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# CIRCUIT CELLAR

THE MAGAZINE FOR COMPUTER APPLICATIONS

#229 August 2009

# EMBEDDED DEVELOPMENT

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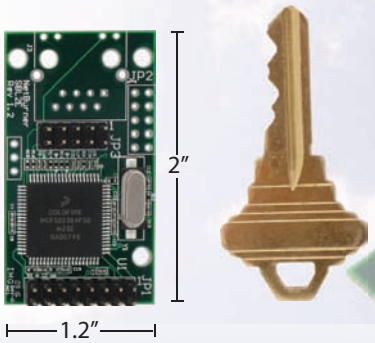

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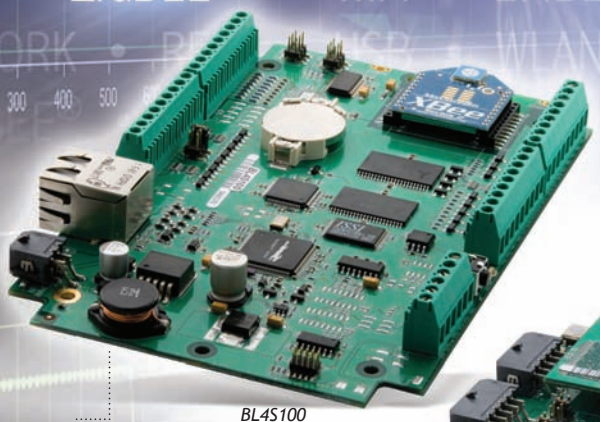

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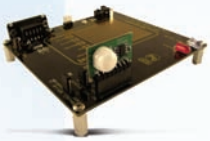

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# TASK MANAGER

## Embedded Development and Beyond

In the 2008 Embedded Development issue, we presented several articles with the intention of helping you hone your embedded development skills. Since then, we've received a fairly constant stream of interesting articles documenting amazing design projects. You've put that issue to good use!

This month we present several new articles that are sure to get you thinking about your next application. But before you turn to the last article and start reading backwards (Don't most of you do it that way?), I encourage you to read the first part of Dale Wheat's article series titled "Get Started With Embedded Development" (p. 14). It's an appropriate point of departure because Dale explains how to use your current design skills and some free software to tackle a new project.

Once you're done soaking in all of Dale's practical tips, you can jump to the article of your choice. To make things easy, I'll present the articles in chronological order.

In "Infrared Radiation Measurement," Michael Hamilton presents an FFT double-beam infrared spectrophotometer, which measures IR radiation to identify various chemical molecules (p. 22). He gets into the nitty-gritty details by describing how a dsPIC30F4012 controls the spectrometer with FFT algorithms.

On page 31, columnist Ed Nisley presents a high-voltage DC dosimeter charger project. If you're unfamiliar with such a design, don't worry. Ed covers all the bases, from transformer measurement to high-voltage power supplies.

The eye-catching design on the cover of this issue is based on Kevin Gorga's cable tracer design (p. 38). The tracer is used to detect underground ("embedded") cables. It works by transmitting a 125-kHz signal into an underground cable. In the first part of this series, Kevin presents the hardware. Next month he covers the software portion of the project.

If a particular design topic confuses you, Robert Lacoste is the man to consult. This month, in "Power Analysis Primer," he demystifies yet another complex engineering topic: power factor control (PFC). Turn to page 50 for the details and a few helpful experiments.

On page 60, Jeff Bachiochi presents a thought-provoking project that highlights a useful way to move data in and out of an embedded application. He uses a USB FIFO IC to move information in his "threat-level indication system." The design retrieves threat-level-related data from the Internet and sends it to an LCD via a parallel connection. You might not need a threat-level indicator, but you can use this basic design to develop an application that suits your current needs.

According to Tom Cantrell, when it comes to chips, "thin is in." This month he presents new "micro-energy cells" and describes exciting advances in battery technology, alternative energy, and nanopower silicon.

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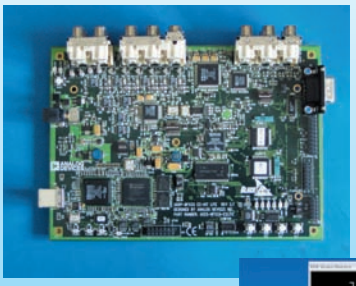

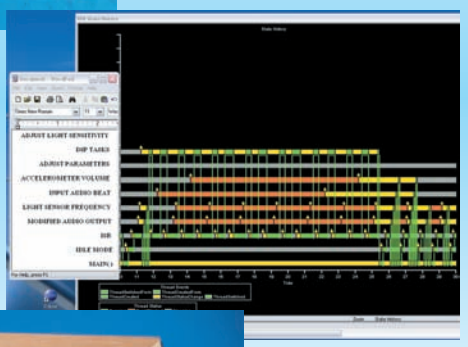

**Issue #225: Time-Triggered Systems (Part 1)**
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**Autonomous Vehicle Design** (Video example supplement only)
Embedded Systems, Sensor Technology, and Motor Control
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**Issue #228: NimbleSig III**
A New and Improved DDS RF Generator
*Thomas Alldread*

**Sound Synthesis Made Simple** (Full article plus video example)
A Multi-MIPS Music Box
*Peter McCollum*

**Issue #229: USB I/O Expansion** Available August 12
*Brian Millier*

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USB I/O Expansion

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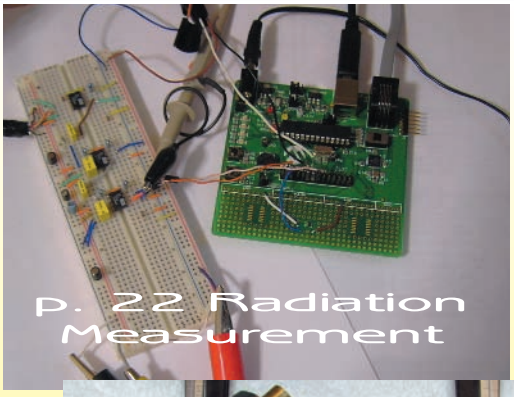



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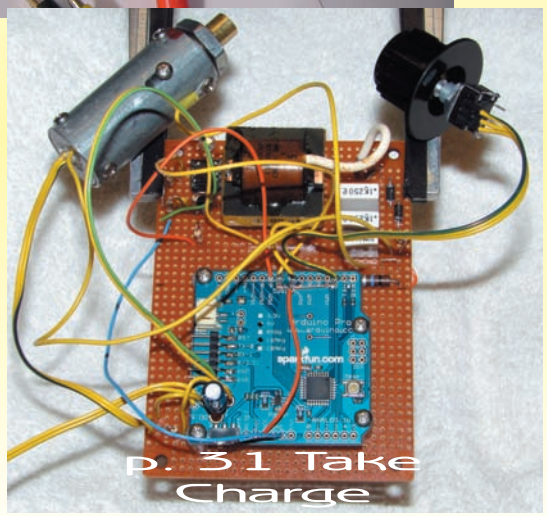

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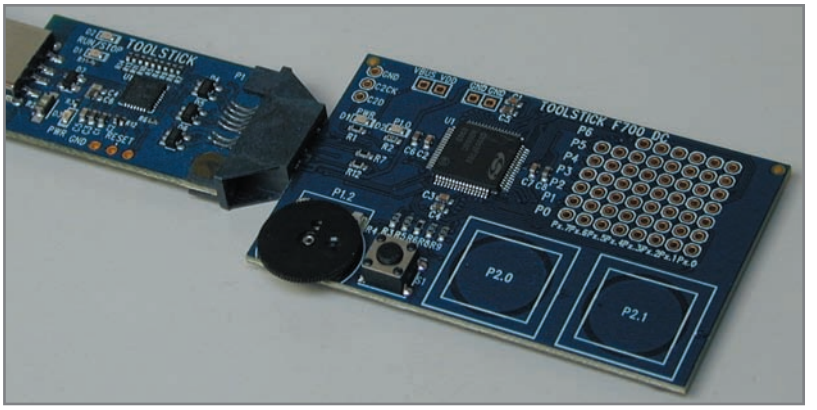
## 8051 DEVELOPMENT SUITE ENHANCED FOR C8051F7*xx*

Crossware has enhanced its **8051 Development Suite** by adding support for the Silicon Laboratories C8051F7*xx* family of high pin-count, touch-sensing microcontrollers. The C8051F7*xx* family is designed for cost-sensitive, high-I/O embedded systems. It offers a new, patent-pending, touch-sensing feature that is robust, accurate, responsive, and easy to configure.

Code creation wizards are provided for all on-chip peripherals and are able to generate configuration code, interrupt routines, and application code. The simulator simulates the 8051 core itself as well as many of the on-chip peripherals. This allows a developer to use the simulator immediately to test the code created using the wizards. The simulator can also be extended using the Virtual Workshop Interface to enable developers to construct a simulation of their complete target system. Switching to on-chip debugging allows the developer to exploit the debugging capabilities integrated into the C8051F7*xx* chips and run programs interactively on the target hardware.

With its advanced C compiler, libraries, wizards, simulator, and debugger, the 8051 Development Suite provides a complete and extremely user-friendly development environment for the Silicon Laboratories microcontrollers. A Silicon Laboratories-specific evaluation version of the Crossware 8051 Development Suite is included on the Third Party Tools and Documentation CD that's supplied with the Silicon Labs MCU development kits. A full version of this is now available from Crossware for developers who do not require support for 8051 chips from other vendors.

The suite is available for approximately **$1,320**.



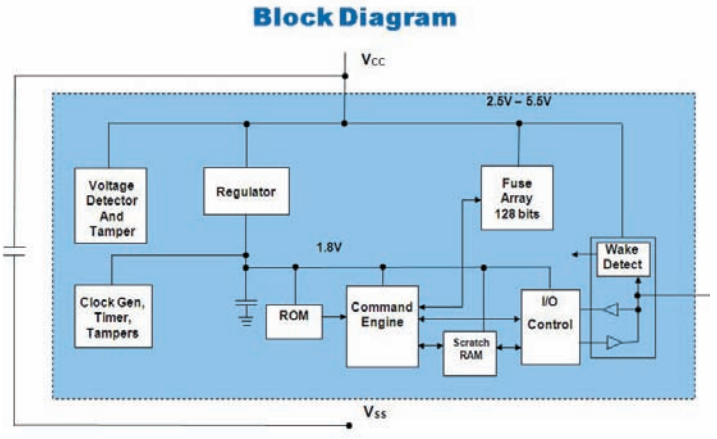

**Crossware**
**www.crossware.com**

## PLUG-AND-PLAY HOST-SIDE CRYPTOGRAPHIC AUTHENTICATION IC

The **AT88SA10HS** allows designers to implement authentication-ready embedded systems, without any knowledge of security protocols or algorithms and without writing any special cryptographic software. The AT88SA10HS CryptoAuthentication host device off-loads key storage and the execution of authentication algorithms from the system MCU, making it ideal in applications with limited microprocessor and memory resources or when reduced system cost and complexity is desired.

The AT88SA10HS is a single-chip authentication host with a 48-bit guaranteed unique serial number, SHA-256 engine, and a 256-bit host key that is inaccessible and unreadable. The AT88SA10HS host device executes all host-side operations including challenge/response (authentication) validation and firmware integrity verification.

The device includes 63 one-time, user-programmable fuses that are used to store a secret personalization value. Twenty-three fuses can be used for status or model number information. Once burned, there is no way to reset a fuse's value. Additional non-burnable fuses contain the manufacturing ID, and a guaranteed unique 48-bit serial number is pre-initialized.




The IC incorporates a number of physical security features designed to protect the keys. These include an active shield over the entire surface of the part, internal memory encryption, internal clock generation, glitch protection, voltage tamper detection, and other physical design features. Both the clock and logic supply voltage are internally generated, preventing any direct attack via the pins on these two signals. It costs **$0.72** in quantities of 1,000 units.

**Atmel Corp.**
**www.atmel.com**

# NEW PRODUCT NEWS

Edited by John Gorsky

## EMBEDDED WORKBENCH SUPPORT FOR FOURTH-GENERATION STELLARIS

**Embedded Workbench** for ARM and **IAR PowerPac** for ARM now feature full support for the fourth generation of Texas Instruments's ARM Cortex-M3-based Stellaris family. New configuration files, flash loaders, and project examples have been added to Embedded Workbench for Stellaris MCUs. The device-specific support achieved by these additions makes it quick and easy to get started with a project and allows you to focus on application development.

New PowerPac Board Support Packages will be made available for the three new kits (EKI-LM3S9B90, EKI-LM3S9B92, and DK-LM3S9B96) from TI. The BSPs include all the drivers and low-level routines needed for the operating system and communication software to interface the hardware and access the peripherals on the boards.

Embedded Workbench for ARM is a set of highly sophisticated and easy-to-use development tools. It incorporates an ARM Cortex-M3 C/C++ compiler, assembler, linker, librarian, text editor, project manager, and debugger combined in an IDE for programming embedded applications.

In addition to supporting debugging through the JTAG port, Embedded Workbench also supports SWO, which is part of CoreSight, the on-chip debug and trace solution used in the Cortex processor family and in the Stellaris family. You have full freedom to configure the types of packets sent over the SWO channel that should be displayed by an IAR C-SPY debugger. Additionally, debug log messages from a printf output can be also displayed by C-SPY without having to halt the execution.

Pricing for Embedded Workbench starts at **$3,395**.

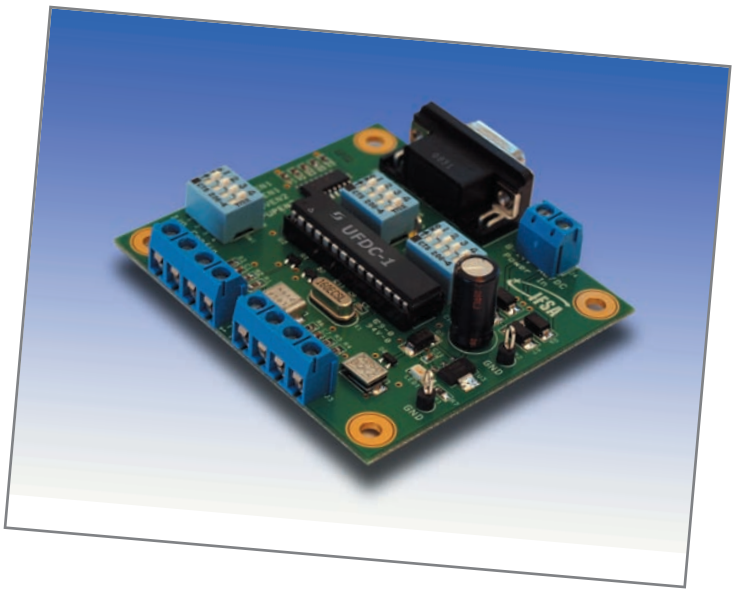
**IAR Systems**
**www.iar.com**

## EVALUATION BOARD FOR A WIDE RANGE OF UFDC ICs

OPTYS Corporation and the International Frequency Sensor Association (IFSA) have recently announced their joint development: an evaluation board for popular integrated circuits of Universal Frequency-to-Digital Converters UFDC-1 and its high-speed version UFDC-1M-16, which is designed for high-performance sensor systems.

With the **EVAL UFDC-1/UFDC-1M-16 Evaluation Board**, you can easily access all functions provided by the innovative UFDC-1 and UFDC-1M-16 integrated circuits. This two-channel evaluation board lets users evaluate the IC's 16 frequency-time measuring modes and one generation mode (for calibration purposes). Users can also use the board to build various sensor systems including smart, self-adaptation, and self-identification systems. All existing frequency, period, duty-cycle, time interval, pulse-width modulated, pulse number, and phase-shift output sensors and transducers can be directly interfaced to this evaluation board. The board can be connected to a PC or master microcontroller through the RS-232 interface and work in slave or master communication modes. The USB interface is possible with the help of an additional USB-to-serial, nine-pin RS-232 adapter cable.

You can connect sensor outputs to the evaluation board, measure any output frequency-time parameters, and test the sensor systems functions immediately. The development kit includes the evaluation board EVAL UFDC-1/UFDC-1M-16 with a PC interface, one IC of UFDC-1 or UFDC-1M-16 in a 28-lead PDIP package, and a CD with the appropriate software (EVAL and Terminal V1.9B) and applications notes.




The evaluation board EVAL UFDC-1/UFDC-1M-16 costs approximately **$132**. It is available through the IFSA and its worldwide-distribution partners.

**International Frequency Sensor Association**
**www.sensorsportal.com**

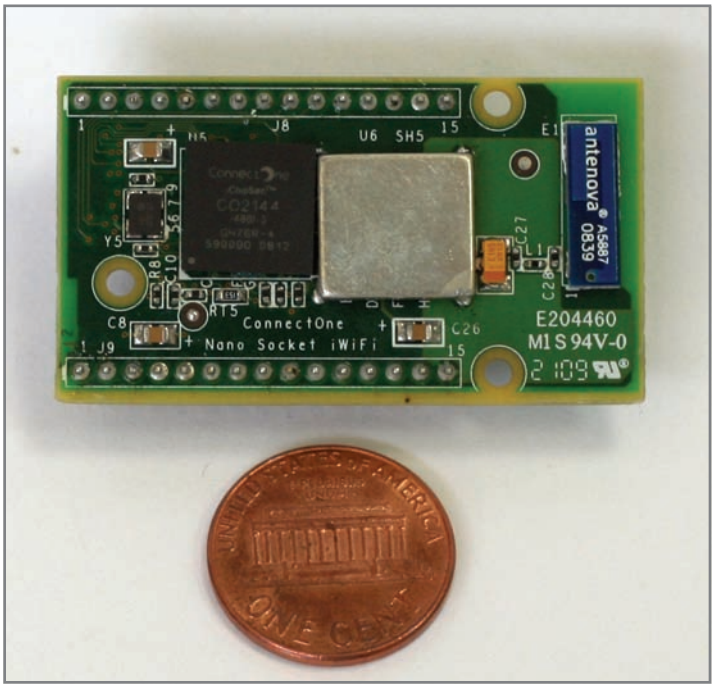
## FAMILY OF Wi-Fi AND LAN EMBEDDED MODULES

The **Nano Socket iWiFi/LAN modules** are based on the CO2144 Internet Controller and target machine-to-machine solutions. Nano Socket iWiFi is an 802.11b/g embedded WiFi module with an integrated WiFi antenna. Nano Socket LAN is a 10/100BaseT LAN module with an integrated RJ45 connector. A logical interface between the host application and the modules is the AT+i Protocol, a simple text-based API that enables fast and easy implementation of Internet networking and security protocols.

Both modules boast high level of Internet security and encryption algorithms (AES-128/256, SHA-128/192/256, 3DES, SSL3/TLS1 protocol for a secure client socket session) for complete, end-to-end encryption support. The Nano Socket iWiFi also includes the latest WLAN encryption schemes (64/128-bit WEP, WPA/WPA2 enterprise). The modules also share the same simple header-based pinout, which means reduced assembly costs and increased flexibility when designing a solution.

The Nano Socket family eases development by including USB, SPI, USART, and RMII interfaces. The Nano Socket LAN operates at an industrial temperature range of –40° to 85°C and is RoHS-compliant. Nano SocketLAN costs less than **$25** for large volume customers. Evaluation can be achieved using an II-EVB-363MS evaluation board (**$160** list price). Nano Socket iWiFi costs less than **$35** for large volume customers. You can perform evaluation using an II-EVB-363MO evaluation board (**$160** list price).

**Connect One**
**www.connectone.com**




## ULTRA-TINY EMBEDDED-LINUX RTOS FOR STELLARIS

**Unison** (version 4) for ARM Cortex-M3 processors is an ultra-tiny, embedded-Linux-compatible RTOS and opens Stellaris MCU families to Linux and POSIX-compatible development for the first time.

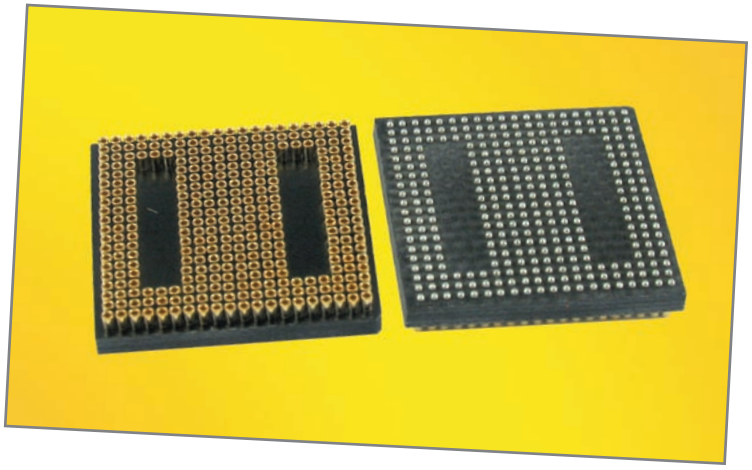
Unison OS and Stellaris MCUs are well suited to a broad set of applications, including lighting, white goods, home automation, industrial automation, power management, and networking applications. Unison increases embedded development productivity and reliability for Stellaris developers by substantially reducing the time and difficulty required to develop complex systems. OEM developers can create improved applications with standard reusable components supported by the Unison product, Texas Instruments's Stellaris MCUs, and CodeSourcery tools.

Over 20 Unison demonstration programs run out of the box on Stellaris evaluation and development kits in just 10 minutes. Using the EKC-LM3S6965, EKC-LM3S3748, and the new EKC-LM3S9B90, EKC-LM3S9B92, and DK-LM3S9B96 with Unison, you can get instant results. Unison's extensive networking protocols, file systems, serial I/O, diagnostics, shell and chip support packages with Stellaris MCUs take "plug and play" to a new level.

Unison V4 is hosted on Windows XP and Vista for x86 platforms. Unison support, training, and consulting for TI's entire MCU portfolio is available from RoweBots. Open-source licenses start at **$695**. Royalty-free licenses start at **$3,999**.

**RoweBots Research, Inc.**
**www.rowebots.com**

## SOCKET ADAPTER FOR ANALOG DEVICES BLACKFIN



The **SF-BGA316C-B-62F** is a high-performance socket that allows 0.8-mm pitch, 17 × 17 mm body, 20 × 20 array Analog Device ADSP-BF539/ADSP-BF539F ICs to be placed in socket and operate without compromising performance in demanding automotive applications. The Giga-snaP BGA SMT adapter pair consists of a SF-BGA316C-B-62F, patent-pending female sockets with machined pins epoxy over molded into an assembly that matches the male pin LS-BGA316C-61. The RoHS-compliant SF-BGA316C-B-62F is soldered to a PCB using standard soldering methods without warping results in reliable connection to PCB. Both adapters are constructed with high-temperature FR-4 body, assuring a match with target PCBs and preventing failures that occur with CTE mismatch. The LS-BGA316C-61 BGA adapter—to which the user attaches a target 316-ball BGA chip—is plugged into the female socket on the board. The adapters have the same solder ball types as the IC they are emulating.

The Giga-snaP BGA Surface Mount Feet Adapters require half the force of conventional adapters at 10 pounds for the 316-pin device. The electrical path of the adapters is a high-priority performance issue. The physical length from the top connection point on the male adapter to the solder ball on the female socket is 4.5 mm. This is the shortest connection length by far for machined pin sockets, therefore providing better transmission of high-frequency signals.

The 0.8-mm Giga-snaP BGA SMT Adapter line is available in many different pin counts and customs can be delivered in days. Pricing for the SF-BGA316C-B-62F is **$200** each. The LS-BGA316C-61 is **$79**.

**Ironwood Electronics**
**www.ironwoodelectronics.com**

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## ULTRA-LOW-PROFILE SMD AND THROUGH-HOLE DC/DC CONVERTERS

Aimtec has released two new series of ultra-low-profile, 1-W, DC-DC converters in surface-mount and through-hole packages for industry-wide integration. Measuring only 19.50 mm × 10.53 mm × 5.10 mm, the **AM1M-NZ** (DIP14) and **AM1LT-NZ** (SMD) converters provide you with the best combination of a small footprint, an ultra-low-profile, and high power density (23 W/in$^3$).

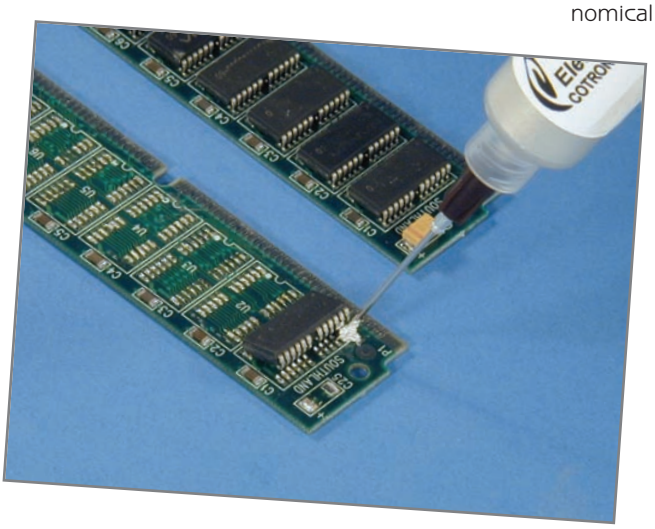
Featuring input voltages of 5 and 12 VDC, single output voltages of 5, 9, 12 and 15 VDC with input/output isolation of 1500 VDC, the AM1M-NZ and AM1LT-NZ series were designed for easy integration into a wide range of applications using distributed power supply architecture.

Operating within a temperature range of –40° to 85°C at full load, without derating, forced air cooling, or external components, the converters boasts a cold start-up temperature of –40°C and an MTBF of greater than 1,500,000 hours, making these self-contained converters ideal for space-critical, battery-powered, portable electronic applications.

Made with high-quality, RoHS-compliant materials for global use, the AM1M-NZ and AM1LT-NZseries is competitively priced at **$5.14** in 1,000-plus-piece quantities with samples available from stock for immediate delivery.

