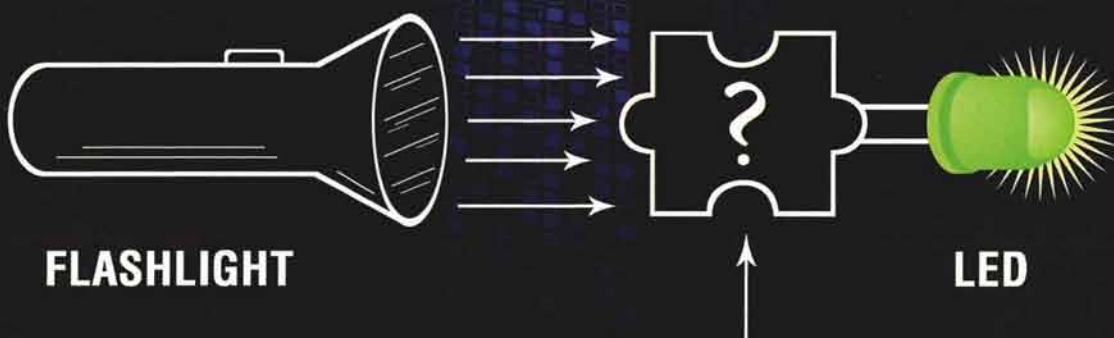
Teleconferencing: How many times on *Star Trek* did they show people on the viewing screen carrying on a real-time conversation with Captain Kirk? Certainly, live images and real-time teleconferencing was a stretch for 1967, but all it took to make it commonplace today was a bigger data pipe and 40 years of evolution.

So, that brings us to why I'd waste your time talking about science fiction fantasy. It's all about ideas and where we get them. I'm sure there are a lot more innovative ideas in the original *Star Trek* series that I don't remember, including some that perhaps inspired you as well. Fortunately, some people can just conceptualize great things while buttering toast or driving to work. But most of us aren't built that way. It's pretty hard coming up with entirely new concepts like the transistor, and new ideas take time to be accepted and commercialized. Most of us prefer adapting and improving other people's ideas simply because the rewards happen sooner.

The question is how many obstacles to the acceptance of "real inventions" are reduced when the concept has already been elaborately portrayed in science fiction? I have no proof, but perhaps commercial acceptance of things like cell phones and PC tablets was faster simply because of all the prepress, albeit science fiction. Hopefully, the *Circuit Cellar* reader who figures out how to produce enough power to make warp drive work will be granted immediate success as well.

steve.ciarcia@circuitcellar.com

Can You Solve This Puzzle?



What is the missing component?

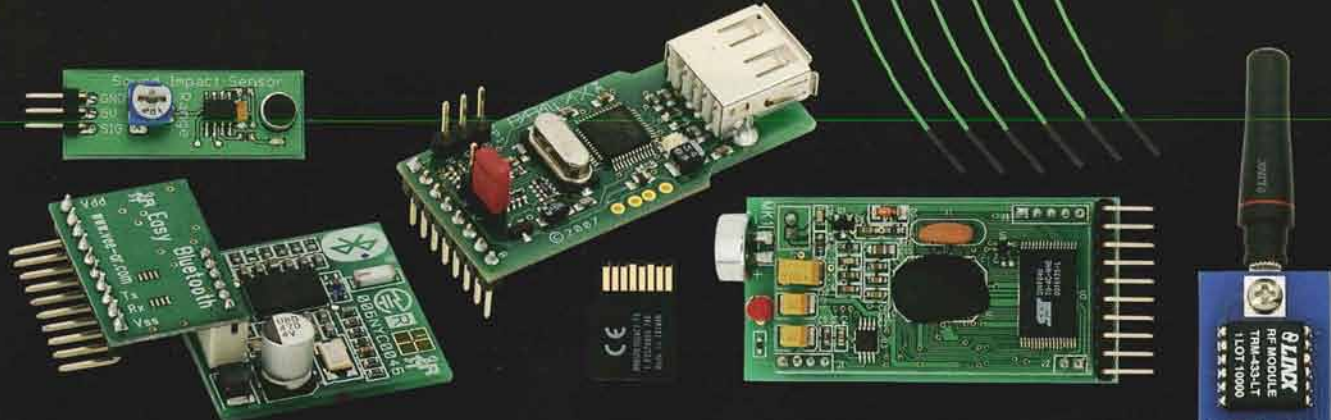


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A Physics professor planned to illustrate a lecture with demonstrations of how light can be intercepted by certain phosphors or various optoelectronic sensors and transformed into entirely new light. He wanted an ultra-simple demonstration of how an LED would glow when biased by a forward current provided by a suitable sensor. He rummaged through his optoelectronic drawer and found two silicon solar cells, several cadmium sulfide photo resistors, a couple of AlGaAs red LEDs, some silicon phototransistors and half a dozen silicon photodiodes. In his parts cabinet he found some transistors, miniature chokes and assorted resistors and capacitors. How did he combine the smallest number of components to do what the phosphor card did? Go to www.jameco.com/teaser8 to see if you are correct.

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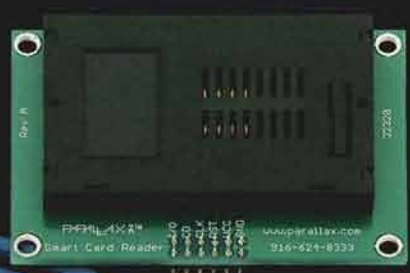
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