**Aimtec, Inc.**
**www.aimtec.com**

## LOW-COST, NICKEL-FILLED CONDUCTIVE ELECTRICAL ADHESIVE



Cotronics's **Duralco 122** nickel-filled adhesive and casting epoxy is specially formulated to provide a low-cost, economical alternative to silver-filled, electrically conductive epoxies. Duralco 122 is the perfect solution for electrical and industrial applications that require a low-cost, electrically conductive adhesive. It is ideal for manufacturing and repairing flexible circuits, solder replacement, bonding semiconductors, EMI shielding, thermistors, wire tacking, heating elements, assembling, electronics, and more.

This two-part epoxy is mixed by hand and flows better. The mixed epoxy cures at room temperature in 16 to 24 hours at 75°F, or it can be fast cured in 10 minutes at 200°F. For optimum conductivity, adhesion, and strength, post cure at 250°F for 2 hours.

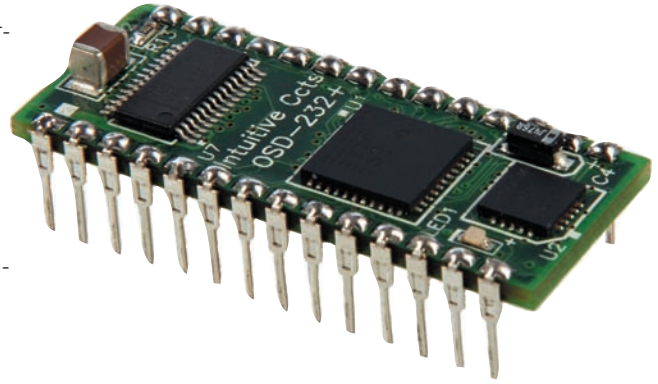
The nickel-based Duralco 122 conductive epoxy bonds exceptionally well to glass, ceramics, plastics, metals including steel, stainless, aluminum, and lead as well as dissimilar materials. Epoxy is resistant to moisture, chemicals, and solvents.

A 4-oz tube of Duralco 133 costs **$74.95**.

**Cotronics Corporation**
**www.cotronics.com**

## COMPOSITE VIDEO CHARACTER AND GRAPHIC OVERLAY DEVICE

The **OSD-232+** is a single-channel, on-screen, composite video character and graphic overlay device in the form factor of a 28-pin 0.6" DIP socket. From any RS-232 or TTL source (such as a PC or microcontroller), control the display of 30 columns × 12 rows (NTSC) or 15 rows (PAL) of information directly onto an incoming composite video source. OSD-232+ can overlay characters and graphics onto either an incoming video source or self-generated background screen. OSD-232+ has 256 definable 12 × 18 pixel characters.



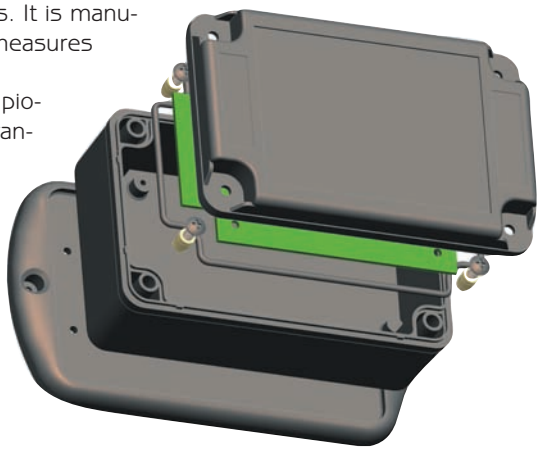

Graphic images (such as logos) can be imported to create on-screen sprites. OSD-232+ firmware upgrades are supported via a PC connection. Included with OSD-232+ is a demonstration utility, firmware update utility, and font editing software. An optional evaluation board EB-OSD-232+ with connectors and wall power supply is also available.

The OSD-232+ is available for **$119** The EB-OSD-232+ evaluation board is available for **$79**.

**Intuitive Circuits, LLC**
**www.icircuits.com**

## WATER-RESISTANT OUTDOOR UTILITY ENCLOSURE

The water-resistant **S-523322** is designed for wireless, outdoor applications. It is manufactured in a highly durable ASA RoHS-compliant material. The rugged case measures 5.1" in length, 3.2" in width, and 2.1"in height.



The enclosure was developed in partnership with Arch Rock Corporation, a pioneer in IP-based wireless sensor network technology headquartered in San Francisco, CA. The S-523322 is available in unlimited colors and with endless CNC modifications. A recessed area on the cover is designed for artwork and accepts both overlays and printing. Options include an O-ring for outdoor applications and a wall mount plate for indoor or outdoor mounting. Screw-together assembly was engineered with brass inserts and stainless screws to ensure longevity in outdoor environments.

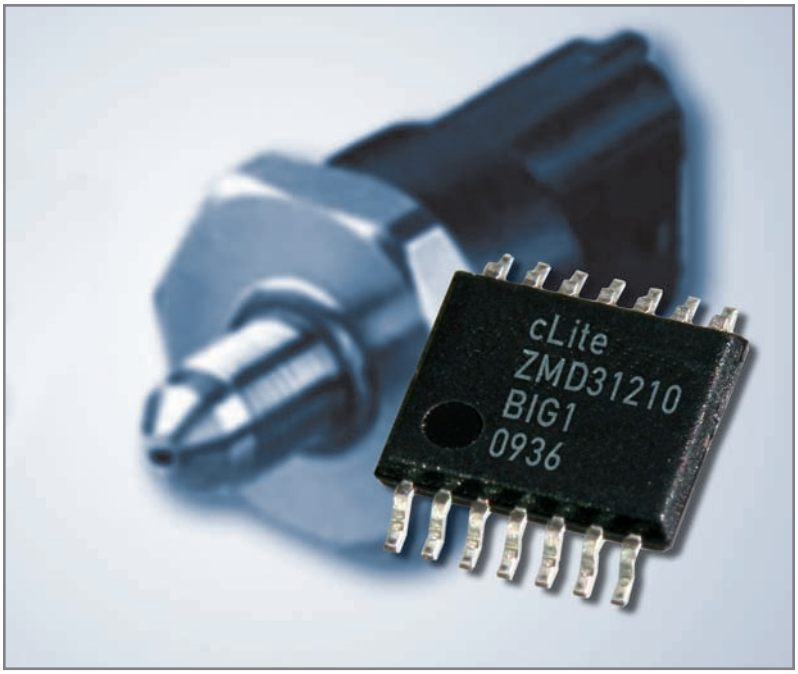
When purchased independently, the enclosure costs **$4.25** in 500-piece quantities.

**New Age Enclosures**
**www.newageenclosures.com**

NPN

## CAPACITIVE SENSOR SIGNAL-CONDITIONING IC

The **ZMD31210 cLite** capacitive sensor signal conditioner delivers 14-bit resolution and 0.5% accuracy over a wide range of capacitances and temperatures. Capacitive sensors offer several benefits, including very-low-power operation, and the ZMD31210 supports this with a low 60-µA current draw over a supply voltage range as low as 1.8 V or as high as 5.5 V.




The ZMD31210 can be configured to interface with capacitive sensors from 2 to 260 pF with sensitivity as low as 125 atto-Farads (aF) per digital bit. The part accommodates both single and differential input sensor configurations. All calibration is digital and completed in one pass. This eliminates the cost of laser trimming and speeds the production of fully calibrated sensor modules.

The conditioner connects to microcontrollers, but it can also be utilized in stand-alone designs for transducer and switch applications. The mixed-signal design offers full 14-bit compensation of sensor offset, sensitivity, and temperature via an internal digital signal processor running a correction algorithm. Calibration coefficients are stored in an on-board nonvolatile EEPROM. The system interface offers $I^2C$, SPI, PDM, or alarm outputs.

Unit prices start at **$2.93**, in volumes of 1,000 devices or more.

**ZMD AG**
**www.zmdi.com**

## SOLDERING STATION WITH ADDED FUNCTIONALITY

The new **WD1002T** microprocessor-controlled soldering station provides you with the same extensive functionality of the WD1002's control unit and the short tip-to-grip precision of its iron, but with the added benefits of a Stop+Go safety stand with an integrated dry tip cleaner.

The WD1002T increases safety and extends tip life by using the WDH10T Stop+Go safety stand and the WD1 control unit. The Stop+Go safety stand features temperature offset, which allows you to easily program setback levels and temperature lockout from the WD1 control unit. The temperature of the soldering iron automatically returns to setback temperature when it is placed in the safety stand; it returns to operating temperature when removed. This process extends the life of the tip.

To save valuable bench space, a dry tip cleaner has been integrated into the Stop+Go stand. The use of the dry cleaner reduces surface oxide build-up and maintains the thermal efficiency of the soldering tip, allowing the soldering iron to operate at lower temperatures—thereby increasing tip life and lowering operating costs.

The soldering station is ideal for use in repair and laboratory environments, as well as for production, design, and R&D applications.

The WD1002T costs **$315**.

**Cooper Tools**
**www.coopertools.com**

by Dale Wheat

# Get Started With Embedded Development (Part 1)

## "Bare Metal" Implementations and "CircleOS" Apps

Dale shows you how to use your natural design skills and some freely obtainable software to get started on new embedded development projects. He provides specific, step-by-step instructions on how to develop applications for the STM32 family of ARM Cortex-M3 devices from STMicroelectonics, both as "bare metal" implementations and "CircleOS" applications.

The STM32 family of devices is the first entry by STMicroelectronics into the realm of ARM Cortex-M3 32-bit microcontrollers. (For more information about the STM32 and Cortex-M3, see Tom Cantrell's article "More Than a Core," *Circuit Cellar* 213, 2008). ST already had several families of 8- and 16-bit microcontrollers, as well as some 32-bit ARM7 and ARM9 derivatives. The introduction of the STM32 family (licensed from ARM in October 2006 and announced in June 2007) was their first offering of ARM Cortex-M3 devices, and they were only the second vendor in the world to produce them, following Luminary Micro of Austin, Texas (now part of Texas Instruments). Having two players in the game has made things much more interesting because of lower prices and a wider variety of development tools.

One of the most inexpensive ways to get a taste of what the STM32 family can do for you is to get your hands on one of the delightful STM32 "Primers" from Raisonance in Montbonnot Saint-Martin, near Grenoble in France. The original STM32 Primer (part number STM3210B-PRIMER) is a self-contained medallion, complete with a neck lanyard, rechargeable batteries, a color LCD, sound, a USB interface, a built-in JTAG, and a three-axis accelerometer (see Photo 1). The new Primer2 (part number STM3210E-PRIMER), which coincides with the expansion of the STM32 line in May 2008, features a rectangular outline, a larger color LCD with touch screen, more flash memory and SRAM, and other design enhancements. Refer to Photo 2 for a comparison of the two devices.

Photo 1—The STM32 Primer (part number STM3210B-PRIMER) is a self-contained medallion. It includes a neck lanyard, rechargeable batteries, color LCD, sound, a USB interface, a built-in JTAG, and a three-axis accelerometer.

I'll show you how to use either of the Primers and some freely obtainable software to get started with your STM32 development projects. The sky and your imagination are the only limits!

### GETTING STARTED

Step One is to get your STM32 Primer or Primer2. At the time of this writing, the Primer2 was just released and was not readily available from all the usual suspects. I hope that by the time you read this that they are in plentiful supply from a source near you. I have a secret weapon (her name is Tracy Acton and she works for Logix Sales & Marketing in Dallas, TX, a manufacturer's representative of STMicroelectronics, but don't tell anyone) and was able to get my hands on a Primer2 in late December 2008. If you don't have a secret weapon, you might have to wait for Annual Gift Man to show up in his red suit and

leave one in your stocking. Alternatively, you might try Mouser Electronics (www.mouser.com) or Digi-Key (www.digikey.com).

Once you get your Primer, open up the box and look at what you have. There's the Primer and its bright orange neck strap, a USB cable, a mini-CD, and a minimal "Getting Started" half-pamphlet, which clues you in to the battery disconnect jumper inside the unit. Here's where you learn how easy it is to get inside the Primer. It's not held together with any sort of fasteners. In fact, the original Primer is not held together much at all. The single, internal PCB sits in one half of the plastic clamshell and the top half sits on top of the PCB. The Primer2 adds three small screws to hold the PCB to the front half of its plastic clamshell, but the back side comes off easily just like the original Primer. In either case, you should be able to see the battery disconnect header and install the supplied two-pin jumper to electrically connect the battery. Remember to disconnect it if you put the Primer on the shelf for any length of time or if you want to leave the original Primer connected via its USB for a long period of time. Both units charge their internal batteries via USB. The original Primer uses two nickel metal hydride (NiMH) cells and employs a simplistic trickle charge circuit that lacks overcharge monitoring, so it's up to you to not let it gobble up too many electrons, otherwise it can get over-warm or worse. The Primer2 uses a single lithium ion cell and a dedicated USB charge monitor circuit, so you can leave it plugged in and not worry about it. A nice improvement. The Raisonance folks definitely pay attention to suggestions from their users and forum members. My minor contributions are credited on the CircleOS web page along with other active members of the stm32circle community.

So now you've got the power hooked up and it's time to play around a little bit before we start any serious work. If you're near a hot USB jack, go ahead and plug in the cable and let the little guy top off. Here you will discover that the Primers have not one but two USB connectors. The one labeled "STM32" is connected directly to the STM32F103 microcontroller, which sports a full-speed USB 2.0-compliant device peripheral. Using the ST-supplied USB libraries you can design your own USB peripheral devices. Many example projects are delivered with the libraries. The other USB connector on the Primer is marked "DEBUG" and is routed to the on-board RLink USB JTAG interface. This is a Raisonance invention and is implemented using another ST microcontroller from their ST7 family of 8-bit devices. This one has a built-in USB interface and implements a JTAG interface although the protocol is proprietary. It is rumored that the Primer3 will have an available JTAG port available for use with third-party JTAG adapters. Plug the USB cable in to the "STM32" port for now to get the battery jump-started while we get the software installed. Once you have all the drivers loaded, you can charge the Primer via either USB connection.

## SOFTWARE SELECTION

You've got a lot of options when it comes to development software, as long as you want to program in C. Your other option at this time is Thumb-2 assembly language,

**Photo 2**—Take a look at both Primers. The new Primer2 (part number STM3210E-PRIMER) is rectangular. Compared to the original, it has a larger color LCD with touch screen, more flash memory, and more SRAM.

which makes me tingle with excitement but makes other people shudder for some reason. One of the unique characteristics of the Cortex-M3 architecture is that you can write complete software projects completely in C, and that includes the start-up, exception, and interrupt routines. All previous ARM families were labeled "Some assembly required," as their start-up and interrupt routines had to be coded in assembly language. This is progress!

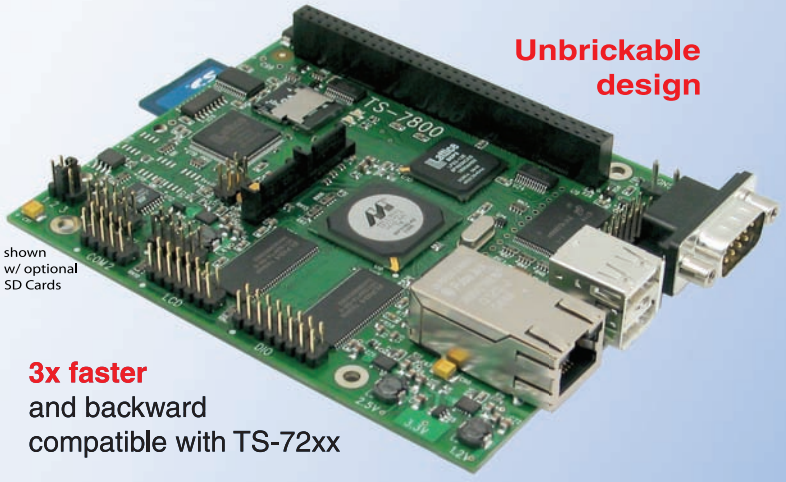
There are several complete toolchains available for the Cortex-M3 in general and the STM32 specifically. The example I will use in this article is from Raisonance and is called Ride7, which includes Raisonance's own IDE wrapped around the GNU GCC toolchain and drivers for their RLink USB JTAG interface. It runs under Microsoft Windows XP and Vista, including the 64-bit variations. Other toolchain suppliers include CodeSourcery (GCC), Altium's Tasking, Keil, and IAR. Each offers various combinations of features and price. Expect more vendors to provide support for this exciting new architecture in the very near future.

You can use the software that comes on the mini CD that was included with your Primer. It is a good bet that it is no longer current. I recommend downloading the freshest flavors and styles from the stm32circle.com, devoted to the Primers and its very own operating system, the CircleOS. Find the "Resources" page and follow the links for either the Primer or the Primer2. There will be a list of downloadable documents including the latest CD-ROM image. It's a big one: 150 MB at the time of this writing.

While you're waiting for those files to download, poke around at your Primer. It comes jam-packed full of stuff

# Embedded Single Board Computers

## High-End Performance with Embedded Ruggedness




shown w/ optional SD Cards

**Unbrickable design**

**3x faster** and backward compatible with TS-72xx

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500 MHz ARM9

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- 128MB DDR RAM
- 512MB high-speed (17MB/sec) onboard Flash — **$269** qty 1
- 12K LUT customizable FPGA
- Internal PCI Bus, PC/104 connector
- 2 host USB 2.0 480 Mbps
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- 2 SD sockets
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- 110 GPIO
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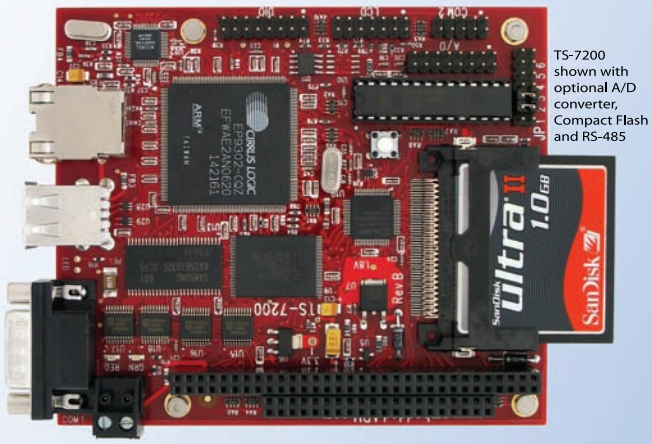
- 2 SATA ports
- Sleep mode uses 200 microamps
- Boots Linux 2.6 in .67 seconds
- Linux 2.6 and Debian by default

## Low Price, Low Power, High Reliability using Linux development tools

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- Watchdog Timer
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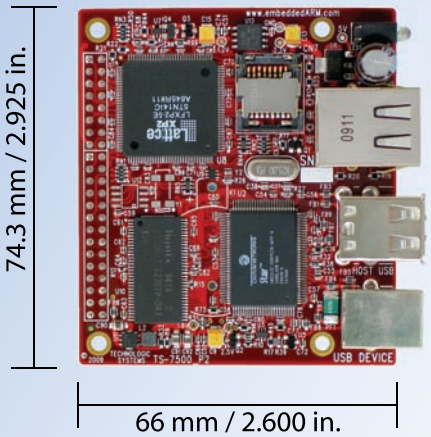


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NEW! 400 MHz PowerPC with Floating Point Unit

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- Dual-execution unit, double-precision FPU
- Multifunctional PC/104 connector
- 12K LUT customizable FPGA
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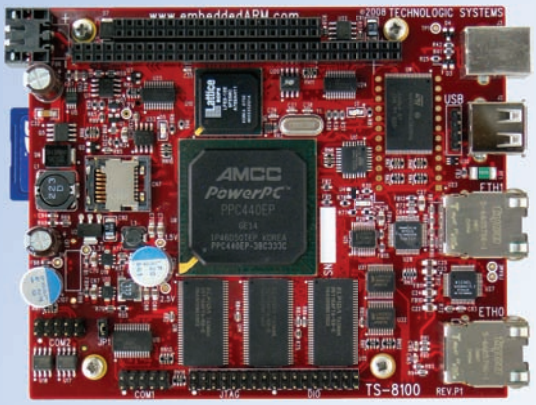
- 1 USB Host, 1 USB Device (12 Mb/s)
- Boots Linux 2.6 in < 2 seconds
- Fanless < 4W, sleep mode < 1mW
- Regulated 5-28V power input
- 2 10/100 ethernet
- 4 COM ports
- SPI & DIO
- RS485/RS422
- 2 SDHC sockets
- 5 10 bit ADC
- RTC & WatchDog
- 2 DMX Channels




shown w/ optional SD Card

$229 qty 100

$269 qty 1

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www.embeddedARM.com

to play with. Push the button to turn it on. The LCD should light up and display the ST and Raisonance logos, along with some butterflies, which seem to be the mascots of the STM32 family. I've named their human spokesmodel "Headband Girl." You'll see her on all the official ST literature for the STM32 family.

The first time you turn on your Primer2, it prompts you to perform a touch screen calibration by pressing a couple of the "function key" buttons at one end of the LCD. Headband Girl will also say "Welcome to STM32 Primer2" in a quite intelligible female voice. This is due to the improved audio circuitry when compared with the original Primer. It sounds even better through headphones. It might not actually be Headband Girl talking, because I think of her as being French or maybe Swiss and the voice has a distinct British accent.

You should see a small, blue dot moving around on the LCD. This is the pointer that responds to tilt information from the MEMS accelerometer. The Primer2 also features a four-direction joystick button for navigation and menu selection. Bounce the blue ball around for a bit until you get the hang of it.

Now turn the Primer sideways. Notice that the screen reorients itself to remain "upright" no matter at what angle it is held. This is another feature brought to you by the accelerometer and common on many other personal electronic devices. It is not without its own drawbacks, as not all software properly accounts for random 90° shifts in orientation. Luckily, the active area of the LCD is square so the aspect ratio need not change to keep up with all your crazy tilting. The slightly longer LCD on the Primer2 is "squared" by permanently allocating a set of "function keys" at one end that can be pressed by plastic tabs overlapping the touch screen or by simply touching the area with your finger. My Texas-sized fingers cover about two buttons at once.

Pushing the button will bring up a menu and let you select from various options, such as playing games

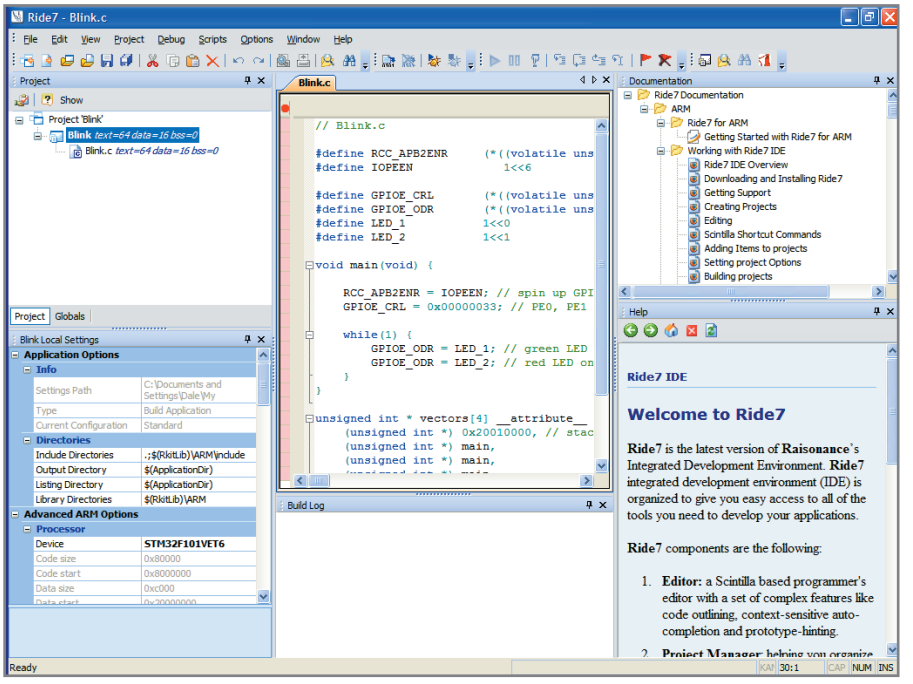



**Photo 3**—This is the Ride7 integrated development environment (IDE).

(Maze, Breakout), configuring system options, and shutting the unit down. You can also turn the Primer off by holding down the button for more than about a second. This only works if the factory software is running. If you write your own software (apart from CircleOS applications, soon explained, which you can also write), then you have to provide your own method for turning off the power. There is no hardware power switch, unless you want to count the somewhat inaccessible battery disconnect jumper. Pushing the button sets a latch which powers up the unit. Resetting the latch is always done in software.

After you get tired of playing the games, it's time to get to work and take the ride. Install the Ride7 package first, then the ARM Tools. It's a very straightforward installation. I used all the default settings. No restart is required, which is a nice change of pace. We'll play with a few of the provided example projects first, then move on to our own notions of what proper firmware looks and feels like.

## TAKE THE RIDE

The default installation of the Raisonance tools creates a program group called, appropriately enough, "Raisonance Tools." Beneath that selection, there is a "Ride7" subgroup that contains the shortcut to launch the Ride7 integrated development environment (IDE). Select that now and the Ride7 application launches (see Photo 3).

The program window is partitioned into several sections, including a project outline, a tabbed editor pane, an output window for compiler messages, and most importantly separate documentation and help areas. Let's open up one of the provided example programs and go through the steps to get a basic program working.

From the main program menu, select "File, Open Project" and navigate to the default installation directory, which on my machine was "C:\Program Files\Raisonance\Ride." Next, click down into the examples directory, "..\Examples\ARM\Primer\," and then either the "STM32" directory for the original Primer or the "STM32Primer2" directory for the Primer2. Under either directory, select the "toggle" project directory and finally open the "toggle.rprj" file that contains all the information about the "Toggle" project. Keep your expectations in check. This is a very simple example program and

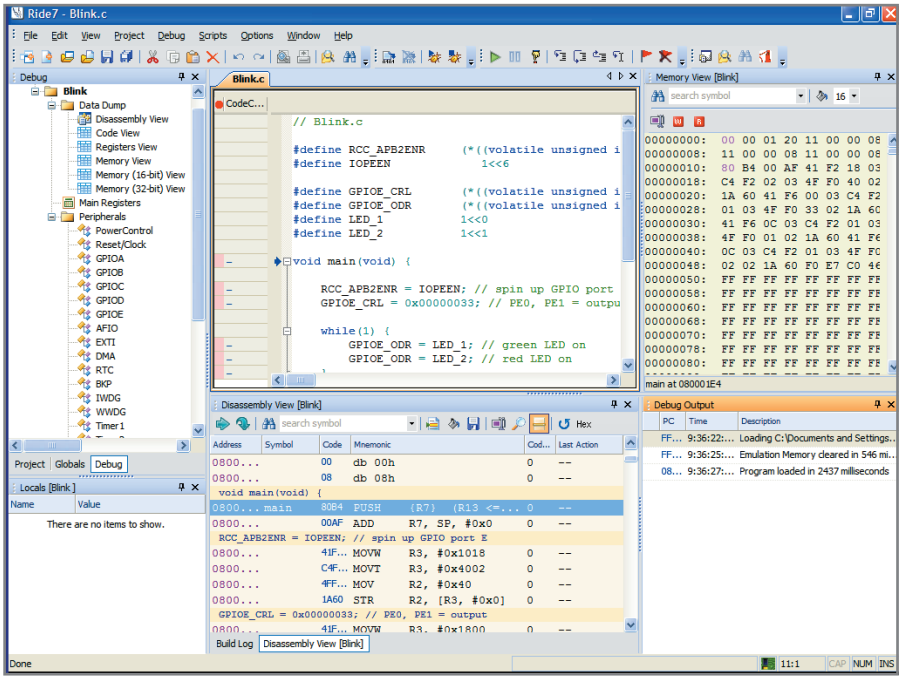



**Photo 4**—The IDE waits for your command to start. To stop the program, select the "Debug/Stop" menu item or the "Pause" toolbar.

not quite as glamorous as "Hello, world."

This simple project contains a single source file called main.c. Take a look at this file if you like and try to get a feel for the general layout. There's not a lot there. This application is a good example of the use of the ST-supplied peripheral library functions, which are quite complete in their coverage of the available architecture features and peripherals. There is a header include statement (`#include "stm32f10x_lib.h"`) that brings in all the function prototypes and required data structures. The complete STM32 library is included with the Ride7 installation. This is followed by some `#defines` that help map out the hardware as used in this example, followed by some local function prototypes and global variables. After that comes the inevitable `main()` function where it all begins.

Within the `main()` function, some clock and peripheral initialization is done via calls to the library functions, followed by an endless `while(1)` loop that executes the body of the program ad infinitum. Within the `while()` loop, the LEDs are toggled and delays are executed. For the Primer2 version, the joystick input lines are scanned and the toggling rate of the LEDs is adjusted. Nothing complicated here, nothing fancy, just a simple program to illustrate basic functionality of the system and prove the toolchain.

To compile the source code, select the menu item "Project/Build Project" or press Alt+F9. If all goes well, and it should, you should see several lines appear in the "Build Log" at the bottom of the window. If you see a final "Build succeeded," then all is in order and we may proceed.

The next step is to send the program over to the Primer. Plug the USB cable from the "DEBUG" USB port on the Primer to your PC. If this is the first time to be connected, Windows will detect the device and offer to install the drivers. If all went well during the installation of the software, the drivers should load automatically and everything will be ready to go. Here is where I reemphasize that you should download the latest versions of the software and drivers, if at all possible. Turn on the power to the Primer by pushing the button. Now select the "Debug/Start" menu item and the compiled program will be loaded into the nonvolatile flash memory of the STM32F103 in

the Primer. This process only takes a few seconds.

Once loaded, the IDE in debug mode waits for your command to start execution of the program (see Photo 4). To start the program, select the "Debug/Run" menu item, press Ctrl+F9, or click the green arrow icon in the toolbar. The program will begin to execute and you should see the LEDs toggling. If you have a Primer2, move the joystick around and speed up or slow down the toggle rate.

To stop the execution of the program, select the "Debug/Stop" menu item or the "Pause" toolbar. This halts the program at whatever point it happened to be at when you interrupted it. At this point, you can examine variables, look at memory locations, add watchpoints and breakpoints, and all the other various tasks of debugging. Note that debugging is limited to the first 32 KB of program memory with the free tools supplied. You can purchase a license from Raisonance for unlimited debugging. There are no limits on code compilation or device programming.

You can now disconnect the Primer and the "toggle" program continues to run. To turn off the Primer, you will have to disconnect the battery using the internal jumper. This simple example program does not implement a software shutdown. Remove the jumper now, then reconnect the jumper. The Primer begins running the program automatically. The program will remain resident in the device's flash memory until overwritten by another program. Once you've disconnected the power, if the debugger was still running, it will beep and produce a warning message that it is terminating the debugging session.

To restore the original programs that shipped with your Primer, download the image files from the CircleOS web site (www.stm32circle.com) for either the Primer or Primer2 (each has its own resources page) and get either the stm32-primer1.zip or stm32-primer2.zip file. Decompress it wherever you like on your machine. Making sure your Primer is plugged into the "DEBUG" USB port and with the power on, run the "reinstall_stm32_primer_demo.bat" batch file for the original Primer or "reinstall_stm32_primer2_demo.bat" for the Primer2. These batch files launch the command line version of the device programmer software, Cortex_pgm.exe, a Raisonance utility that talks to the RLink USB JTAG adapter inside the Primer. Hey, presto! Your Primer is as good as new.

## STARTING FROM SCRATCH

Building someone else's code is fine for working through a basic example of how the toolchain works, but let's dig in deeper and write our very own trivial example from the ground up. For this exercise, we will need two more documents: the schematic diagram of your particular Primer from stm32circle.com and the STM32 Reference manual from ST.com. These documents are both available as PDFs, so you will need Adobe's Acrobat Reader or equivalent to view them. They will give us the clues we need to blink things ourselves.

First, let's set up a new project. From the Ride7 main menu, select the "File/New/Project" menu item. This brings up the "New Application" dialog box. Leave the "Type:" dropdown combobox as "New application to be built." In the "Processor:" tree view, expand the "ARM" node and scroll down to select the correct processor. For the original Primer, select STM32F103RBT6. For the Primer2, select STM32F103VET6. Once you've selected the processor, the "Description:" area is filled with the distinguishing characteristics of the chip, including memory sizes and available peripherals. This is a good way to browse for a new chip when you're *really* starting from scratch and designing your own circuit. There is also a link to the datasheet for the selected device. Now think up a clever name for your first application and type it in where it says "Name:." I'm going to use "Blink" for this example. Select a directory for your project or use the suggested one. I recommend setting up a new directory somewhere under your "My Documents" folder. Finally, click the "Finish" button and the project is created.

Now select the "File/New/Source File" menu item or press Ctrl+N to create a new source file. Go ahead and use the "File/Save As..." menu item to save the file and give it a more descriptive name than the supplied "C File1.c." I

**Listing 1**—This complete minimalist C code blinks the LEDs on the Primer2. Only slight changes are required to make it work with the original Primer.

```
// Blink.c

#define RCC_APB2ENR      (*((volatile unsigned int *) 0x40021018))
#define IOPEEN           1<<6

#define GPIOE_CRL        (*((volatile unsigned int *) 0x40011800))
#define GPIOE_ODR        (*((volatile unsigned int *) 0x4001180C))
#define LED_1             1<<0
#define LED_2             1<<1

void main(void) {

    RCC_APB2ENR = IOPEEN;       // spin up GPIO port E
    GPIOE_CRL = 0x00000033;     // PE0, PE1 = output

    while(1) {
           GPIOE_ODR = LED_1;   // green LED on
           GPIOE_ODR = LED_2;   // red LED on
    }
}

unsigned int * vectors[4] __attribute__ ((section("vector"))) = {
    (unsigned int *) 0x20010000,     // stack pointer
    (unsigned int *) main,
    (unsigned int *) main,
    (unsigned int *) main
};
```

used "Blink.c." I will detail a simple program that works for the Primer2, and then later show you what needs to change for the use with the original Primer, as the LEDs are connected to different pins.

Add the lines in Listing 1 to your source file or download the file from the *Circuit Cellar* FTP site. Let's take a look at what we have so far. The program listing starts out with some `#define` statements that describe the addresses of some registers that we need to initialize as well as some bit positions within those registers. By defining these addresses as pointers, we can then refer to them in the code just as if they were variables, allowing us to read from and write to them using simple assignment statements, which I find easier to initially code as well as easier to understand later when I'm scratching my head and asking myself, "What was I *thinking*?"

Within the body of the `main()` function, we see two cryptic initialization statements followed by an infinite `while()` loop. The first statement, `RCC_APB2ENR = IOPEEN;`, enables a bit in the "Reset and Clock Control/Advanced Peripheral Bus 2/clock enable register" that effectively "turns on" Port E and allows us to read and write to its control and data registers. Port E happens to be where the LEDs are connected and we know this by looking at the schematic diagram of the Primer2. Coming out of reset, all the general-purpose input and output (GPIO) peripherals have their clocks disabled. This saves power and reduces radiated emissions. Selectively enabling the peripherals might seem like a pain but in the big picture it is what you want in an embedded system. There are several other peripherals that can be simultaneously enabled by this single register write. All we want is Port E right now, so that's all we enable for now.

The other cryptic initialization statement is `GPIOE_CRL = 0x00000033;` and requires a little more explanation. Each of the GPIO ports has control and data registers. There are 16 I/O lines per port. Each I/O line has four bits of basic configuration information associated with it. This determines the characteristics and performance of the line in operation. For example, an I/O line can be an input or an output with various options such as open-collector outputs, analog inputs, etc. Refer to the STM32 Reference Manual for more details. The reference manual is also where we find the register addresses and the bit positions within the registers that we're interested in. `GPIOE_CRL` is the "General purpose input and output Port E/Control register (low)." Since each of the 16 I/O lines per port requires four configuration bits, this register is spread across two 32-bit registers called "high" and "low." The magic number `0x00000033` configures the lowest two bits of Port E as outputs with push-pull capability and a top speed of 50 MHz. Get it? Good, let's move on.

The assignment statements within the `while()` loop alternately write a logic "1" to bit positions 0 and 1. Since we've configured the I/O lines as outputs, this produces high and low outputs on the physical pins of the device which are connected, via current limiting resistors, to green and red LEDs. A logic "1" turns the LED on and a logic "0" turns the LED off. You can't get much simpler than that.

I've intentionally left out any sort of delay between assignments so that we can step through the program using the debugger and actually see the LEDs turning toggling on command. If you run the program at full tilt, both LEDs appear to be on at the same time.

Now that we have programmed in everything that we want to happen, we have to take care of a little bit of housekeeping. The Cortex-M3 requires a vector table to be present at the beginning of physical memory. This vector table informs the processor where to execute code upon coming out of reset and the position of the initial stack pointer, as well as pointers to a couple of very basic exception handlers. The minimum vector table consists of these four items. A real application would have additional vectors specified for interrupt and additional exception handlers. We define the vector table as an array of pointers to unsigned integers, initialized with the values that we require for this simple example program.

That's all there is to writing the firmware. Notice that there are no `#include` statements for header files or additional libraries required.

## MOVING ON

In this article, I have introduced you to STMicroelectronics's entry into the world of ARM Cortex-M3 microcontrollers, the STM32. I described some exciting new tools, including Raisonance's low-cost development hardware and software, and walked you through some simple examples to get your appetite going.

Next month, I'll conclude this article series by taking you to the next level in application development using the new CircleOS framework. The CircleOS project allows you to easily write applications that take advantage of the available peripherals and extra hardware on the STM32 Primers, including the touchscreen LCD, sound, and the three-axis accelerometer, among others. Be sure to look for it next month!

*Dale Wheat (dale@dalewheat.com) is a full-time freelance writer working primarily with embedded systems and shiny things that blink or beep. Dale is married and the father of two adult children. He lives near Dallas, where he enjoys mowing two acres of grass in the summer and not mowing it in the winter. Find out what he's been up to at his personal web site www.dalewheat.com.*

## SOURCES

**CircleOS**
Raisonance | www.raisonance.com | www.stm32circle.com

**STM32 Microcontrollers**
STMicroelectronics | www.st.com

by Michael Hamilton

# Infrared Radiation Measurement

## FFT Double-Beam Infrared Spectrophotometer

This innovative FFT double-beam IR spectrophotometer measures IR radiation to identify various chemical molecules. A dsPIC30F4012 controls the spectrometer with FFT algorithms. The dsPIC's 10-bit ADC has the ability to use VDD and VSS as references so you don't need a separate voltage reference.

I studied chemical engineering in college because of my interests in chemistry and electronics. Today, I'm always looking for new ways to combine my chemistry and electronics knowledge. This project enabled me to do so. The design enables me to measure infrared radiation (tungsten lamp) using an ST60R thermopile detector and an Analog Devices AD623 low-noise instrumentation amplifier. In this article, I'll explain how to transmit this information via USB (a Microchip Technology PIC18F2450) to your PC for graphing. I'll describe how I used a Microchip Technology dsPIC30F4012 digital signal processor (DSP) to implement fast Fourier transforms (FFTs). Lastly, I will present how to experiment with encoder signals, pulse-width modulation (PWM) outputs, and a Microchip Technology MCP9700 temperature sensor.

With a little bit of research, I determined that there are two main types of instruments that can measure infrared radiation. One is the dispersive type and the other is the Michelson Interferometer type. The dispersive type separates the infrared radiation into individual wavelengths and measures the absorbance of the chemical sample at each wavelength. This design has the advantage of being accurate at a particular wavelength, but the disadvantage of being slow. The Michelson interferometer is very fast, but it uses an extremely expensive and fragile beam splitter. Almost all used spectrometers of this type that you can obtain inexpensively have a bad beam splitter because they have been damaged by moisture. It was decided that the dispersive type would be best for this project.

Prototypes can be expensive when you start from scratch. Instead, you can find various pieces of used equipment that have the key parts you need. I needed the ability to identify various chemical samples. A new infrared spectrometer would've cost me around $25,000. Fortunately, I found a broken dispersive unit (1954 Perkin Elmer 337 Spectrophotometer) on the Internet. Although the unit was broken, the optics were in perfect condition (see Photo 1).

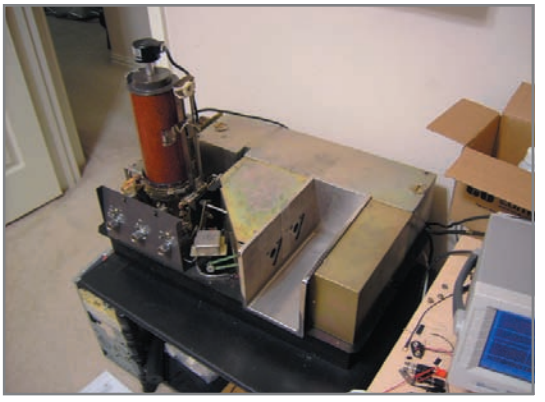


**Photo 1**—This 1954 Perkin Elmer 337 spectrophotometer generates infrared radiation and passes it through a chemical sample. Depending on the molecular structure of the sample, it will absorb only at specific wavelengths. The absorption at each wavelength is measured and plotted. The plot is then used to determine the chemical sample.

The spectrophotometer takes a source of radiation (tungsten lamp) and splits it into two paths (using mirrors), as you can see in Figure 1. One travels through the reference (air or solvent that the chemical sample is dissolved in) and the other travels through a chemical sample. A 13-cycle chopping mirror is used selectively to

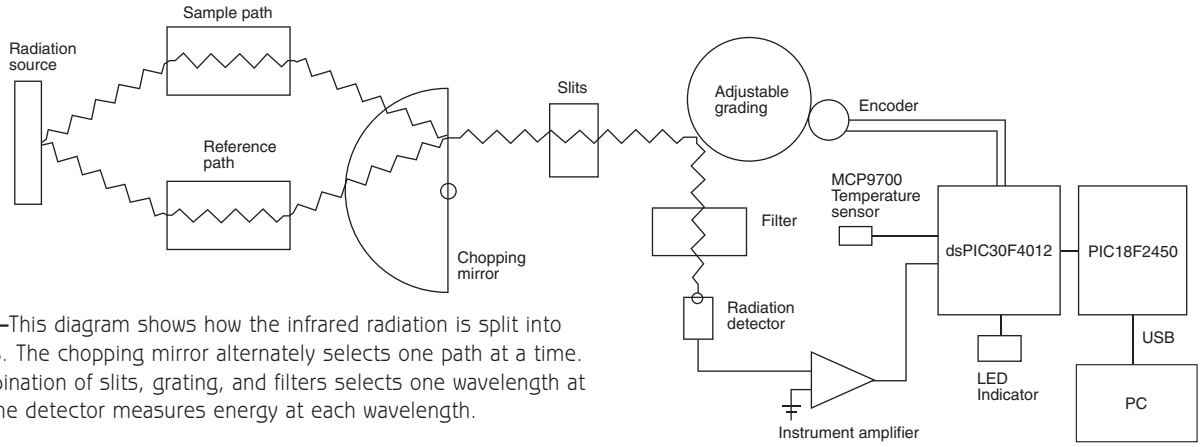



**Figure 1**—This diagram shows how the infrared radiation is split into two paths. The chopping mirror alternately selects one path at a time. The combination of slits, grating, and filters selects one wavelength at a time. The detector measures energy at each wavelength.

pass the radiation signal from the sample and then from the reference (13 times per second). This creates a square wave with a frequency equal to 13 Hz. When the reference and the sample are the same, the square wave will have an amplitude of zero. Then, when the chemical absorbs, the amplitude of the square wave will increase.

The radiation from the chopping mirror then travels through a series of slits, mirrors, an adjustable grating, and a filter (see Photo 2). Then a parabolic mirror is used to focus the signal onto a thermopile—a radiation detector made up of multiple miniature thermocouples (see Photo 3). A motor moves the adjustable grating to enable one wavelength at a time to hit the thermopile. The exact position of the grating is tracked with an encoder so you know what wavelength is currently being scanned. The chemical sample will absorb only specific wavelengths of radiation depending on its molecular structure. By plotting the wavelengths scanned versus the energy absorbed at each wavelength, you can identify a chemical sample.

## HARDWARE DETAILS

The spectrometer's original electrical system consisted of 18 vacuum tubes and several motors. A two-phase servo balance motor was used to proportionally block the reference signal path. This had the effect of weakening the reference signal to match the sample signal when the chemical sample absorbed at a particular wavelength. A chart pen was also attached to this balance motor and effectively drew the chart during the wavelength scan. This mechanical system had built-in lag time and reduced the resolution of the system so it was removed. Using today's DSP chips, you can replace the old mechanical technology with the FFT technique. When you analyze a signal with an FFT, you will see the amplitude at each frequency similar to a frequency-selective voltmeter. A frequency-selective voltmeter could be implemented in hardware, but the goal of this article is to demonstrate how much easier this can be accomplished in software by using FFT technology

The existing thermopile (a device with multiple thermocouples in series) detector was bad, but all the optics were in good condition. I replaced the thermopile with a new inexpensive thermopile (ST60R). The thermopile is designed to generate an electrical potential of only a few microvolts, so I needed a powerful noise-free amplifier. I chose to use the AD623, which has a high common-mode rejection ratio greater than 100 dB. This is needed due to all the noise generated from the AC motors that drive the grating and the chopping mirror (see Photo 4).

I chose a 16-bit, 28-pin starter development board and ICD2 programmer (half-price discount) from Microchip Technology. I used the dsPIC30F4012 so that I would have enough memory for the FFT algorithm. The 10-bit ADC on the dsPIC30F4012 has the ability to use $V_{DD}$ and $V_{SS}$ as references so you don't need a separate voltage reference. The DSP FFT algorithm requires that the input signal be scaled to ±0.50 fractional units to avoid an overflow. The amplifier was then designed to give a signal of ±0.50 V on a 2.5-VDC level.

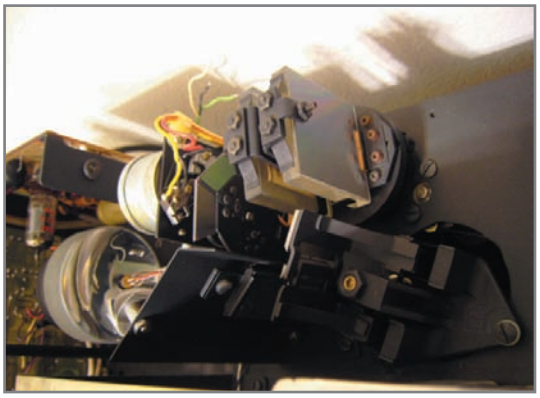


**Photo 2**—An infrared radiation signal first passes through an adjustable slit (bottom right). Then the signal hits an adjustable grating to select the specific wavelength (top right). The signal is then filtered (top middle) and sent to the parabolic mirror (bottom left).

This project replaced the vacuum tube amplifier for the thermopile detector with an instrumentation amplifier and replaced the two-phase servo balance motor with FFT technology. The instrument amplifier consists of three stages. The first stage amplifies the signal 20× ($V_{OUT}$ = (1 + 100 kΩ/$R_{GAIN}$) × $V_{IN}$) and is band-pass filtered to pass the 13-Hz chopping frequency (remove DC and 60-Hz noise). The second and third stages further amplify and filter the signal. The final signal

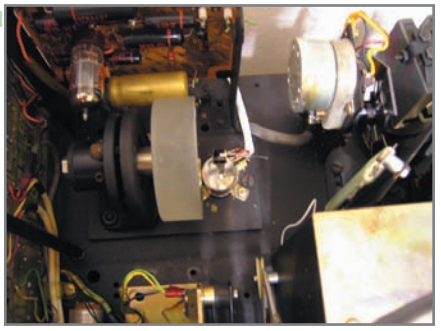


Photo 3—The parabolic focusing mirror is on the left. This mirror concentrates the radiation signal and focuses it on the thermopile (middle of the photo).

is designed to be ±0.5 V and centered at 2.5 VDC. This signal is then fed to a dsPIC30F4012 for processing. At the same time, a quadrature encoder is used to determine the position of the adjustable grating (determines the current wavelength being analyzed). The temperature is also measured using a MCP9700 and fed to the dsPIC30F4012 (see Figure 2).

The dsPIC30F4012 computes the FFT of the infrared radiation signal. This creates a table of amplitude versus frequency. The amplitude of the signal at 13 Hz (matches the 13-cycle chopping mirror) is selected versus the position of the encoder (current wavelength) and the current temperature. The amplitude is scaled to give a relative transmittance. In addition, the signal from the MCP9700 temperature sensor is scaled to degrees Celsius units. All this information is then serially transmitted over USB to a computer for plotting. This USB interface is accomplished using a PIC18F2450 (on the development board). To verify the microcontroller is running at the proper speed, LED 1 on the development board is flashed once per second (PWM with 50% duty cycle). This is also handy for troubleshooting the USB serial interface since the timing of the transmission is critical.

## FIRMWARE

The dsPIC30F4012 has the ability to calculate the FFT. This process can take a time domain signal that is made up of hundreds of different sine waves added together and convert them into the frequency domain. You can then plot the amplitude versus frequency of each sine wave. By doing this, you can focus on the amplitude of a specific sine wave. In this project, the two sine waves with the largest amplitude are at 13 and 60 Hz. The 13-Hz frequency matches the chopping mirror that alternates back and forth between the sample and reference. The 60-Hz frequency is noise that comes from the AC power that is used to drive the various motors. As the grating moves, the infrared radiation signal is separated into individual wavelengths. The chemical sample will absorb specific wavelengths depending on its molecular structure. So all you have to do is monitor the amplitude of the 13-Hz sine wave to determine how much of the infrared radiation has been absorbed.

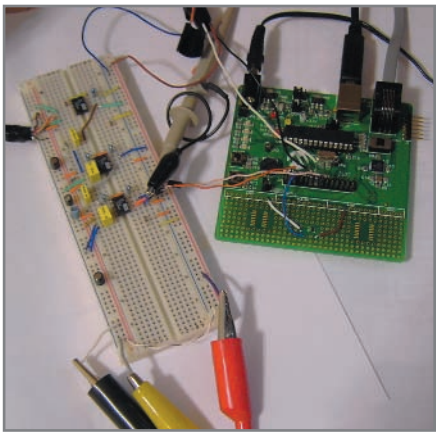


Photo 4—The instrumentation amplifier/filter network is on the left. The scaled signal is then fed to the Microchip 16-bit, 28-pin starter development board that holds the DSP chip (dsPIC30F4012).

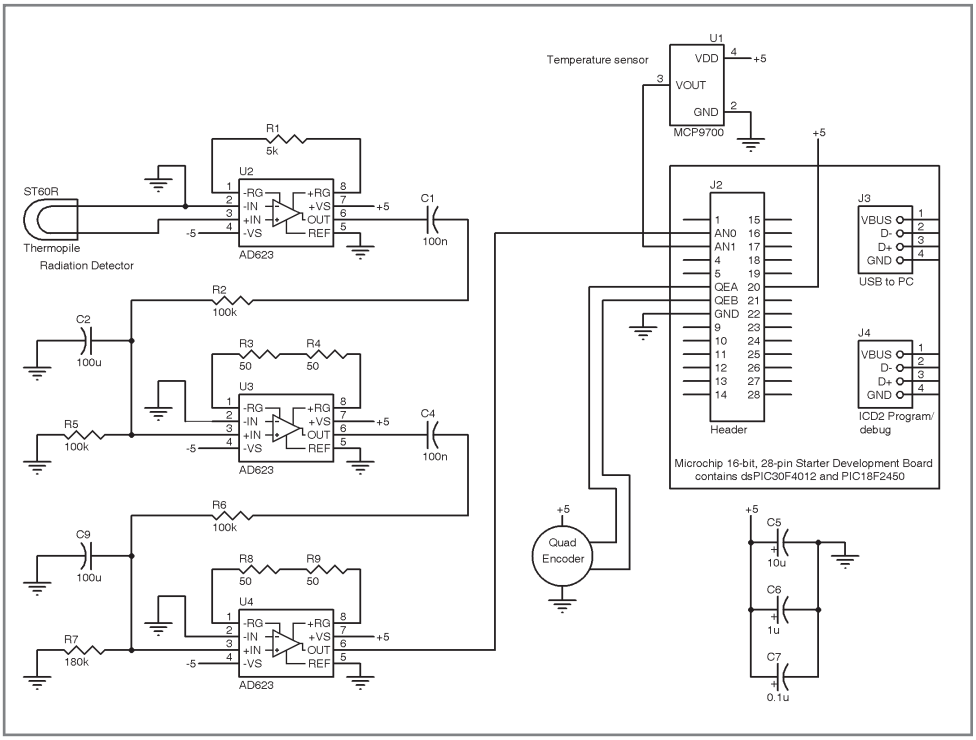



Figure 2—Starting at the top left, you will see the thermopile detector (ST60R) that converts the radiation signal to an electrical signal. An amplifier/filter network consisting of three AD623 amplifiers is used to magnify and filter the signal. The signal then passes to AN0 on the dsPIC30F4012. Also shown is the MCP9700 temperature signal going to AN1 and the encoder signal going to QEA and QUB inputs.

The first step in the software is to declare the external reference to the `SquareMagnitudeCplx` function, which is used to calculate the square magnitude of each frequency bin. Then the external reference to the `twiddleFactors` is set up. These factors need to be generated only once for a particular FFT block size. Then they can be reused over and over by the FFT algorithm. Next, the fractional variables are declared.

The 10-bit ADC is set up for

**Listing 1**—This sample code listing shows how the FFT algorithm is calculated and how the temperature signal is scaled –40° to 125°C.

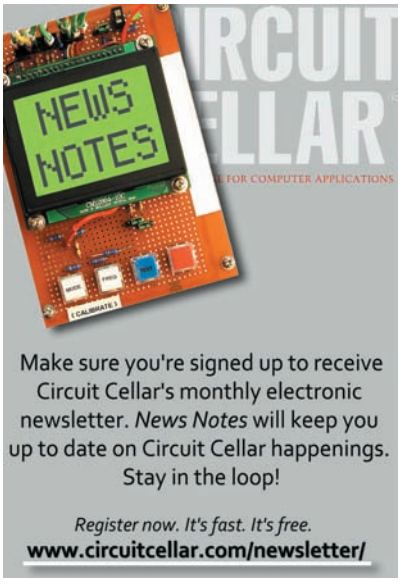
**FFT algorithm to determine signal strength at 13-Hz chopping mirror frequency**

```
/* Compute the in-process FFT algorithm */
FFTComplexIP (LOG2_BLOCK_LENGTH, &sigCmpx[0], (fractcomplex *) __builtin_psvoffset(&twiddleFactors[0]),
    (int) __builtin_psvpage(&twiddleFactors[0]));

/* Restore original order of data */
BitReverseComplex (LOG2_BLOCK_LENGTH, &sigCmpx[0]);

/* Compute the square magnitude of the complex FFT output array */
SquareMagnitudeCplx(FFT_BLOCK_LENGTH, &sigCmpx[0], &sigCmpx[0].real);

/* Get and scale the IR signal to 0-100% transmittance */
sig_strengh = sig_strengh+sigCmpx[15].real+sigCmpx[15].imag;
sig_strengh = (350 - sig_strengh)*100 / 350;
```

**Averaging and scaling of MCP9700 temperature sensor input**

```
for (i=0;i<16;i++)
        {
        temp_sum = temp_sum + *adcPtr++;  // Sum up 16 samples in buffer
        }
temp_sum = temp_sum / 16;                 // Calculate average temperature
temp_sum = (temp_sum-34078);              // Adjust for 100-mV offset (0 V = 32767 -> 100 mV = 34078)
temperature = temp_sum*165/21626;         // Scale signal to 165°C per 1.65-V range (1.75 V - 0.10 V)
temperature = temperature - 40;           // Offset temperature by 40°C (-40°C = 0.10 V)
```

two analog inputs: AN0 and AN1. AN0 is the IR signal from the spectrophotometer. AN1 is the temperature from the MCP9700 sensor. The UART is set up for 9,600 bps, 8 stop bits, no parity, and 1 stop bit. This serial connection is set up for transmission through the virtual COMM port that the PIC18F2450 on the



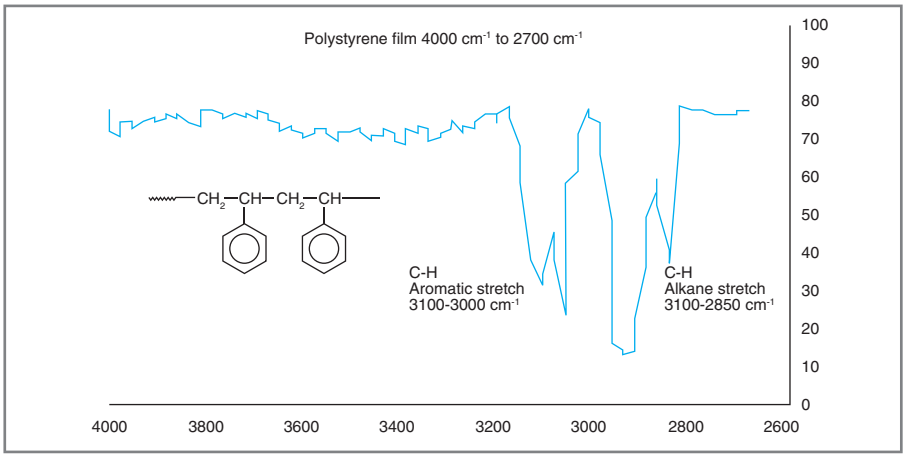



Figure 3—The graph was generated using this project. It shows a scan of Polystyrene from 4000 $cm^{-1}$ to 2700 $cm^{-1}$. Notice the two large dips in transmittance. These are used to identify the chemical being analyzed.

development board sets up. The quadrature encoder is then set up for 4× with no index. Finally, the PWM output to control LED 1 on the development board is set up for 50% duty. This causes the LED to flash on and off approximately once per second.

The program then enters a `while` loop. During this loop, timer 3 is counting and the ADC is sampling the input. Each time timer 3 expires, the ADC then converts the input. After 16 samples are retrieved, the A/D buffer is full and creates an interrupt. During the first interrupt, the current temperature from the MCP9700 (AN1) is calculated. Then the A/D channel is changed to the IR Signal (AN0) and exits the interrupt. Next, 16 samples are collected, an interrupt created, and the interrupt routine saves the samples in the `sigCmpx` array. The interrupt exits again and collects another 16 samples. This process of gathering samples and interrupting continues until the `sigCmpx` array is full. The size of the array is determined from the `FFT_BLOCK_LENGTH` constant, which is set to 256. Then the main part of the program starts. Listing 1 is a sample of the code.

First, the imaginary part of the complex `sigCmpx` array from the previous cycle is cleared to zero. Next, the in-process FFT algorithm is called. This converts the data from the time domain to the frequency domain. The in-process algorithm stores the output in reverse order so the `BitReverseComplex` is called to restore the normal order. Next, the `SquareMagnitudeCplx` routine is called to calculate the magnitude of each frequency bin. You now have an array of data that shows the magnitude of each frequency. The two highest amplitude frequencies are the 13 Hz from the chopping mirror and the 60-Hz noise that was not filtered out. The DSP library also includes filtering functions such as FIR and IIR that can be used to remove the 60-Hz noise, but it was not necessary in this project.

The amplitude from the 13-Hz chopping mirror is then scaled to 0 to 100% transmittance. The A/D channel is then switched back to the temperature input (AN1) to collect the next set of data. The encoder position (current wavelength from grating), IR transmittance (amount of energy that the sample absorbs), and current temperature are then transmitted to a PC. On the PC, the data is captured with HyperTerminal and analyzed with Excel. Excel then enables you to import the formatted .CSV file where you can generate the graph. The `while` loop will then continue to repeat over and over during the scan of the chemical sample.

## OPERATION

The operation of this device is quite simple. You turn on the power and allow the unit to warm up until the temperature is stable. The IR

source (tungsten lamp) will warm up and the chopper mirror will start. This requires about 5 minutes. Next, you prepare your sample and place in the sample path. For demonstration, I used a piece of polystyrene film that is designated as a calibration sample. On the PC, you start HyperTerminal to capture a text file. You will see the current position of the encoder at the start, the current transmittance (at this point should be around 80%), and the temperature. If HyperTerminal does not start collecting data, you need to check LED 1 on the development board. It should be flashing at approximately one time per second (50% duty from PWM output). This allows you to verify that the microcontroller is running at the proper speed. If you still have problems, you will need to verify your communication settings are at 9,600 bps, 8 bits, no parity, and 1 stop bit.

When you are ready, you simply turn on the grating motor. The motor will slowly turn the grating starting at a wavelength of 2.5 µm (4,000 $cm^{-1}$). The signal strength will vary slightly until you get to a wavelength that the chemical sample absorbs. This slight signal variation can be attributed to noise in the system due to the imperfections in the mirrors and the grating.

For polystyrene, you will see a huge drop in transmittance at approximately 3.25 µm (3,050 $cm^{-1}$). This indicates that the chemical sample contains an aromatic ring with a C-H bond (see Figure 3).

## FUTURE DEVELOPMENTS

This project turned out very well. I used polystyrene calibration film to verify the operation. Figure 3 shows the results in the transmission. Future improvements can be added to allow the dsPIC30F4012 to control the motor for the chopper mirror and the motor that actuates the grating. This will give added benefits such as the ability to scan only a specific wavelength over and over for increased accuracy.

*Michael Hamilton earned a BSE in chemical engineering from Ohio University. He runs his own electronics company that specializes in industrial automation (www.a-dtechnologies.com). You may contact him at mike@a-dtechnologies.com.*

## PROJECT FILES

To download the code, go to ftp://ftp.circuitcellar.com/pub/Circuit_Cellar/2009/229.

## RESOURCES

Analog Devices, Inc., "Single-Supply, Rail-to-Rail, Low Cost Instrumentation Amplifier," AD623, 1997–2008.

Dexter Research Center, Inc., "ST60 TO-5 and ST60R TO-5," ST60R, 2006.

P. R. Griffiths et al., "Fourier Transform Infrared Spectrometry," Wiley-Interscience, 1986.

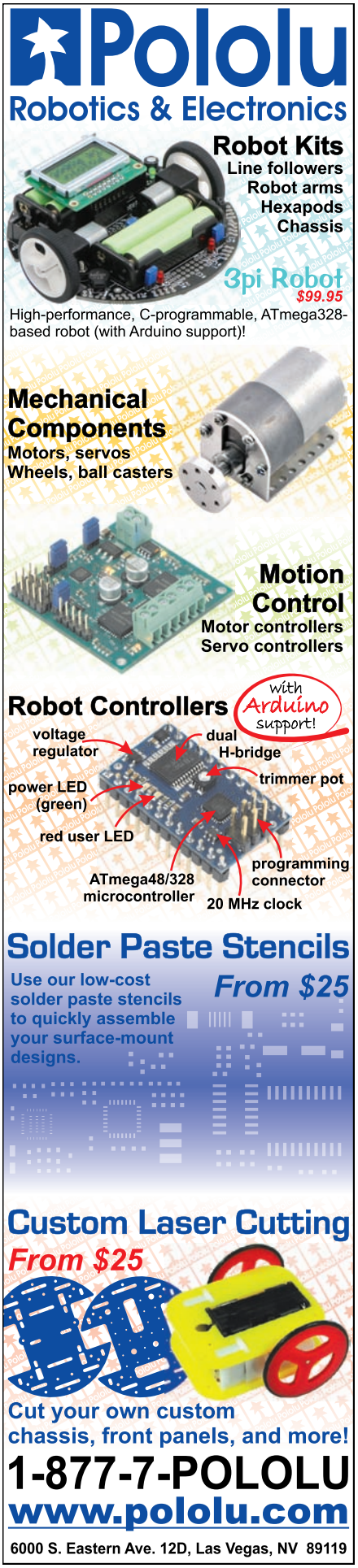
Microchip Technology, Inc., "dsPIC30F Family Overview," 70043F, 2005.

———, "dsPIC30F4011/4012 Data Sheet," 70135F, 2008.

## SOURCES

**AD623AN-ND Instrument Amplifier**
Analog Devices, Inc. | www.analog.com

**DM300027 Kit (includes PIC18F2450), dsPIC30F4012-20E/SP DSP processor, MCP9700AT-E/TT temperature sensor, DV164005 MPLAB ICD2 module**
Microchip Technology, Inc. | www.microchip.com



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| Specification |
|---|
| Microchip dsPIC33FJ256GP710 / 16-bit, 40MIPs DSC |
| VLSI Solution VS1033 MP3 CODEC |
| NXP UDA1330 Stereo Audio DAC |
| Texas Instrument TPA6110A2 Headphone Amp(150mW) |
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- Focusing for MP3 Player
- SD Card interface
- Power: battery
- offer full source code, schematic

| Item | Specification |
|---|---|
| MCU | Atmel ATmega128L |
| MP3 Decoder | VS1002 / VS1003(WMA) |
| IDE Interface | Standard IDE type HDD(2.5", 3.5") |
| Power | 12V, 1.5A |
| LCD | 128 x 64 Graphic LCD |
| Etc | Firmware download/update with AVR ISP connector |

### • myAudio (MP3 DIY KIT IDE)

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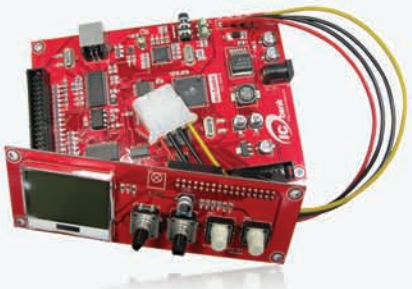

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by Ed Nisley

# A Blast for the Past

## High-Voltage DC Dosimeter Charger

Applying the proper analysis enables you to use any small high-voltage transformer. Ed covers the topics of transformer measur ement, a step-up DC-to-DC converter, and high-voltage power supplies.

The United States Office of Civil Defense produced and distributed millions of radiation-monitoring instruments during the Cold War years in anticipation of a nuclear attack. Instruments built during the 1960s have long since passed their best-used-by dates and entered the surplus market: you can buy them on eBay for pennies on the dollar.

I recently acquired a few V-742 pencil-style electrostatic radiation dosimeters that measure gamma-ray exposure up to 200 Roentgen—if you're exposed to that much radiation in a short time, you'll be a very sick puppy indeed. Their V-750 chargers, while literally designed to withstand an atomic bomb attack, have become cranky old gadgets, so I decided to build a charger using contemporary parts and techniques.

Photo 1 shows my first-pass high-voltage dosimeter charger. Where the V-750 ran from a single 1.5-V D dry cell and used a single PNP transistor, this one depends on a pair of CR123A lithium cells and an Arduino microcontroller. I doubt that it'll survive even a dirty bomb, but that wasn't part of the design.

The key part of any high-voltage supply is the transformer that converts a low input voltage to a high output voltage. As you saw in my last several columns, even simple transformers require careful consideration, so

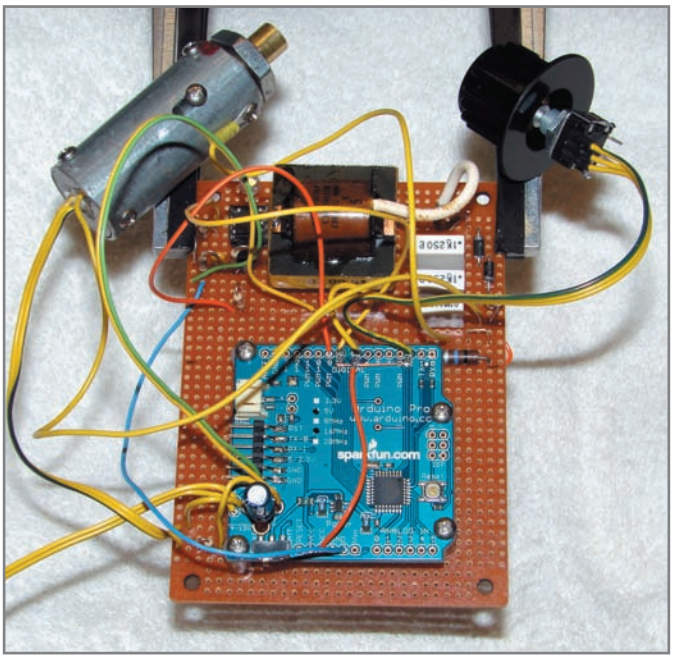


Photo 1—The Arduino Pro microcontroller handles the encoder knob and generates drive pulses for the high-voltage DC-DC converter. The steel-and-brass cylinder is my homebrew charging pedestal, with a large white LED for illumination and an 8-pound spring to close the dosimeter's internal contact.

| Parameter | Primary | Secondary |
|---|---|---|
| Voltage | 1.08 V | 22.32 V |
| Resistance | 2.03 Ω | 349 Ω |
| L – other open | 15.5 mH | 9.68 H |
| L – other short | 45 µH | 31.3 µH |

Table 1—These are measured values for the high-voltage transformer.

I'll describe the transformer measurements and modeling. The rest of the circuit will be easy after that.

Caution: Although this circuit operates at very low power, its high-voltage output can give you a nasty scorch. Connect your test equipment first, apply power, record the measurement, then remove power before adjusting anything.

## TRANSFORMER PARAMETERS

The V-750 achieves its one-transistor simplicity with an intricate three-winding transformer that both boosts 1.5 V to about 220 V and switches the transistor off when the core saturates. Duplicating that transformer requires far more coil-winding ability than seems reasonable, so I used a surplus ferrite-core high-voltage transformer and moved the pulse-generation timing into firmware.

The transformer is part number G16821 from Electronic Goldmine, but, as with all surplus items, it will probably be out of stock when this issue reaches you. You can use any small high-voltage transformer by applying the proper analysis, which is what this column is all about.

Table 1 summarizes the electrical measurements of the primary and secondary windings. The separate, heavily insulated pigtail secondary winding connection should remind you to apply a very low primary voltage during the test.

I wound 20 turns of fine magnet wire around the existing windings, routing them between the transformer's bobbin and the side legs of the core. That forms the Test winding, with its number of turns Nt = 20.

Applying small sine-wave signals to the original windings and measuring the resulting voltages in the test winding yields the number of turns in each. For the primary winding:

$$Np = Nt\left(\frac{Vp}{Vt}\right)$$

$$68 = 20\left(\frac{136\ mV}{40\ mV}\right)$$

Similarly, for the high-voltage secondary winding:

$$Ns = Nt\left(\frac{Vs}{Vt}\right)$$

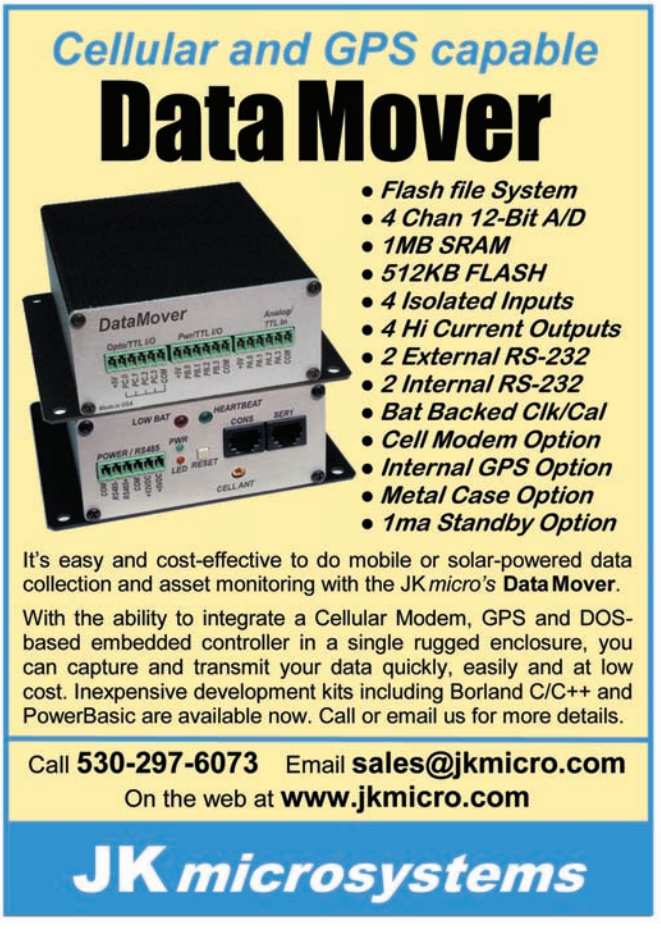
$$1739 = 20\left(\frac{4000\ mV}{46\ mV}\right)$$

Filling in Table 1 requires a few more minutes with an inductance meter and some clip leads, but provides the values required for the transformer's Spice model and a cross-check of the turns ratio. The ratio of the primary and secondary turns should come very close to the voltage ratio if you've done everything right.

$$N = \frac{Np}{Ns} = \frac{68}{1739} = 0.0391$$

$$N = \frac{Vp}{Vs} = \frac{22.32}{1.08} = 0.0394$$

With all of those numbers in hand,

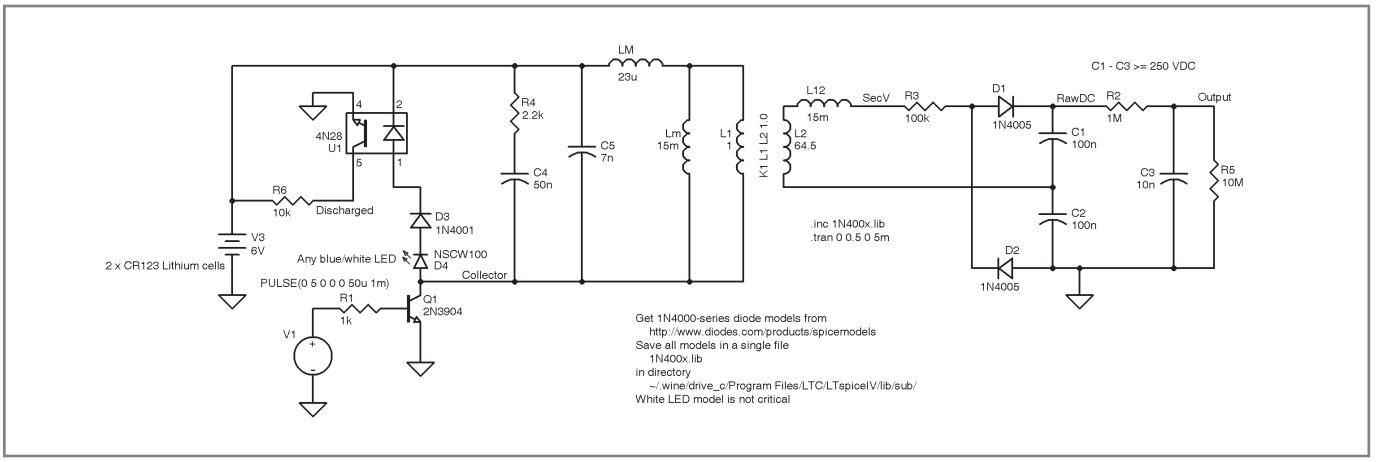



**Figure 1**—The transformer and voltage doubler produce over 200 VDC from a 6-V battery, but at an extremely low current. The 10-MΩ load resistor provides a DC path that stabilizes the output voltage, because the electrostatic radiation dosimeter is essentially an open circuit. Components on the secondary side of the transformer must have voltage ratings over 250 VDC. I added a 1-Ω resistor, which is not shown here, in Q1's emitter lead to measure inductor current at 1 A/V for the oscilloscope images.

the transformer model requires only a few more equations.

The coupling coefficient k defines how effectively the windings transfer energy. Its value depends on Lps(open), the primary inductance measured with the secondary winding open, and Lps(short), the primary inductance with the secondary shorted. Table 1 lists those as 15.5 mH and 45 µH, respectively.

$$k = \sqrt{1 - \frac{\text{Lps (short)}}{\text{Lps (open)}}}$$

$$k = \sqrt{1 - \frac{45\ \mu\text{H}}{15.5\ \text{mH}}} = 0.9985$$

The primary (LI1) and secondary (LI2) leakage inductances represent the magnetic flux that doesn't link the windings through the core.

$$LI_1 = (1 - k) \cdot \text{Lps(open)} = 23\ \mu\text{H}$$

$$LI_2 = (1 - k) \cdot \frac{\text{Lps(open)}}{N^2} = 15\ \text{mH}$$

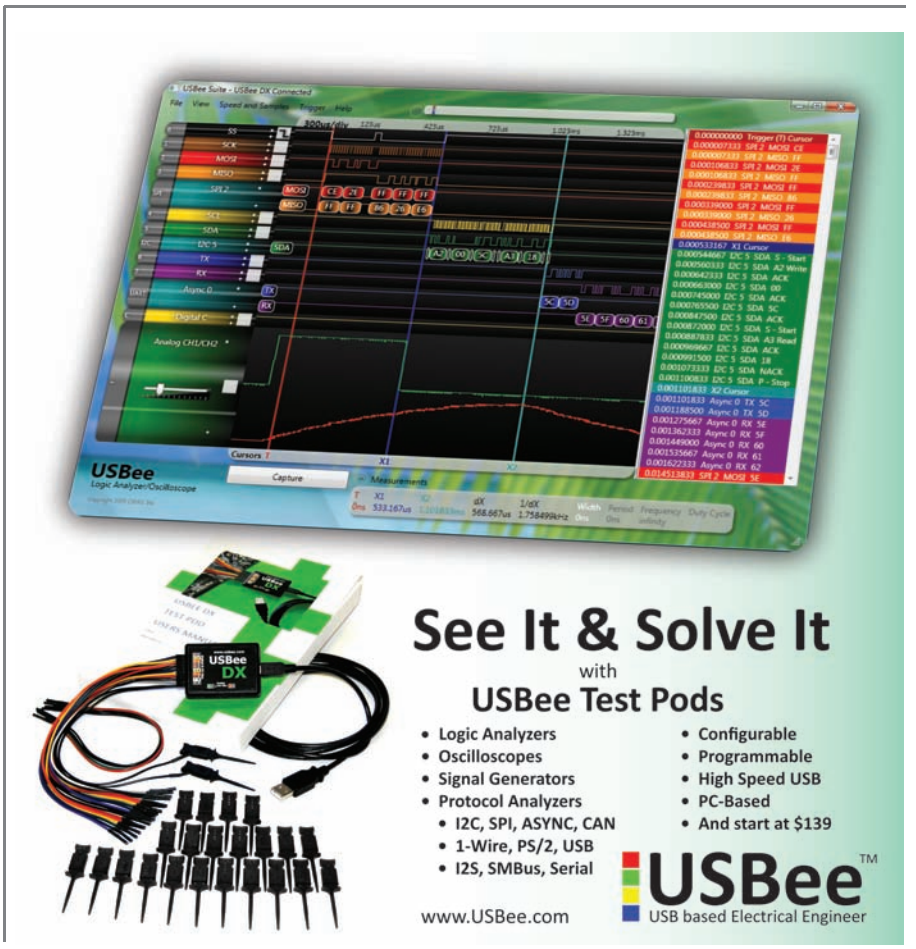
Because k will be just less than 1.0 in a good transformer, (1 – k) will be very nearly zero and the values of LI1 and LI2 depend strongly on the number of significant figures you carry in the calculations. That, in turn, implies that their actual values have less importance than you might imagine. If changing them affects your simulation in any dramatic way, your circuit design may have other problems.

The Spice inductor models for LI1 and LI2 can contain the measured primary and secondary DC resistances, respectively, or you can add those resistances as separate Spice components. I chose to put the resistances in the inductor models, so they don't appear in the circuit schematic in Figure 1.

The magnetizing inductance Lm represents the energy stored in the transformer core and unavailable to the secondary winding.

$$\text{Lm} = k \cdot \text{Lps(open)} = 15\ \text{mH}$$

Finally, L1 and L2 are coupled inductors that represent an ideal transformer with the actual turns ratio.

Their coupling coefficient should be as close to 1.0 as your simulator will allow. The primary inductance L1 should have a much higher reactance than any other component in series with it, so I picked 1 H. The turns ratio and the inductance of L1 determine the inductance of L2, the secondary winding L2.

$$L2 = \frac{L1}{N^2} = 645 \text{ H}$$

Those values appear in the components in the middle of Figure 1, all of which model the transformer. The model does not include the effect of core saturation, which is acceptable because I don't plan to saturate it!

In order to prevent saturation, however, you must measure the core's properties to determine the upper limit for the primary current. I described the measurement setup in my February 2008 column "Transformers" (*Circuit Cellar* 211), which also includes the equations relating the measured voltages to the core parameters.

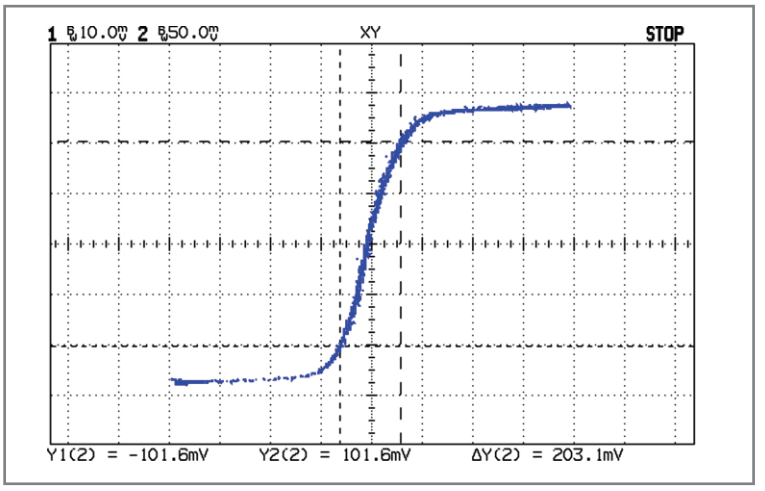
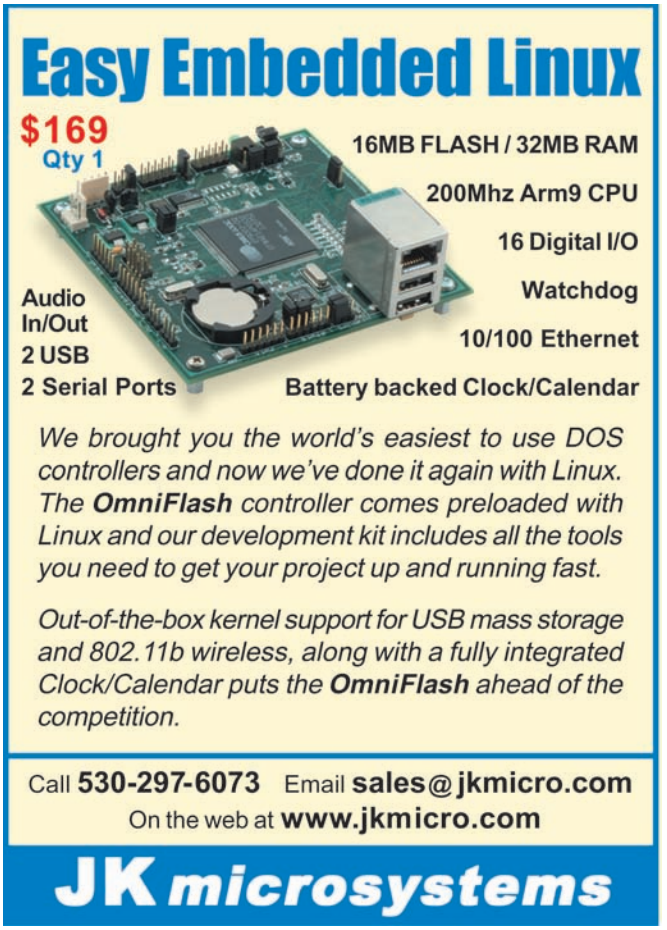


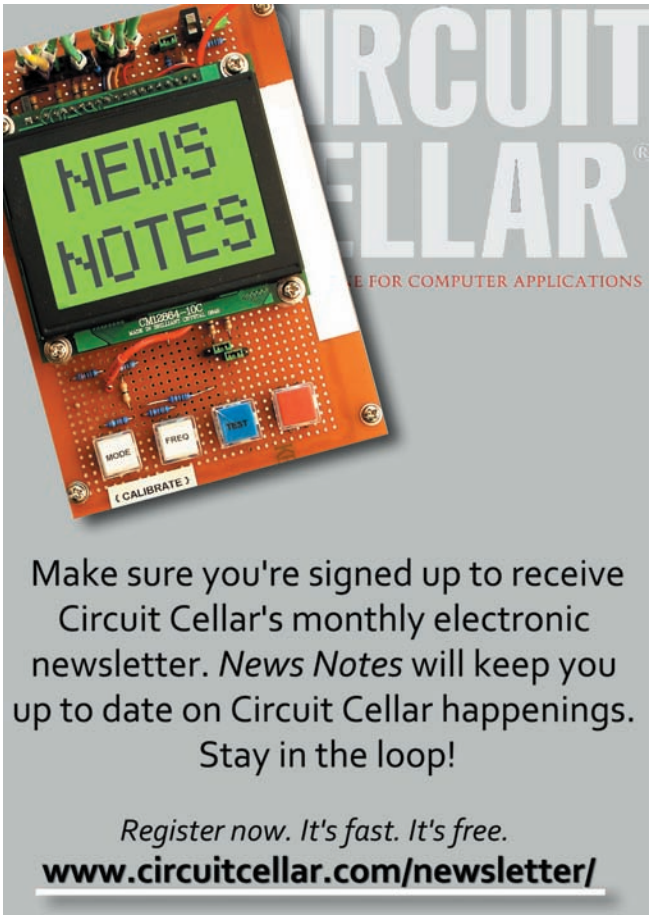

**Figure 2**—The transformer's BH curve shows the amount of primary current that drives the core into saturation: the knee is around 120 mA. The core has very little loss, as shown by the essentially zero area inside the curve. The X-axis scale is 100 mA/V.

I drove the transformer primary from a 6-VAC wall wart plugged into a Variac and monitored the current with a 100-mΩ resistor to get a voltage Vsense proportional to the magnetizing force. On the secondary side, an RC integrator made from a 1-µF capacitor and 220-kΩ resistor produced a voltage proportional to the core flux density.

The BH curve shown in the oscilloscope trace in Figure 2 reveals core saturation for primary winding currents beyond about 120 mA. The cursors mark the limits of the nearly linear region around the origin: primary currents below about 60 mA will be fine.

Homework: run through the equations I presented in the February 2008

column to derive the actual B and H values and verify that they make sense for a ferrite core transformer. Refer to ON Semiconductor's application note AN-1679/D for more background.

Unlike most of the transformers I've tested recently, this one has very little core loss. The nearly zero area inside the BH curve came as a pleasant surprise.

With the transformer parameters in hand, it's time to build the circuit.

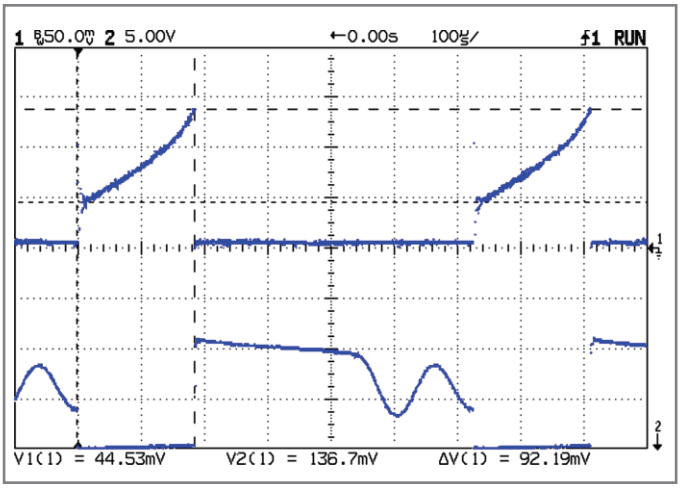



Figure 3—As predicted, primary current rises linearly at 380 A/s from 50 to 100 mA, then begins an exponential increase as the core saturates (Y scale 1 A/V). The collector voltage in the lower trace shows the clamping effect of the diodes across the transformer.

## FORWARD CONVERSION

The Spice model in Figure 1 has all the essential elements required for the dosimeter charger shown in Photo 1, albeit with a microcontroller replacing the voltage source driving Q1. I handwired the board, rather than constructing a PCB, simply because the circuit has so few parts.

The gray cylinder is a homebrew charging pedestal incorporating a stout spring to activate the dosimeter's charging pin and a 10-mm white LED to illuminate its reticle. I won't describe the pedestal in detail; it was an interesting machine-shop project.

Firmware in the Arduino Pro board generates the PWM signal represented by voltage source V1 and reads the rotary encoder knob to adjust the PWM period. The original V-750 charger implemented the same functions with a single-transistor oscillator and a slug-adjustable transformer. That difference pretty much summarizes the radical changes in circuit design enabled by five relentless decades of Moore's Law.

The voltage booster is a simple variation of the standard forward-converter topology with a manual voltage-control feedback loop: a human eye reading the electrometer and fingers adjusting the PWM period to set the dosimeter fiber to the zero point. The usual forward converter has electronic voltage feedback which wouldn't serve any useful purpose here.

Each PWM pulse turns transistor Q1 on for a fixed duration that's predetermined from the core saturation limits. The upper trace in Figure 3 shows the primary current during a 180-µs drive pulse, far longer than the 50 µs used in the Spice simulation. The primary current begins curving upward on its exponential path toward saturation at about 130 mA, close to the value shown in Figure 2. At about 200 µs the current is off-scale high, so the saturation limits in Figure 2 are very real.

The initial linear part of the current rise follows the fundamental equation relating the voltage and current in an inductor.

$$v = L\frac{di}{dt}$$

The current rises from 50 mA to 100 mA in 130 µs, a rate of 380 A/s, so the voltage across the primary is:

$$5.7\ V = 380\ A/s \cdot 15\ mH$$

That agrees well with the actual circuit: a 6-V power supply and saturated transistor switch.

The initial 50-mA step represents the power transferred to the secondary winding. The magnetic flux jumps rapidly to support the load current, then begins climbing as the core begins storing energy.

Those measurements suggested the fixed 50-µs pulse width that I used in the simulation and built into the firmware. Of course, the firmware can adjust the width for testing purposes, which is a simple matter of software.

At the end of the drive pulse, Q1 turns off, but the energy stored in the core and modeled by Lm doesn't simply vanish. Anyone who has ever controlled a relay with a simple switch has discovered that the current through an inductor is continuous: just after the switch opens, the voltage across the contacts rises to whatever level will support the current. Typically, this triggers a nasty arc that can destroy the contacts as the voltage exceeds air's kilovolt-per-millimeter breakdown level.

A forward converter must completely dump the core's energy before starting the next cycle. Any residual energy will steadily walk the core into saturation as each successive cycle stores more energy in the magnetic field.

Rearranging the inductor equation to solve for the current and using discrete time intervals gives this equation:

$$\Delta i = \frac{v}{L}\Delta t$$

The time required to discharge the energy stored in an inductor is thus inversely proportional to the voltage

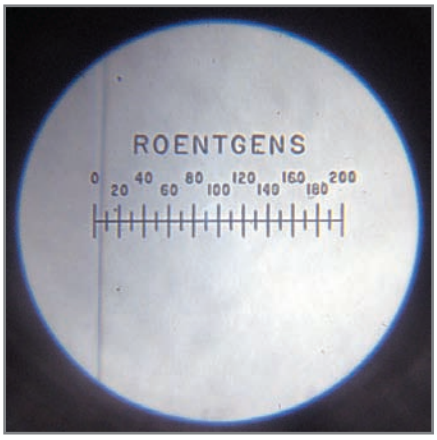



Photo 2—This dosimeter requires about 170 V to reach the initial 0 setting. The white LED makes the reticle much more visible than the original incandescent bulb; the shading results from a slight misalignment of the camera with the dosimeter's optical axis.

across the winding: higher voltage = higher power = faster discharge.

That's why the common practice of putting a diode across a relay's coil works only for human-scale switching speeds. The inductor must discharge its energy across the low voltage presented by single forward-biased diode, greatly slowing the dump.

I put a white LED, an optocoupler, and an ordinary diode all in series across the transformer primary winding to clamp the voltage at about 5 V. The lower trace in Figure 3 shows the voltage at Q1's collector snapping from 0 V to 11 V as the transistor shuts off, then remaining nearly constant for the next 200 µs as the diodes dissipate the energy.

Some of the core energy, of course, goes into the secondary circuit, but for light loads and cores near saturation, the clamp circuit must dissipate much of the energy.

Throughout all of this the transformer's secondary voltage follows the usual rules. While Q1 is on, the primary sees nearly +6 V and the secondary produces:

$$Vs = Vp\left(\frac{Ns}{Np}\right)$$

$$153\ V = 6\ V\left(\frac{1739}{68}\right)$$

When Q1 switches off, the winding current passes through the diode stack. The sign of the primary voltage flips and the secondary voltage becomes:

$$-128\ V = -5\ V\left(\frac{1739}{68}\right)$$

Both voltages remain nearly constant for the entire pulse, because the transformer core remains well out of saturation and the output waveform closely matches the input pulse.

The firmware can monitor the primary current in the diode stack through the optoisolator to ensure the shortest period doesn't walk the core into saturation. Again, that's a simple matter of firmware.

On the secondary side, D1, D2, C1, and C2 form a voltage doubler that can produce well over 250 VDC. R2 and C3 filter the output voltage.

R3 limits the secondary current to 1.5 mA when the capacitors are completely discharged. That prevents core saturation as the primary winding tries to pass enough current to instantaneously charge the capacitors.

Because an electrometer is basically an open circuit, the dosimeter's DC load current is zero. R5, a 10-MΩ resistor, draws about 10 µA to stabilize the output voltage and bleed the capacitor voltages to zero when the circuit power is off.

Measuring the output voltage of this circuit poses a challenge, as an ordinary multimeter has an input resistance of about 10 MΩ. In most circuits, that's far higher than any other circuit resistance, but here it doubles the load current.

For example, if the unloaded output is 150 V across R5, the voltage on the other side of R2 is about 165 V. A multimeter across C3 will show only 138 V. You can watch the primary current change as you attach the multimeter.

Because Q1 is on for a fixed time, the circuit delivers the same amount of charge to the capacitors in each cycle. The average output voltage is therefore roughly proportional to the pulse repetition frequency or, equivalently, inversely proportional to the period. The firmware changes the period from 200 µs to 10 ms, producing 250 to 50 VDC.

The firmware adjusts the period by 2% for each digital encoder knob *click*. That moves the fiber smoothly across the reticle in roughly equal increments over the usable range.

Photo 2 shows the view through a dosimeter mounted on the charging pedestal. The gold-plated quartz fiber appears as a vertical dark hairline that moves horizontally with the applied voltage. A completely discharged dosimeter fiber will be off-screen to the right, so the firmware starts with a 1.2-ms period, about 100 V, that positions the fiber somewhere within the reticle.

Even though it's not built to take a direct hit, the power supply works quite well. My dosimeters, of course, are uncalibrated and certainly not useful for background radiation found in a typical household.

## RESONANT SNUBBING

Figure 4 shows the normal 50 µs base drive pulse and the corresponding collector voltage without the R4-C4 snubber. As before, the collector voltage snaps up to 11.5 V at the end of the pulse, then drops to about 10.5 V as the diode stack dissipates the core energy.

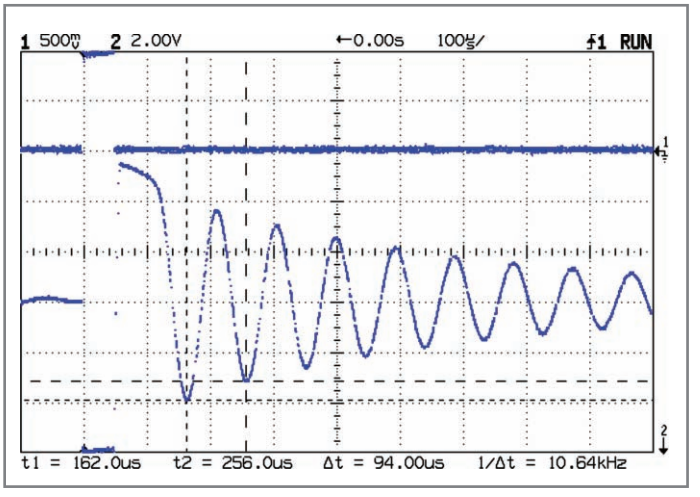



Figure 4—The collector voltage in the lower trace rings around the supply voltage after the clamp diodes across the transformer primary cut off. There's very little energy in the oscillations, but they certainly look dramatic.

This is not, however, a purely inductive circuit. Both transformer windings, but particularly the 1700-turn secondary, present a significant amount of parasitic capacitance both in parallel with the primary winding and to circuit ground. An inductor in parallel with a capacitor forms a classic tank circuit that oscillates when the voltage or current isn't exactly zero.

That's exactly what happens when the voltage across the diode stack drops below the level required to keep them turned on. Because the

inductor current isn't zero when the voltage is zero, it begins recharging the parasitic capacitance represented by C5, but the voltage never gets high enough to turn the diodes on again. The winding resistance is only a few ohms, so the tank Q is very high and the collector voltage rings like a bell.

I picked C5 so the simulated oscillation frequency matched the 10 kHz shown in Figure 4, which makes its 7 nF value largely arbitrary. Maxim's application note AN-3835 gives an experimental way to determine the actual value in real circuits.

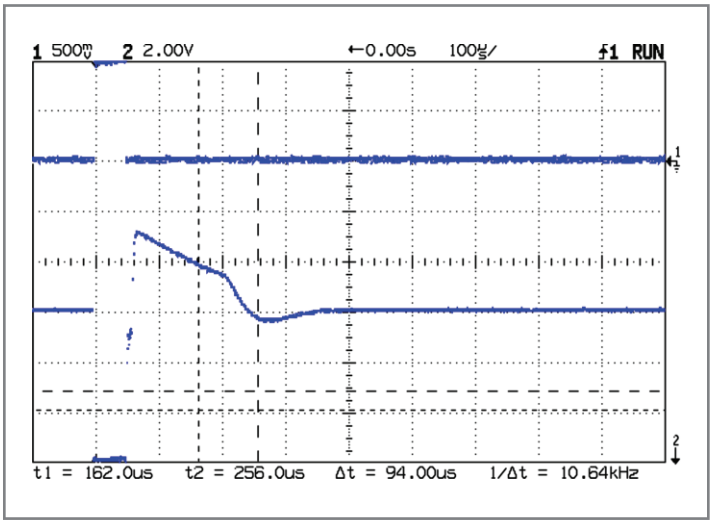



Figure 5—An 820 Ω + 100 nF snubber eliminates the ringing. Notice that the clamp voltage remains lower and therefore takes longer to dissipate the core energy, which affects the DC-DC converter's output voltage.

The trick is to add enough capacitance, by soldering test capacitors into the circuit, to cut the oscillation frequency in half. The tank's frequency is inversely proportional to the square root of the inductance and capacitance:

$$f = \frac{1}{2\pi\sqrt{L \cdot C}}$$

The total capacitance must increase by a factor of four to decrease the frequency by a factor of two, so you will add three times the original parasitic capacitance. Make sense?

My breadboard circuit required 60 nF of additional capacitance across the primary, so the actual parasitic capacitance was 20 nF. That doesn't match C5 in the Spice model, which should not come as a surprise.

Maxim's application note recommends setting the snubber capacitance to "four to ten times the parasitic capacitance," which works out to at least 80 nF. I picked 100 nF, a standard value.

Knowing the oscillation frequency and the parasitic capacitance, you can find the actual inductance:

$$L = \frac{1}{(2\pi f)^2 \cdot C}$$

$$13\ \text{mH} = \frac{1}{(2\pi \cdot 10\ \text{kHz})^2 \cdot 20\ \text{nF}}$$

That's reasonably close to the measured value of the primary winding with no load on the secondary.

The inductance and capacitance of a tank circuit define Z, its characteristic impedance:

$$Z = \sqrt{\frac{L}{C}}$$

$$800\ \Omega = \sqrt{\frac{13\ \text{mH}}{20\ \text{nF}}}$$

The snubber resistor should equal Z, so I picked 820 Ω, another standard value.

Figure 5 shows the rather impressive result: no ringing at all and just the remnant of a single half-cycle! The voltage snaps up to only 9 V and declines more slowly, because the diode stack dissipates less power at the lower voltage.

The total core energy here is very small, but you must pay attention to the power dissipated in high-voltage and high-current circuits. Remember to account for the power dissipated when the driver transistor switches on and discharges the snubber capacitor through the resistor, too.

Use this information in peace!

## CONTACT RELEASE

The turns ratio definition may seem upside-down, but that's how the ON Semiconductor application note defines it and I'll run with it here. Either way works, assuming you understand what the equations represent.

*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.*

## PROJECT FILES

To download schematics and data, go to ftp://ftp.circuitcellar.com/pub/Circuit_Cellar/2009/229.

## RESOURCES

Arduino project, http://arduino.cc.

C. Basso, "How to Deal with Leakage Elements in Flyback Converters," On Semiconductor, AN-1679/D, 2005, www.onsemi.com/pub/Collateral/AN1679-D.pdf.

Electronic Goldmine, www.goldmine-elec.com.

Maxim Integrated Products, "CCFL Push-Pull Snubber Circuit," AN3835, 2006, www.maxim-ic.com/appnotes.cfm/an_pk/3835.

Radiation units and effects, The University of Georgia, www.esd.uga.edu/rad/RSM%202003/rsm_chapter2.doc.

Spice models, http://homepages.which.net/~paul.hills/Circuits/Spice/ModelIndex.html.

by Kevin Gorga

# Cable Tracer Design (Part 1)

## Underground Cable Detection Made Simple

The Cable Tracer is used to detect underground cables. The system works by injecting a 125-kHz signal into an underground cable. A pick-up coil receives a sample of the field. The field's strength indicates the presence and direction of a cable.

Several years ago we stopped stringing temporary overhead power cables for our church bazaar and created a more permanent solution. We ran an underground cable from the church to the back of our parking lot to a new power distribution panel. This worked well for a few years until it went dead. After many hours of digging through hardpan, we found the break. A tent spike had nicked the aluminum cable. After a year, the aluminum conductor had completely disintegrated. We had marked where we thought the cable was, but we were off by a few feet. We needed a cable tracer to be able to locate the cable in the grass field every year. The rental companies in our area didn't have one, a new one would have been too costly, and the local power company was not cooperative. As a result, I designed and built my cable tracer (see Photo 1). In this article, I'll describe the hardware portion of the project. In the second part of this series, I'll cover the software portion as well as how to operate the system.

### SYSTEM OVERVIEW

My cable tracer is designed to detect underground cables. It is primarily an M-field (magnetic) device (instead of an electric, or E-field, device). I theorized that in a buried cable situation, the magnetic field would travel through the ground and pass through metal conduits better than an electric field. The use of a coupled magnetic field also makes it possible to accurately determine direction.

Although I designed and tested the tracer on un-energized electric power cables, it can be used on any underground cable. It consists of two pieces: a signal generator used to inject the signal into the cable and a detector to pick up the signal radiated from the cable. I originally used a Hewlett-Packard 3310B generator, which had up to a 30-V output level to inject the signal. I was able to sense cables buried around 2′ deep with only a 10-V output. The circuit breaker was turned off in the panel box, and the signal generator output was connected to the cable. I later added a dedicated signal generator capable of generating a higher output level. The signal generator's output voltage level affects a cable's detectable depth.

As in any wireless system, it is easier to increase the transmitted signal level than it is to try to improve the sensitivity of the receiving system. If the signal level is down in the noise level of the system, not much more can be done. I tried placing a preamp between the pickup coil and the RFID chip, but it produced only a marginal improvement. It would also prevent using a Microchip Technology MCP2030 tuning feature. The only solution was to boost the injected signal.

Microchip Technology dsPICs are ideal microcontrollers for the system. The dsPIC2023 with its switch-mode power supply module made it a good choice for the signal generator. With multiple PWMs, it supplied the 125-kHz cable signal as well as a simple variable voltage power supply for the output section of the signal generator.

The receiver consists of an MCP2030 RFID chip that's used as the analog front end and a PIC24FJ64GA004 general-purpose processor (see Figure 1).

## PICKUP COIL

The pickup coil receives the weak magnetic field generated by the injected current flowing through the underground cable acting as an antenna. The theory behind the coil design is covered extensively in Microchip's application note AN678.[1] Basically, it boils down to the following equation:

$$V_O = 2\pi f\, NAB\cos\alpha$$

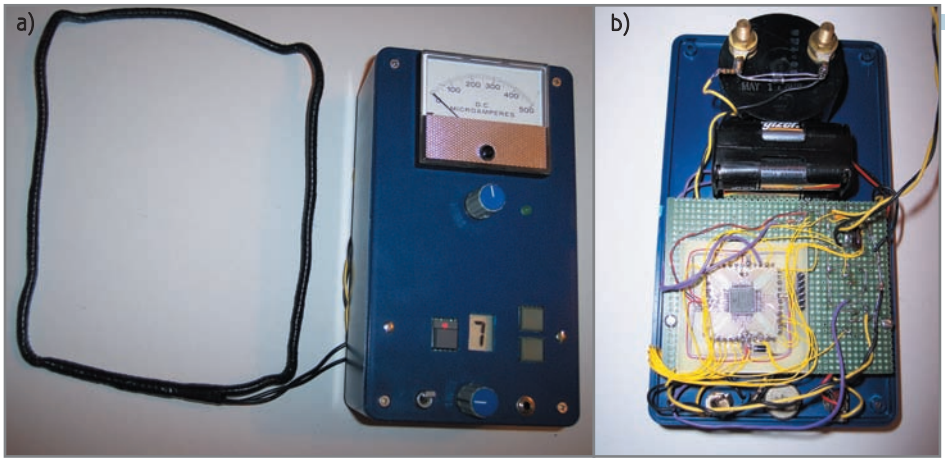



**Photo 1a**—This is the cable tracer showing the degaussing coil used as a Search Coil. **b**—Take a look inside. The microcontroller in a TQFP package is mounted on a fanout board. The rest of the electronics was point-to-point wired on a 0.1″ perf board. The battery pack is mounted between the analog meter and perf board.

f is the frequency, N is the number of turns in the pickup coil, A is the loop's area ($m^2$), B is the signal strength (μWebers/$m^2$), and α is the signal's angle.

I want to maximize the received signal voltage. It would seem that simply increasing any of the terms would work. As always in engineering, this amounts to trade-offs. The frequency is somewhat bound by the MCP2030's design. It is optimized for 125 kHz. This is the frequency I keep. The number of turns in the pickup coil is also somewhat fixed. As you increase the number of turns, you also increase the coil's capacitance. This is also true of the coil's area. I used an old degaussing coil from a small CRT monitor. The coil dimensions were 8″ × 7″, 60 turn, 24-gauge wire. This coil had an inductance of 2 mH. Surprisingly, it had a self-resonant frequency (SRF) of only 200 kHz. This meant that it had a parasitic capacitance of 316 pF. I tested a larger degaussing coil (22″ diameter, 23.4 mH) with more turns and it had an SRF of 20 kHz. This meant it had a parasitic capacitance of 2,700 pF. This SRF was too low to be used. I needed an SRF of 200 kHz or more to allow for cable and circuit capacitance.

Circular, square, or slightly rectangular geometries all work well. You can wind your pickup coil on a circular form (or for square or rectangular coils), place four nails (cover them with heatshrink tubing so that you don't scratch the insulation) in a board, and wind with magnet wire. A wire gauge number of 26 or smaller (larger diameter wire) is recommended to prevent skin effect from becoming an issue.

To test the coil, I coupled a signal generator to the coil (see Figure 2). Placing the coil across the output of the signal generator with a scope won't show any peaks because the signal generator's low output impedance (typically 50 Ω) can swamp out the coil's higher impedance. I used about a 10-turn coil on the output of the signal generator and placed it in the center of my pickup coil. The pickup coil's output was displayed on a scope.

You can sweep the signal generator through its ranges and observe the peak. This will be the SRF of the coil. You can measure the inductance with an inductance meter. The parasitic capacitance will be:

$$C = \frac{1}{(2\pi SRF)^2 L}$$

The resonant capacitance for 125 kHz will be:

$$C = \frac{1}{(2\pi 125\ kHz)^2 L}$$

The required tuning capacitor will be resonant capacitance minus the parasitic pickup coil capacitance and wiring capacitance.

The pickup coil will be used perpendicular to the ground. The pickup coil is extremely directional, which even allowed for detecting the curving of the cable. The underground cable that I was searching for was about 200′ long and consisted of 3 conductor 00 wire. I was even able to locate a cable break by a substantial decrease in signal level as I traced along the cable. The meter was very useful in indicating the direction by seeing the minor level changes as the direction of the coil was rotated (as predicted by cos α).

## RECEIVER

The receiver consists of an MCP2030 RFID chip, a Microchip Technology MCP6S26 variable gain amplifier, and a Microchip Technology PIC24FJ64GA004 microcontroller. The MCP2030 RFID chip provides a convenient analog front end for the tracer (see Figure 3). It has an AGC-controlled receiver with 3-mV sensitivity, a carrier detector, a received signal strength indicator (RSSI), input coil tuning, and other RFID features that aren't required for this application.

There are three input channels for x-, y-, and z-axis pickup coils for RFID applications. For this application, only one channel is used or needed. The 3-mV sensitivity

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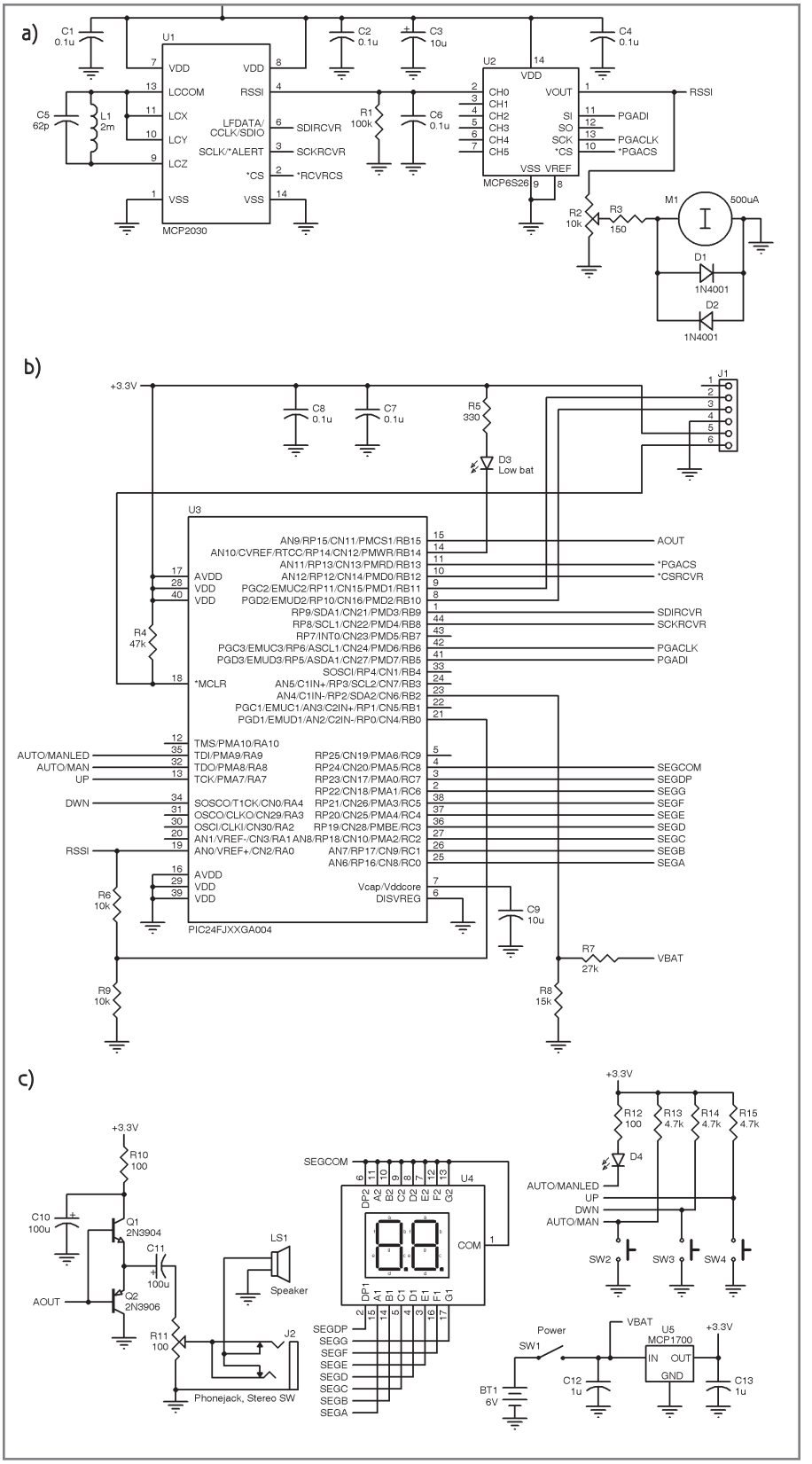



Figure 1a—This is the tracer analog section. U1 is the RFID chip. U2 is the variable gain amplifier. b—U3 is the PIC with the debugging/programming interface J1. c—Check out the tracer power supply and I/O. Here is the LCD U4, LDO voltage regulator U5, and the speaker buffer.

is excellent. I tried adding a preamp, but it was only marginally better. It was not worth the added complexity and the loss of the pickup coil tuning

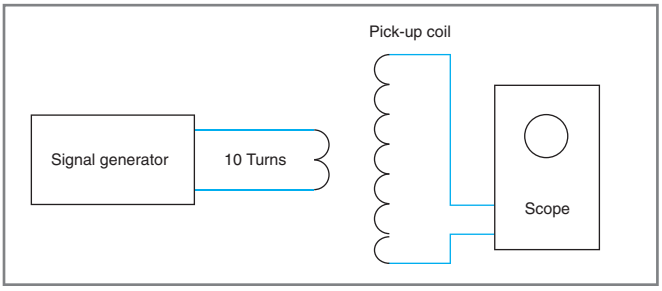



Figure 2—This is the test fixture for testing the pick-up coil. A signal generator couples a signal into the pick-up coil under test by a 10-turn loop. The voltage output of the pick-up coil under test is shown on the oscilloscope to measure the self resonant frequency.

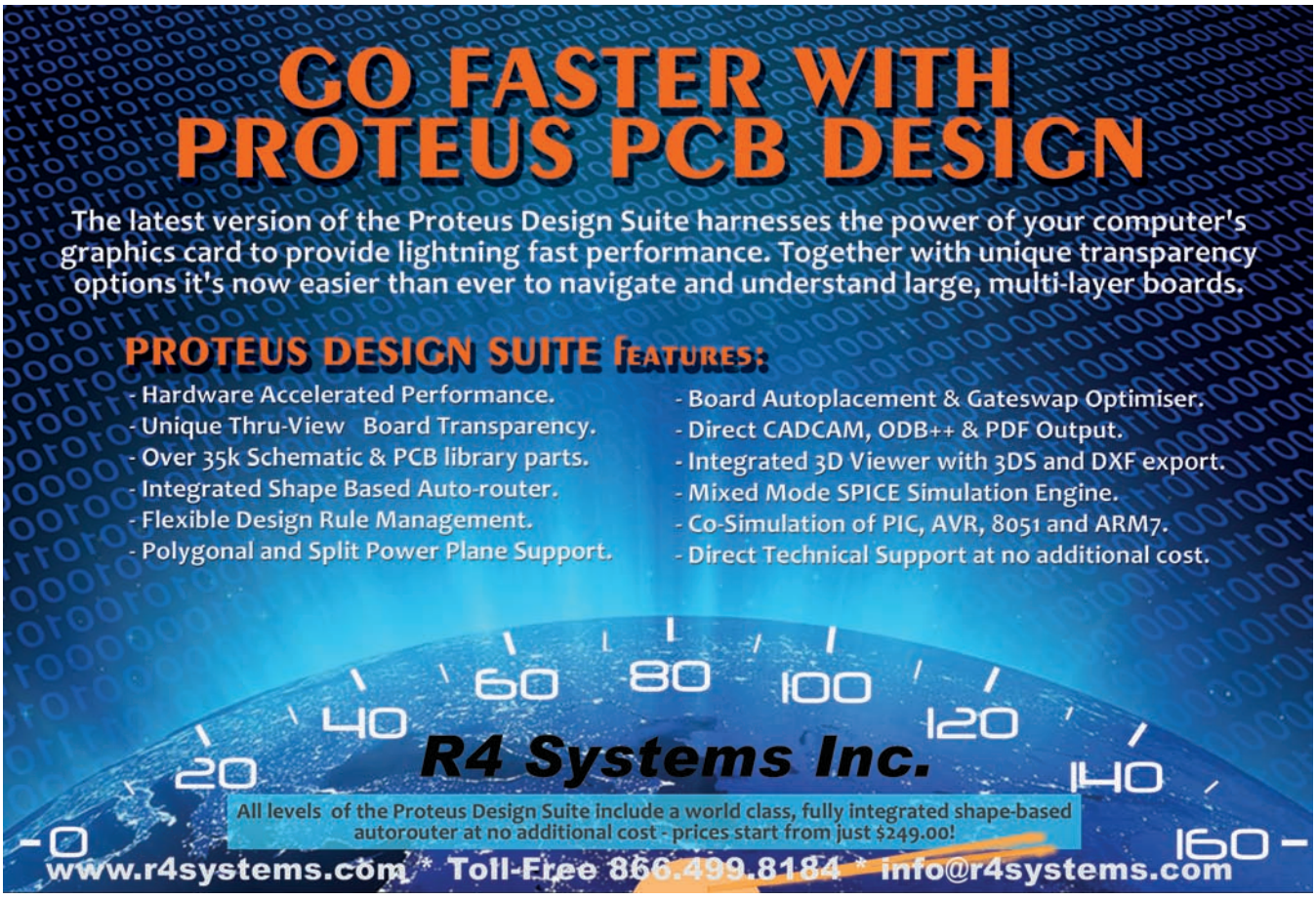
feature. The MCP2030 has a software tuning feature. It can vary the input capacitance by 63 pF in 1-pF steps. This is useful to peak the unit to compensate for changes in stray capacitance.

The RSSI output is a current output. It is approximately 20-µA per input volt. It develops a voltage across a 100-kΩ load resistor. The ADC on the processor uses a 3.3-V internal reference. The ADC will full scale at 33 µA with the 100-kΩ load resistor. This corresponds to an input voltage on the pickup coil of 1.65 V. Unless you are right next to the cable, this will never be an issue.

The MCP2030 has internal software-selectable attenuators, but in actual cable tracing tests, overloads were not a concern. It uses a SPI to communicate with the microcontroller. It only needed to be initialized so it did not require a fast SPI. It uses a bidirectional data pin. The MCP2030 is turned off when CS is low for programming the registers and not driving the SPI data line. CS must be high to turn on the MCP2030, and at that point it drives the SPI data line. I found it was easier to control this by not using the SPI controller in the PIC and just bit-banging the port pins.

In order to increase the RSSI output for indicating weak signals, a variable gain amplifier (MCP6S21) is used on the output. This can add a gain of up to 32. In most cases, you will be running with the 32× gain. The VGA also provides buffering of the RSSI signal. This is needed to drive the analog meter as well as compensate for the low input impedance of the ADC on the PIC. The VGA also programs with a SPI. It is attached to the SPI controller on the PIC. The SPI controller was used to drive the VGA for quick updates.

The amplified RSSI signal is used to drive a conventional analog 500-µA meter. R2 is a meter sensitivity adjustment. On weak signals maximum sensitivity is needed, but at this setting, a strong signal would overload the meter. Clamp diodes (D1 and D2) and a series resistor (R3) provide protection for the meter. The analog meter is useful for seeing minor drops in signal strength. This is used to detect cable direction by slightly rotating the pickup coil (cos α). The RSSI signal feeds an ADC (AN0)



and comparator on the PIC. The A/D RSSI value is used to vary the audio tone and increase the VGA gain. The comparator input is the resistor divided by two with R6 and R9. This was done because the maximum comparator reference voltage is 0.66 $V_{DD}$. The comparator trip point is set to approximately 1.5 V in firmware. The resistor divider increases this to an RSSI trip point of 3 V. The ADC tops out at 3.3 V using the PIC $V_{DD}$ as the A/D reference. A comparator interrupt is generated when the RSSI signal hits 3 V. The comparator interrupt is used to drop the gain quickly to prevent an overload. The PIC then drops the VGA gain a step to keep things in range. The firmware checks the A/D value for the RSSI signal in a software loop. If it is below the low-gain trip point, the firmware boosts it up a step.

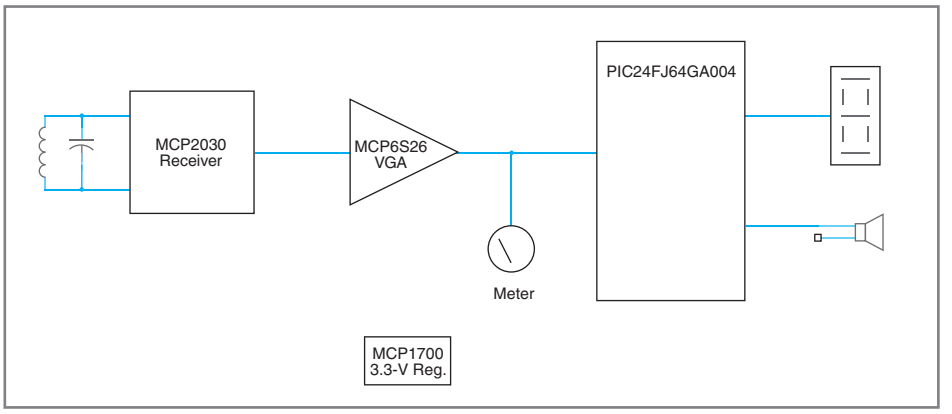



Figure 3—The search coil feeds the signal to the MCP2030 RFID receiver. The output is amplified by the MCP6526 VGA, which drives the analog meter and the microcontroller. The microcontroller controls the parts by a SPI and drives the LCD and speaker.

The A/D value is used to generate an audio variable frequency oscillator. This gives an audio indication of signal strength similar to a metal detector. This is sometimes useful if you can't keep an eye on the meter. The A/D value is inverted to give a low-to-high tone and scaled to range from 120 Hz to 15 kHz by 32-bit timer pair 4 and 5. The timer interrupt for the audio oscillator toggles port pin RB15. The port pin is current amplified by complementary emitter followers Q1 and Q2. It drives a small speaker or headphones through volume control R11.

The second comparator is used as a low-battery indicator. The trip point is the same for both comparators (1.5 V). Divider R7 and R8 scales the battery voltage to give a trip point of about 4.2 V. The Microchip Technology MCP1700 low-dropout regulator requires about 200 mV over the 3.3-V output. This sets the minimum

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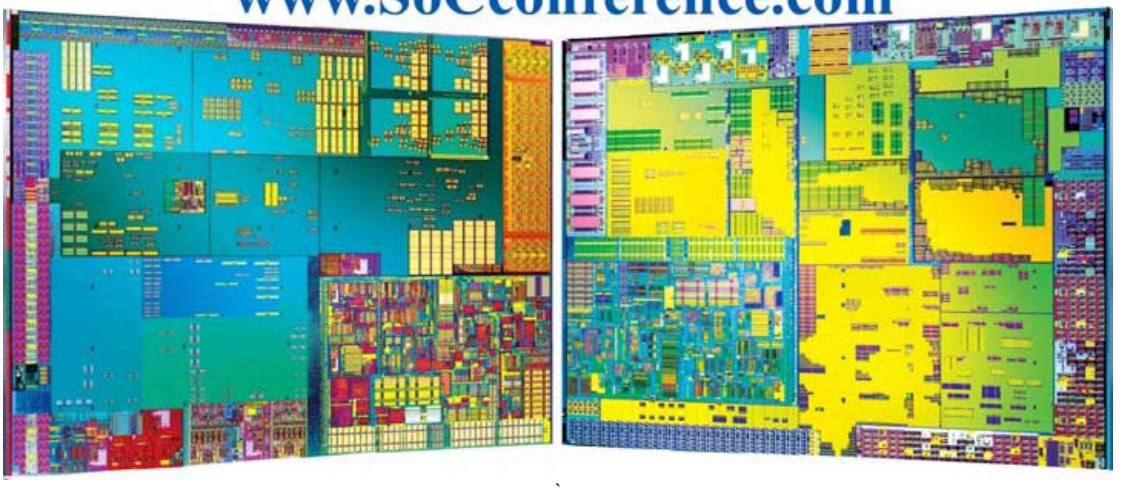

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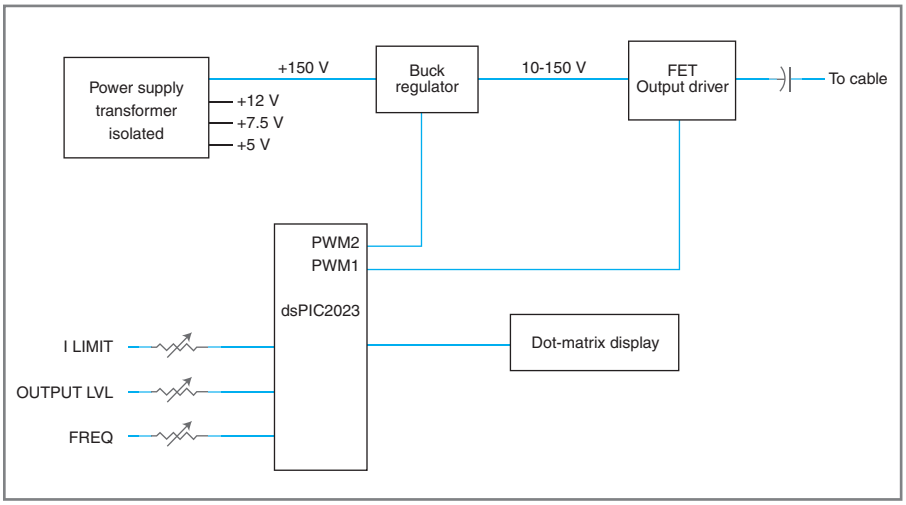


Figure 4—The power supply provides the control voltages and 150 V to the buck regulator. PWMs in the PIC control the buck regulator to adjust the signal level and provide the 125-kHz output signal. The PIC also reads the adjustment pots and displays information on the LCD.

usable battery voltage at 3.5 V. When the battery voltage falls below 4.2 V, the firmware turns on the "LOW BATTERY" LED.

Four AA batteries provide 6 V. The 6-V battery supplies the power to a 3.3-V low-dropout regulator (MCP1700). The Cable Tracer's power consumption is low enough to not cause heating of the LDO. The 6-V source and LDO provide a reasonable amount of operational time before the battery discharges to an unusable level.

A seven-segment LCD indicates the VGA's amplification factor of the VGA. An LCD is used to conserve battery power. It requires an AC drive signal to prevent deplating of the display. This is simply done by an output port in conjunction with the firmware. A second timer pair (2 and 3) generates an interrupt at about a 60-Hz rate. A "0" is applied to the segment common and a "1" to the desired segments. This is all on port C. When the interrupt occurs, the firmware compliments the port. This puts a "1" on the segment common, places a "0" on the desired segments, and accomplishes the required AC drive.

The display indicates the amplification factor and is used to determine if the signal source is at an appropriate level. With some operator practice, it will also help indicate relative depth changes and cable breaks.

There is also an Auto/Manual switch and Up and Down buttons. In some cases, operating the amplification factor manually is useful. An LED is used to indicate Auto or Manual operation. In Manual mode, the buttons enable you to adjust the VGA's amplification factor. In Auto mode, comparator 2 is used to indicate if the signal level is too high and the gain should be dropped. The firmware then drops the VGA amplification factor. The comparator and interrupt were used to provide a faster response so that the meter would not get "pinned." The AN0 input also monitors the RSSI signal level. The firmware checks to see if the AN0 level is too low, requiring more amplification by the VGA. The firmware trip point is 0.25 V.

The peripheral pin select was particularly useful in this application for selecting the microcontroller's features. The comparator outputs and the SPI were selected by the peripheral pin selects and routed to the desired pins.

## SENDER

The sender is shown in Figure 4. It consists of a power supply, a variable voltage buck regulator, a Half-bridge output driver, dsPIC microcontroller, and a 2 × 16 LCD (see Figure 5). The cable characteristics that the sender will have to work into can vary greatly. The ideal situation would be a single conductor cable with infinite resistance to ground and no capacitance. This would require little power to drive. But in the real world, it is more likely that the cable will be two or three long conductors. The circuit breaker will disconnect the one or two powered line conductors, but the neutral will mostly likely remain grounded. This will mean a high capacitance between the line conductors and the neutral. There may also be leakage resistance (but hopefully not a load resistance).

I decided the most useful signal source would have to be capable of driving a high-capacitance load. The sender has a voltage range of 10 to 150 V. This is potentially a lethal power level. Extreme care should be exercised if the sender is turned up this high. I included a flashing red LED that illuminates if the drive voltage goes above 50 V. A beeper also sounds a warning. If you don't need high voltage, cut the voltage down on T1 to 28 V. I assume that if you are in the panel box with its higher voltages that you will exercise enough caution that the sender won't be a hazard. The generator is capacitively coupled to the output so there won't be a DC component to the output. Also, at 125 kHz, there could be more of an RF burn hazard than a shock hazard.

If you feel uncomfortable with the voltages, or if you aren't using it on power cables, you can always use just an audio signal generator. My original version used an HP 3310B, which has up to a 30-V output level. The only problem is that your cable search depth will be limited if it doesn't have enough output.

In order to provide this power level, a battery-operated device is not practical. This should not be a limitation in most cases. There should be plenty of power around the panel box. I used a PC-type power cord male power connector (from a scrapped PC power supply) on the sender. Thus, I can use a standard power cord to plug into an outlet. I also made another power cord with alligator clips in place of the power plug. This enables me to clip onto power in the panel box.

The power supply is transformer-isolated from the line.

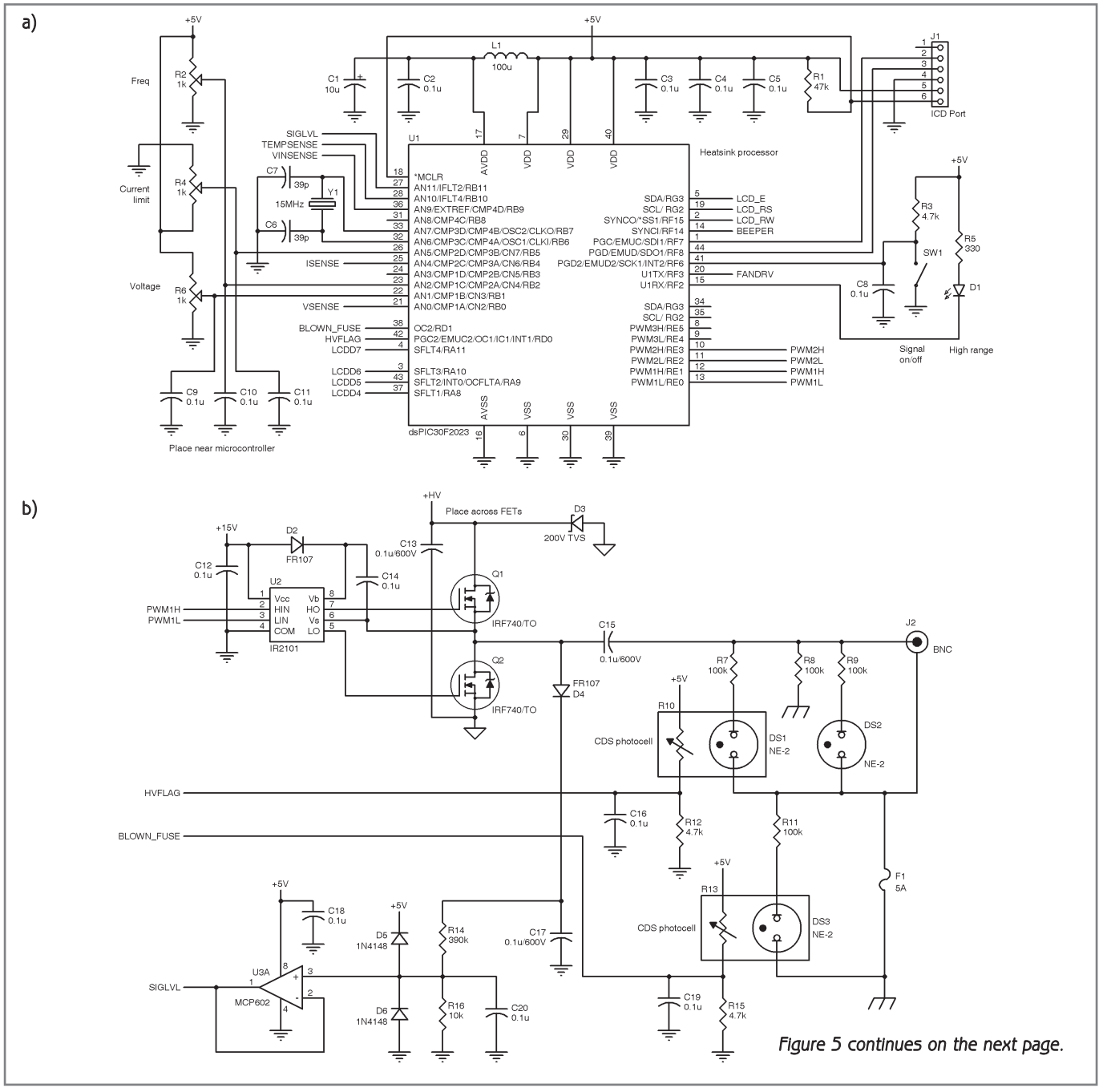


Figure 5 continues on the next page.

**Figure 5a**—This is the sender processor. A dsPIC U1 is used to read the adjustment pots and provide PWM control signals to the regulator and output section. Be sure to heatsink U1 since it dissipates about 1 W. **b**—This is the sender output section. The output driver U2 feeds the IRF740 FETs. The FETs require a heatsink. Buffer U3 feeds back the output level to the microcontroller. Note the three different grounds that need to come together at a common point. [Figure 5 continues on the next page.]

It has a high- and low-voltage section. The low-voltage supply uses a 12-VCT transformer. The full wave bridge rectifier provides a 15-V output to power the FET drivers. The center tap of the transformer provides a 7.5-V output to power a 5-V three terminal regulator (U7). It also powers the LED backlight for the LCD. Running the LED backlight off the unregulated 7.5 V reduces the power dissipation in the 5-V regulator. The regulator needs a heatsink to dissipate about 1 W. The 5-V transient voltage suppressor (TVS) is used to dissipate any transients that the clamp diodes steer into the 5-V supply. The dsPIC30F2023 draws so much power that the TVS will protect only for large transients. It's a good idea to use a TVS or Zener diode on the microcontroller's power supply for low-power devices in noisy environments. Transients on the inputs—which usually have internal clamp diodes—can raise the supply voltage up on micro-power parts. I also recommend the external clamp diodes because the internal ones are mainly meant for static protection, and they don't have the current rating to handle more persistent large transients.

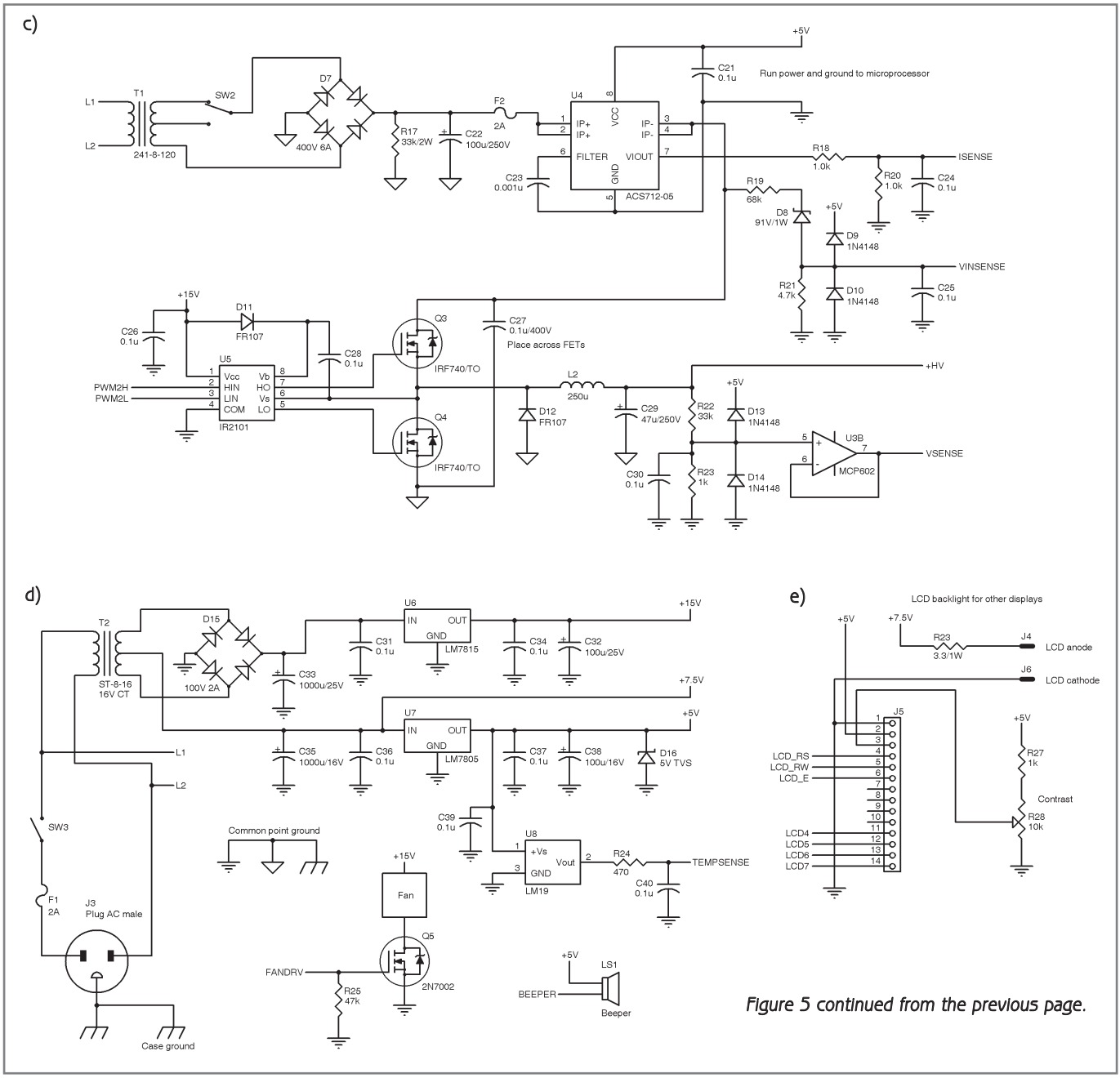


*Figure 5 continued from the previous page.*

**Figure 5c**—This is the HV power supply and buck regulator. U4 is the Hall effect current sensor. If you ignore synchronous rectifier FET Q4, it will look more like a conventional buck regulator topology. The FETs require a heatsink. **d**—This is the LV power supply. All of the regulators and FETs are mounted on a large common heatsink with the LM19 temperature sensor. **e**—Take a look at the LCD interface. A standard 2 x 16 LCD is used with an LED backlight.

The high-voltage power supply uses a 120-V CT power transformer. This will provide about 160 VDC. If you don't want to run that high, you can connect one side of the bridge rectifier to the center tap instead. This will provide about 80 VDC. You can also use a 28-V transformer. This will provide about 42 VDC. The 120-V transformer is basically a 1:1 isolation transformer. You could also make an isolation transformer by using two back-to-back transformers. Any combination of about 120 VA will work. You could use two 12-V at 10-A transformers with the 12-V windings wired together. I used an overrated (6 A) bridge rectifier to handle the inrush current to charge C22. A lower current bridge could be used with a PTC thermistor in series to limit the inrush current. The trade-off is that at this current level the bigger bridge is cheaper and you don't have to deal with the heat generated by a PTC.

The bleeder resistor R17 will take several seconds to bleed off the 160-V charge on C22, but it was a compromise to limit power dissipation. I have a switch to select high voltage or low voltage. I sense the voltage with R19, D8, and R21. I use a digital

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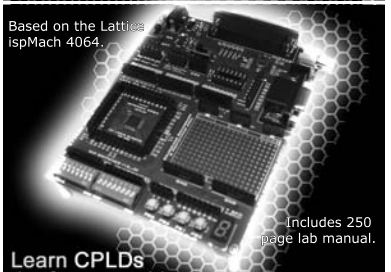
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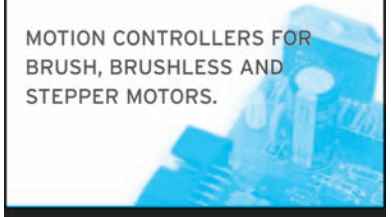
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By the author of *Serial Port Complete*

input on the microcontroller for this. In order to get a nice logic level change, I use a 91-V Zener diode instead of just a resistive divider. This provides for 0 or 1 mA through R21 giving a nice 0 or 5-V logic level. The problem is that the high voltage being sensed varies with the loading on the power supply, which could be nearly 0 to over 1 A. This no-load-to-full-load voltage variation makes the selection of divider resistor critical to ensure the divided voltage level is in valid logic 1 or 0 levels for the input. The firmware uses this input voltage sense to adjust the scaling so that the voltage level potentiometer has a full range at either input voltage.

The high-voltage power supply runs through an ACS712-05 (U4) Hall effect current sensor. This will provide the current sensing for the dsPIC and will be used for short-circuit protection. This is useful if you are pumping power into a shorted cable or a cable with a load. The ACS712 is ratiometric. This eliminates output errors when the same 5-V supplies the sensor as well as the A/D reference. Supply voltage variations will be the same ratio for the sensor and the ADC, so they will not affect the measurement. The ACS712 output ranges from 0.5 to 4.5 V centered at 2.5 V for zero current. The output is resistively divided by 2 with R18 and R20. This is also to bring it in range of the dsPIC comparator. The current sense is fed to a dsPIC pin used as both a comparator and A/D input. The comparator is used as fault sensing. This will immediately turn off the PWM. The A/D is used to set the current limit in firmware.

The buck regulator takes the high voltage and drops it down to 10 to 160 V. This is easy to do with the dsPIC, especially because the regulation requirements for the output section are not very demanding. Although it is a conventional buck regulator, it might not look like it from the diagram.[2] If you imagine Q4 as just a diode (D12), the topology will look more familiar.

N-channel FETs are cheaper and have lower $R_{DS}$ on than P-channel FETs. To use an N-channel FET for the switch element Q3, you need to be able to raise the gate above the input source voltage. When the FET Q3 is on, the source will be at the same voltage as the drain (160 V). This means that the gate would have to be at 160 V+$V_{GS}$, or about 175 V. A separate isolated bias supply will work, but it's costly. The IR2101 FET driver provides an ideal solution. It provides the gate driver and voltage boost for a Half-bridge circuit. The gate voltage boost comes from a bootstrap circuit. When FET Q4 is on, $V_{GS}$ is at ground. Capacitor C28 charges to 15 V through diode D11. This provides the gate drive voltage for Q3. When Q3 switches on, $V_S$ rides up to 160 V and the charge in C16 follows it. $V_B$ is 15 V referenced to $V_S$, but 175 V referenced to ground. Diode D11 blocks the 175 V from the 15-V supply. This is a great part for a Half bridge, but tricky for a buck regulator. In order for it to work, you cannot have 100% duty cycle. Q4 needs to turn on in order to replenish the charge in C28. The firmware will prevent 100% duty cycle.

The positive current flowing through C28 to ground would be blocked by the diode D12. FET Q4 provides the path for C28 charging current to ground. It is basically a synchronous rectifier. As a synchronous rectifier, Q4 is also providing a path for the negative inductor current through L2 when Q3 is off.

An FET is basically a voltage-controlled resistor. It can pass current in both directions. There is an intrinsic diode from the source to drain. This diode would normally conduct the negative current (as will D12), but turning on the FET will have a lower voltage drop by shorting out the diode and conducting the negative inductor current and the needed positive C28 capacitor-charging current. D12 is redundant because Q4 is doing its work. I left it in during the prototyping and firmware debugging processes as a safety backup. I also like to put a reverse-biased diode on the microprocessor power pins during prototyping. I can't tell you how

many times I accidentally applied power backwards when I was in a hurry to try something.

The output section is a Half-bridge driver. The Half-bridge output section along with a variable-voltage power supply will be a more efficient driver section than an analog power amplifier. The Half-bridge output section will produce a square wave output of an amplitude equal to the supply voltage. An International Rectifier IR2101 FET driver is also used here to drive the output FETs. The firmware fixes the duty cycle to 50%. Capacitor C15 provides DC blocking in case of a FET short. It also provides high impedance to 60 Hz. This prevents line voltage from damaging the FETs if you accidentally connect to a "hot" wire. Neon lamp DS2 will alert you to a hot wire.

An optoisolator made from a neon lamp and a CDS photocell can also detect a hot wire. The optoisolator detects the hot wire and interrupts the microcontroller. A conventional LED optoisolator is not ideal for this application. You need to drop 100 V or more for the LED part of the optoisolator. A typical isolator has a current transfer ratio of 100% (current into the LED equals current through the output transistor). And for reliable LED operation, you'll want several milliamps flowing through it. Dropping 100 V or more at several milliamps would dissipate some power in a resistor. At 60 Hz, the impedance of a capacitor is a good way to drop the line voltage from a hot wire instead of dissipating heat in a resistor. The problem is that with both 60 Hz and 125 kHz this won't work. The Xc at 60 Hz would go to practically zero at 125 kHz and "fry" the LED. A neon bulb is ideal. It has built-in hysteresis with a firing voltage around 90 V. This provides a nice transition on the output. The LED optoisolator would have a linear change with voltage, which would lead to bad logic levels. The slow response time of the CDS photocell is an advantage because it helps to smooth out the 60-Hz signal for the microcontroller. The firmware will "beep" when high voltage is present

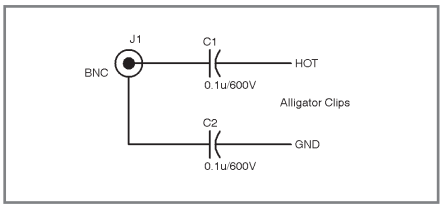


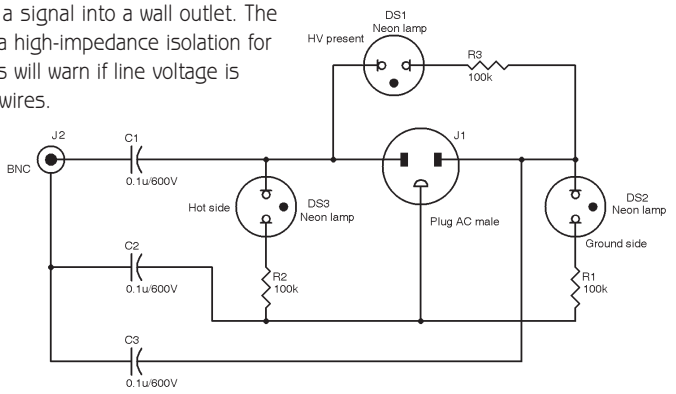

Figure 6—A BNC cable, with series isolation capacitors, connects to alligator clips for signal injection to the cable to be traced. The Xc of the capacitors at 60 Hz helps to protect from shorts if inadvertently attached to a hot wire.

from a hot wire or a high cable voltage drive level. The neon light DS2 will also come on at high voltage drive as a warning.

The output signal is rectified by D4 and filtered by C17. It is level-shifted by a resistive divider (R14 and R16) and further filtered by C20. The unity gain amplifier U3A buffers the signal to drive the low-input impedance of the microcontroller's ADC. A diode clamp (D5 and D6) prevents transients from damaging U3A. The output BNC should be an insulated type. The outer barrel is returned to ground through the fuse F1. Thus, if you accidentally connect the ground lead to a hot line, you will blow this fuse instead of vaporizing the ground clip. When the fuse blows, the second neon optoisolator will detect the blown fuse and signal the microcontroller to turn on the alarm. Don't forget to change the fuse right after you remove the ground clip because the alarm will be active only if the fuse is blown and the fault voltage is still applied. A 200-V TVS is used to absorb any high-voltage transients that might ride in from a hot wire. You might think that there is too much over-design associated with noise, transient, and safety issues, but these are things I added after replacing blown-up parts.

A 2 × 16 dot-matrix LCD is used to display particular information: frequency, signal level, and drive current. Although the dsPIC30F2023 has several unused port pins, I couldn't group eight together to drive the LCD in byte mode. Four bits were the best I could do. The LCD is driven in nibble

Figure 7—This is the AC plug adapter test box. It is a handy tool to inject a signal into a wall outlet. The capacitors provide for a high-impedance isolation for 60 Hz. The neon lamps will warn if line voltage is present on any of the wires.




mode. An analog temperature sensor (U8) is used to monitor the box temperature and turn on a fan if things start getting warm. This happens only when injecting into a heavy load.

The dsPIC30F2023 runs off a 15-MHz crystal. A crystal was used to make the frequency measurement accurate and generator frequency stable. The internal FRC oscillator had a tendency to drift with temperature. The dsPIC2023 needs a heatsink. The high-resolution PWM requires the high-frequency PLL to be enabled. The PLL will be running at 32× the crystal frequency, or 480 MHz. At this frequency, the part dissipates around 1 W. I cut up an old Pentium heatsink to fit the dsPIC30F2023's case. I used thermal tape to keep it attached and provide low thermal resistance.

## TEST LEADS

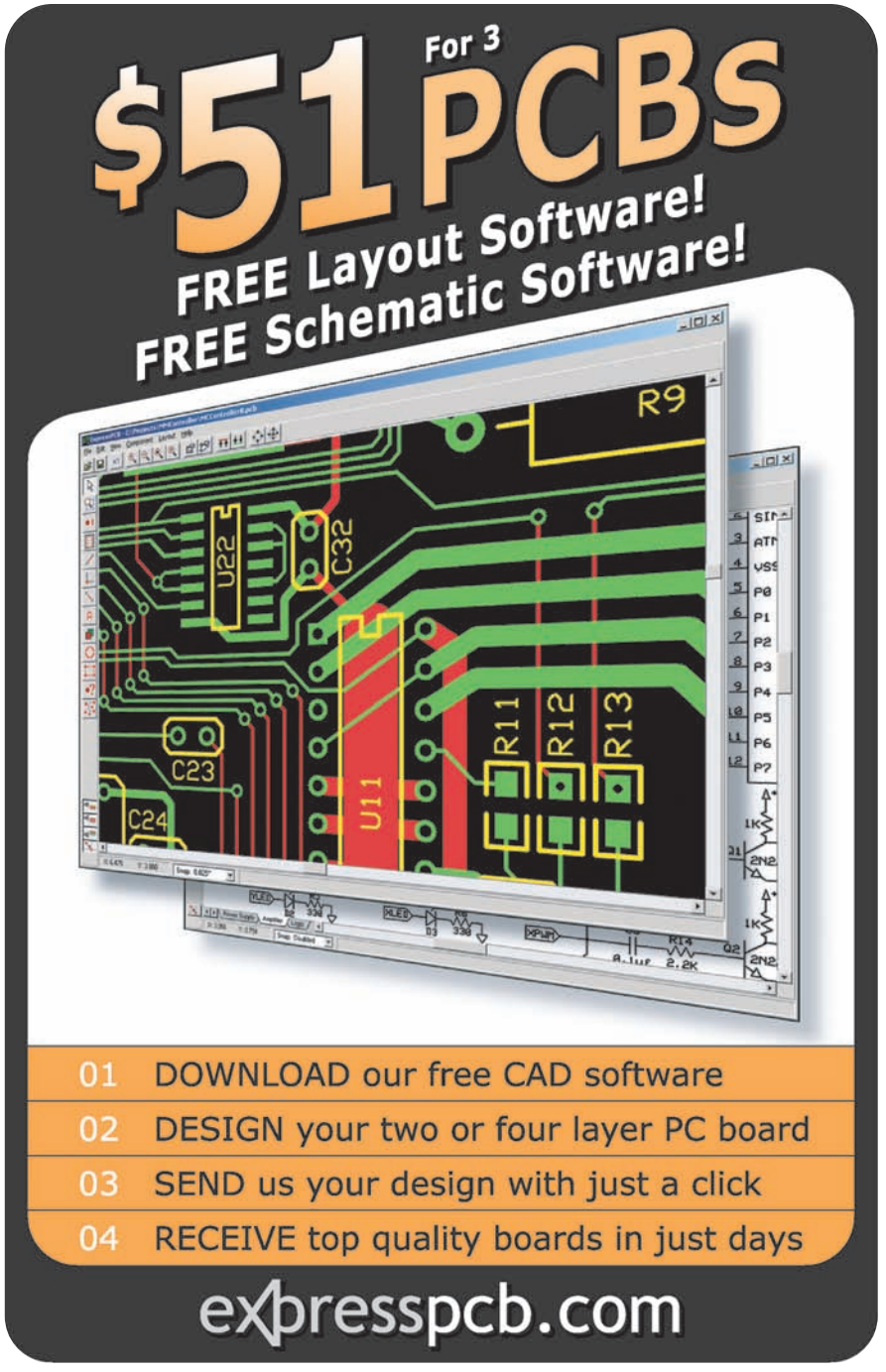
Figure 6 shows a simple set of test leads. The series capacitors are important. They offer high impedance to 60 Hz. Thus, if you accidentally put the ground clip on a hot line, sparks won't fly.

The elaborate but very useful tool in Figure 7 provides for the isolation capacitors and a male power plug to plug into an outlet. The three neon bulbs indicate if there are any hot lines—even if they are wired incorrectly. This is a useful tool for injecting the signal into an outlet and tracing the wiring in a wall.

## SOFTWARE TO OPERATION

At this point, you have a good understanding of the cable tracer's hardware. In the second part of this article series, I'll cover the software for both the tracer and sender. I'll finish by describing the system's controls and explaining how to operate the design.

*Kevin Gorga (kgorga@stny.rr.com) has an MSEE and has been a design engineer with IBM in Endicott, NY, for the past 31 years. His technical interests include embedded system design, power systems, and motor controls.*



## PROJECT FILES

To download the code, go to ftp://ftp.circuitcellar.com/pub/Circuit_Cellar/2009/229.

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[1] Y. Lee, "AN678: RFID Coil Design," Microchip Technology, Inc., DS00678B, 1998.

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[3] A. Bersani, "AN1207: Switch Mode Power Supply (SMPS) Topologies (Part II)," Microchip Technology, Inc., DS01207A, 2008.


## RESOURCE

Microchip Technology, Inc., "MCP2030 Bidirectional Communication Demo Kit User's Guide," DS51637A, 2006.

## SOURCES

**ACS712-05 Current sensor**
Allegro MicroSystems, Inc. | www.allegromicro.com

**IR2101 FET Driver**
International Rectifier | www.irf.com

**MCP2030 RFID Receiver, MCP6S21 VGA, PIC24FJ64GA004 microcontroller, MCP1700 LDO, dsPIC30F2023, and MCP602 op-amp**
Microchip Technology, Inc. | www.microchip.com

by Robert Lacoste

# Power Analysis Primer

## From Power Line Measurements to PFC

Are you familiar with the topic of power factor control (PFC)? Robert explains how to measure the power consumption of line-powered devices. After introducing the topic of power factor controllers, he presents some experiments to shine a light on this sometimes confusing topic.

Welcome back to The Darker Side. This month, I will start by describing how to measure the power consumption of line-powered devices. This may seem like a basic topic that's less exotic than usual, but RMS power, apparent power, or power factors are sometimes misunderstood. Additionally, measurement tools are not so easy to use efficiently and, more importantly, safely. I will then introduce the topic of power factor controllers (PFCs) and describe experiments with a couple of pretty cool chips. Ready? Let's go!

### POWER BASICS

Assume that you need to measure the power consumption of your latest device, powered from a 110- or 220/240-V line voltage (depending on whether or not you like ketchup). What would you actually need to measure? Let's cover the basics of AC power.

If a device is connected to a source providing a voltage V(t), usually a sine wave, and draws a current I(t), the instantaneous power consumption over time is simply:

$$P(t) = V(t) \times I(t)$$

The real power used by the device—also called "active power" or sometimes "RMS power"—is the average of this instantaneous power over time, which is an integral:

$$P_{REAL} = \frac{1}{T}\int V(t)\, I(t)\, dt$$

When the instantaneous voltage and power are measured at discrete time steps and not continuously—which is usually the case in actual electronic systems—you can simply rewrite this integral as a discrete average of the voltage samples multiplied by the current samples. This means the sum of the V × I samples divided by the number of samples:

$$P_{REAL} \approx \frac{1}{N}\sum_{i=1..N} V_i \times I_i$$

The first difficulty: This average must be calculated over exactly one or more full AC periods to avoid measurement errors. Of course, the number of sampling points per period must be high enough for a proper averaging. Thanks to the Nyquist-Shannon sampling theorem, you know that this means more than twice the frequency of the highest significant harmonic (the current is usually not a sine wave), which usually translates into a few thousand samples per second.

The AC voltage and AC current can be independently measured through their RMS values, which are calculated as follows:

$$V_{RMS} \approx \sqrt{\frac{1}{N}\sum_{i=1..N} V_i^2}$$

$$I_{RMS} \approx \sqrt{\frac{1}{N}\sum_{i=1..N} I_i^2}$$

Once again, these sums must be calculated on exactly one or more full periods to avoid errors. Usually, the line voltage is a sine wave of amplitude $\pm V_{PEAK}$, so you probably know that the RMS values are simply the peak values divided by the square root of two. For example, a 220-V line voltage corresponds to a 220-V RMS voltage or a sine voltage ranging from –311 to 311 V (i.e., 220 × 1.414 = 311).

The ratio between the peak value and the RMS value is called the crest factor. This crest factor is obviously 1.414 for a sine wave. For a stable DC signal, the RMS value is equal to the peak value, so the crest factor is one, which is the minimum. However, it can be far higher for pulse-type signals. For instance, if the current is

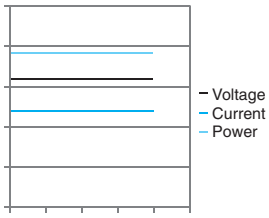
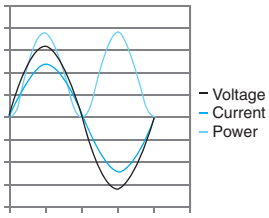
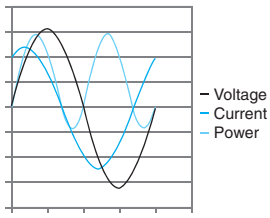
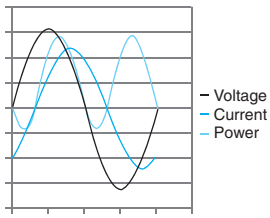
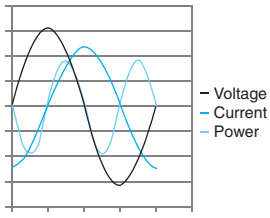
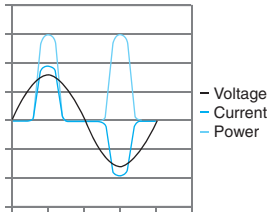
| Load | Waves | Current crest factor | Powers | Power factor |
|---|---|---|---|---|
| DC | DC   | 1 | $P_{REAL} = P_{APPARENT}$ | 1 |
| AC, resistive load | Sine waves, current and voltage in phase   | 1.414 | $P_{REAL} = P_{APPARENT}$ | 1 |
| AC, slightly capacitive load | Sine waves, current ahead from voltage   | 1.414 | $P_{REAL} < P_{APPARENT}$ | cos(ϕ) |
| AC, slightly inductive load | Sine waves,voltage ahead from current   | 1.414 | $P_{REAL} < P_{APPARENT}$ | cos(ϕ) |
| AC, fully inductive or capacitive load | Sine phases, 90° shifted   | 1.414 | $P_{REAL} = 0$ | 0 |
| AC, pulsed load | Complex waves   | Higher | $P_{REAL} << P_{APPARENT}$ | low |

**Figure 1**—With a DC voltage or a purely resistive load, there's no difference between real and apparent power. The situation is drastically different with more complex impedances.

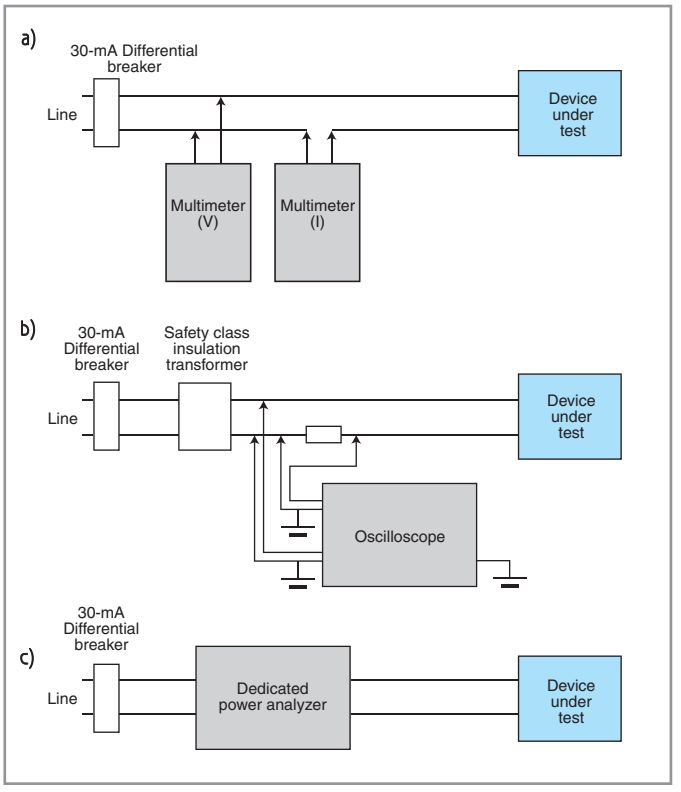



**Figure 2a**—Using a simple multimeter to measure the power consumption of a line-powered system allows you to measure the apparent power but not the real power. **b**—You can use an oscilloscope, but be careful. In particular, a good insulation transformer is mandatory even if you have an insulated differential probe. **c**—A dedicated power analyzer makes life easier.

10 A during 2 µs and then 0 the remaining 19.998 ms per 50-Hz period, the peak current will be 10 A—but the RMS current will be 0.1 A (i.e., the square root of $10^2/10{,}000$), giving a crest factor of 100 (i.e., 10/0.1). Thus, the crest factor is a good measurement to evaluate the shape of the instantaneous current, voltage, or power. Figure 1 depicts the different situations.

What could you do with the RMS voltage and current? Of course, you can multiply them, and this will give you the apparent power used by the device, a quantity usually measured in volts × amps in order to differentiate it from the real power, which is measured in watts:

$$P_{APPARENT} = V_{RMS} \times I_{RMS}$$

This apparent power is always equal to or higher than the real power. Trust me or try it yourself. The ratio is called the power factor, which is always lower than one:

$$PF = \frac{P_{REAL}}{P_{APPARENT}}$$

If the voltage is a sine wave and the load is a pure resistor, the current will be an in-phase sine wave. In that case, the apparent power will be equal to the RMS power, giving a power factor of one. If the load is slightly capacitive or inductive, the current will still be a sine wave, but with phase shift, either positive or negative (see Figure 1). The power factor is then easily calculated. It is equal to the cosine of the phase shift between voltage and current. This is why this power factor is also called "cos(ϕ)." In fact, this is also nearly the same even if the current wave is more complex than a sine. Imagine that the current is a complex periodic shape. It can be reduced to a sum of sine waves thanks to a Fourier transform. It can be shown that some energy could be transmitted to the load only when a given harmonic of the current has the same frequency as a given harmonic of the voltage. If the voltage is a pure sine, the real power is dependent on only the fundamental bin of the current Fourier transform: all powers due to higher harmonics are nullified if you perform the calculation.

The formula for the real power is:

$$P_{REAL} = V_{RMS} \times I(\text{fundamental})_{RMS} \times \cos(\phi)$$

The angle ϕ is simply the phase of the fundamental current frequency relative to the voltage. The power factor for complex currents is directly related to the current's total harmonic distortion:

$$PF = \frac{\cos(\phi)}{\sqrt{1 + THD^2}}$$

## REGULATIONS

OK, enough theory. Let's cover the topic of regulations before switching on the power.

As I explained in my April 2008 article titled "Low-Power Techniques" (*Circuit Cellar* 213), energy efficiency is a must for battery-powered systems. But why measure the power consumption of a line-powered device? To reduce it, of course. Fortunately, we're becoming more energy-conscious to fight against global warming and reduce our electricity bills.

Regulators do help us too, with increasingly stringent requirements. This is especially true in Europe and in Asia. For example, we have harmonic current limitation standards to help mitigate EMC issues and to enable efficient energy use on the distribution network. The EN 61000-3-2 and IEC 1000-3-2 standards have been applicable since 2001 for nearly all devices using more than 75 W and up to 16 A per phase. In a nutshell, these standards forbid us

**Photo 1**—The PowerSpy is a power analyzer based on a small plug-type measurement system linked through Bluetooth to a PC hosting real-time waveform calculations and a user interface.

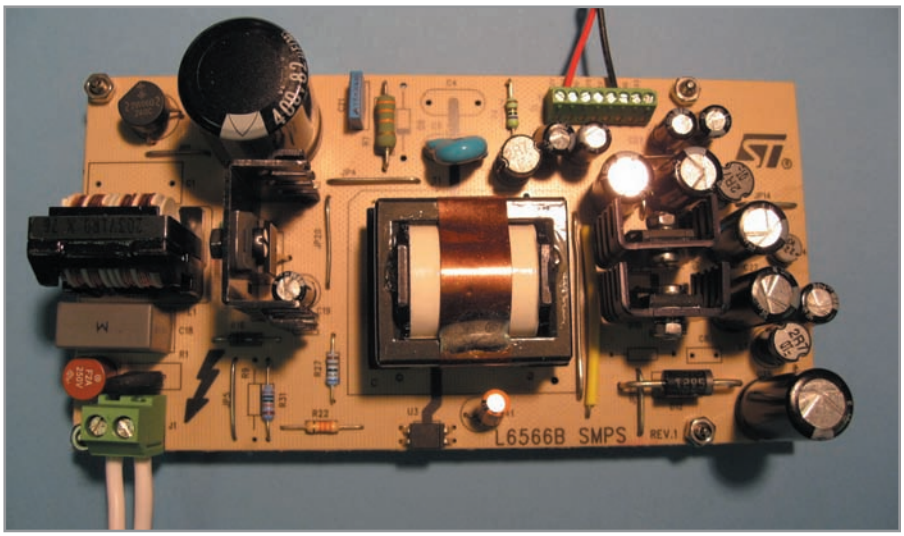



**Photo 2**—This is the STMicroelectronics AC/DC power supply I used for the tests. From left to right, you see the input filter, diode bridge, ballast capacitor, FET switch, HF transformer, and output sections. The feedback optocoupler is at the bottom.

from selling a product that would use energy in an inefficient way (i.e., with a low power factor). Note that a low power factor isn't a problem for the end user because only the real power is usually charged by the electricity supplier. But it is a big problem for the supplier because resistive losses in the lines are linked to current ($P = RI^2$), whether or not this current is in phase with the voltage. So a low power factor means the same bill for the user but higher costs for the supplier. You know why this is regulated. Moreover, harmonic currents are definitively an EMC concern because high-frequency currents will radiate from the lines.

Standards like the IEC 1000-3-2 are related to the power factor and harmonic distortion, but they don't limit the amount of energy used. Newer standards are emerging that actually limit the energy consumption of devices. In particular, the so-called energy-using products (EuP) directive (2005/32/CE) was signed in July 2005 and has been applicable since the end of 2008 in Europe. One of its targets is to reduce the overall power used by equipment in Standby mode, with a target of no less than a 70% reduction in the next 10 years! As of January 2010 in Europe, you won't be able to sell equipment using more than 1 W in Standby mode—or 2 W if information is displayed when the device (e.g., a digital clock) is sleeping. These limits will be reduced by 50% in 2013 down to 0.5 or 1 W, respectively. I bet that the majority of computer power supplies, DVD recorders, and TVs will need to be redesigned. But this will allow countries to shut down a couple of nuclear power plants.

Even without mandatory regulation concerns or power efficiency labels like EnergyStar, the consumers are becoming more energy-efficient. Thus, it makes sense for companies to promote low-power devices to gain market share.

## MEASUREMENTS

*Caution! Even if you follow my recommendations, remember that line voltage measurements are risky and can be lethal. Don't try to reproduce these experiments without first taking the proper safety precautions.*

Now you know why you may need to measure your line-powered device's power. But how would you measure it?

The most affordable test setup is to use a multimeter. You would measure the line voltage, the line current, and then multiply them (see Figure 2a). Unfortunately, this will enable you to measure only the apparent power (in VA) and not the real power. You will know neither the phase relationship between the voltage and current nor the current's harmonic content (even if the multimeter can reliably measure the RMS value of the voltage and current). This may be enough if you're working on a resistive heater, but it absolutely won't be if you have an AC-to-DC power supply, either switching or linear, because of possible degraded power factors.

Without dedicated test equipment, the only other solution is to use an oscilloscope, especially if you are lucky enough to have a digital model with features like curve multiplication and measurement. It seems easy: obtain the voltage on channel 1, obtain the current on channel 2 (through a voltage measurement on a shunt resistor or a current clamp), ask the oscilloscope to calculate channel 1 × channel 2 (which is the instantaneous power), and then calculate the average value over an integer number of periods. Unfortunately, your oscilloscope will explode if you don't take some basic precautions—and if you aren't dead first. This measurement is *really* dangerous, so think twice before connecting your probes to a line-powered system.

The issue is that the inputs on a classic oscilloscope are referenced to

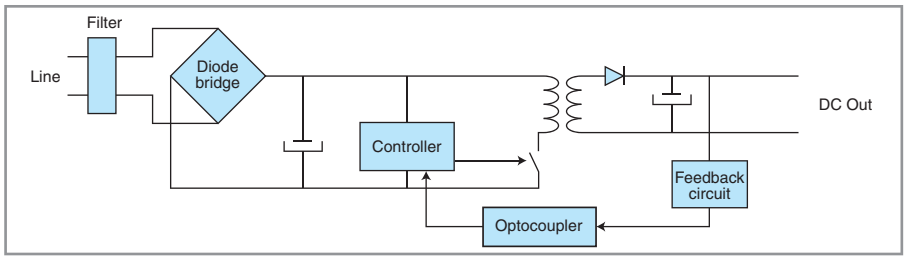



**Figure 3**—This is the classic architecture of a flyback isolated AC/DC converter. The line voltage is first transformed into a high-voltage DC voltage and then switched into a high-frequency transformer thanks to an integrated controller. The output voltage is regulated through a feedback loop that's usually made with a Zener diode and an optocoupler.

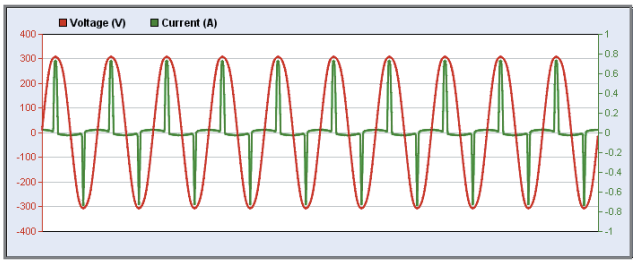



**Figure 4**—The measurements done on the AC/DC power supply with a 15-W load at the output shows a very peaky current linked to the diode bridge and large ballast capacitor. You can also see a small sine current in quadrature with the voltage due to the input filter of the design.

its chassis, which is grounded. If you connect the probe's ground tip to a line voltage, you have a perfect short circuit between the line and the ground through the scope. This measurement setup is possible, but you should take a few precautions (see Figure 2b).

Use an insulation transformer between the line and the device under test (it should be double-insulated). The only alternative is to use an isolated differential probe, but that's far more risky. I recommend the isolation transformer anyway.

Make sure your oscilloscope is grounded and that your installation is protected by a good differential safety breaker (30 mA or less). Never disconnect the oscilloscope's ground to make it "float" or its metallic parts will become lethal.

Double-check your probes' maximum voltage ratings. Take care to ground them to a single point to avoid dangerous ground currents.

And lastly, implement the basic electrical-work-related safety rules. Never perform dangerous tests alone. Always keep one of your hands in your pocket as long as the power is on. Switch on the power only when you are away from the device.

A more expensive yet drastically simpler solution is to use dedicated test equipment such as an energy analyzer (see Figure 2c). You can find low-cost wattmeters for less than $20, but they won't be measurement grade and they won't provide the details for optimizing products like harmonic contents or U/I waveforms. You'll find professional energy-analysis systems from companies like Fluke (the model 43B is a classic), Yokogawa, and Voltech. These systems are basically insulated V/I dedicated oscilloscopes with on-board measurement features.

Last year, after searching the Internet for a dedicated power analyzer with enough features for the optimization of AC/DC power supplies, I ended up with only two solutions: either buy an expensive one or spend some time to design the product I had in mind. I selected the second solution, and now Alciom (my company) is starting to sell the PowerSpy shown on Photo 1.

Technically speaking, the PowerSpy includes a nonisolated fast measurement circuit and minimal on-board real-time processing mainly for triggering. However, the V and I waveforms, digitized at 16 ksps, are then transferred in real-time to a nearby PC through a Bluetooth link. This wireless connection provides an easy, bullet-proof insulation barrier. The PC manages the calculations and user interface thanks to the associated software.

## TO THE BENCH

Let's move on to some actual measurements. I could have used any switching-power-supply-based design as an example, but I chose an STMicroelectronics EVL6566B-40WSTB AC/DC power supply evaluation kit simply because the architecture was documented and easy to understand (see Photo 2). The module is a classic 40-W, low-cost flyback converter based on an STMicroelectronics L6566B integrated circuit. Figure 3 depicts the generic architecture of a switching power supply. You can review the board's schematics at www.st.com.

I connected the power supply's line input to the PowerSpy, connected an electronic dummy load set to 1.7 A on one of the outputs, switched everything on, and, voila, I got what you see in Figure 4. The current wave is far from sine shaped, and this translates into a very low power factor. With 1.7 A on 9 V drawn from the output (15.3 W), the real power used from the line was 19.2 W, which gave a reasonable 80% efficiency. However, the apparent power was 44 VA, giving a power factor of less than 0.45! Now you understand why you should not use a multimeter to evaluate the power consumption of such a device: you will be 50% off. The current harmonics are also impressive (see Figure 5).

Don't be confused. This L6566B-based power supply is not a bad system. Nearly all simple AC/DC converters will show the same behavior. Why is the current so peaky? Refer back to Figure 3. The answer is in the second component—the diode bridge and its large ballast capacitor. How does

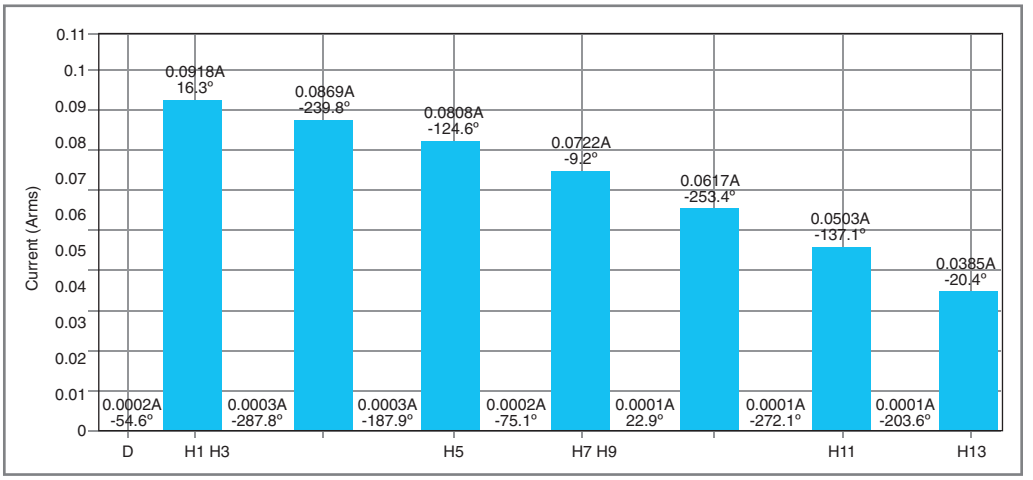



**Figure 5**—A power analyzer also enables you to display the harmonics of the current through a fast Fourier transform. Here the harmonics are of course very high—nearly as high as the fundamental.

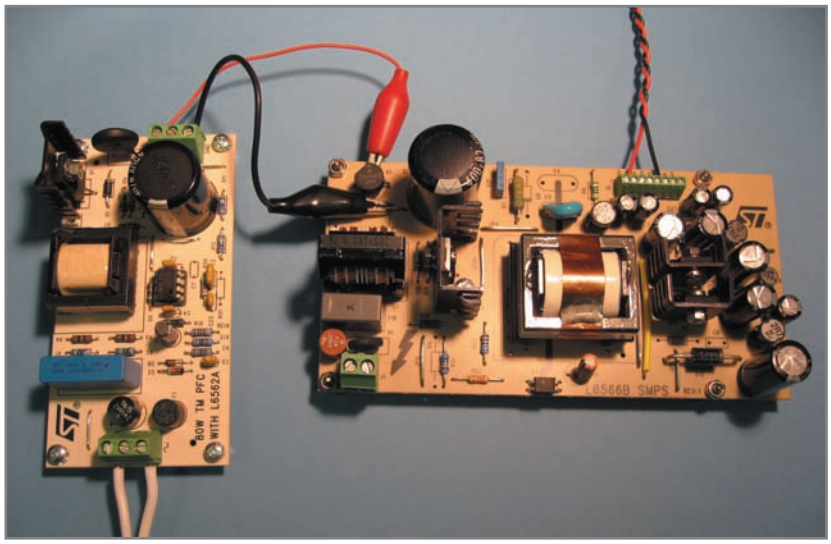


Photo 3—I connected the PFC evaluation board to the AC/DC power supply evaluation board. The input section of the latter is no longer used; it is replaced by the PFC controller connected directly at the diode bridge's output.

such a bridge work? Simply by allowing current to flow when the line voltage is above the capacitor's voltage level. This means the current from the line will be zero, except during a short period around the maximum voltage, and this is exactly what is demonstrated in Figure 4. The higher the load on the output, the wider the current peak. By the way, the situation is nearly the same with a plain old linear power supply.

The diode bridge in that case will be after a 50/60-Hz transformer. But there will be power peaks when the secondary voltage is above the voltage of the ballast capacitor, even if the transformer will help to smooth things out a little.

Such a low power factor is actually not a big issue for low-power systems, and that's why regulations don't yet impose limits on harmonics under a given power limit, generally 75 W. What are the solutions for higher power supplies? PFCs, of course. A PFC is a circuit that replaces the first stages of the AC/DC converter architecture—namely from the line input to the ballast capacitor—and ensure that the circuit will behave more or less like a pure resistive load from the network viewpoint. A PFC can be passive; just think about it as an LC 50- to 60-Hz band-pass filter. However, the majority of the PFCs are now based on electronic systems, either dedicated chips or DSPs, just because it is cheaper than a large coil and more efficient. The idea is to replace the diode bridge with a direct AC-to-DC switched mode converter, usually a non-isolated boost converter, with a control algorithm that will mimic a resistive load: the higher the line voltage, the higher the current drawn from the line to charge the capacitor. A feedback loop must be implemented to increase or decrease the value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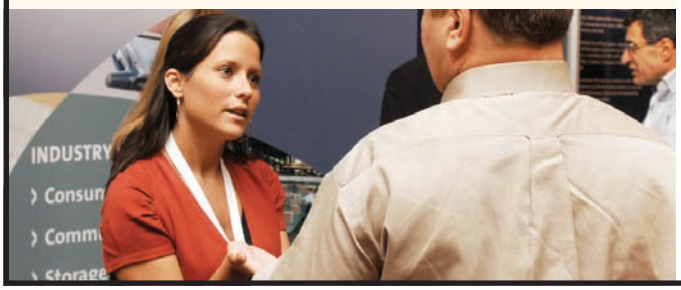


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### Monday August 24

***Server Systems I***
- NHM-EX CPU Architecture — **Intel**
- Innovation Envelopes: Hot Chips in Blades — **HP**
- Formula 1 Blade Computing with the AMD Magny Cours Processor — **AMD**

***Keynote 1*** **Jen-Hsun Huang, CEO**
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***I/O***
- The World's First USB 3.0 Storage Controller — **Symwave**
- 40Gb/s Optical Transceivers Implemented in 0.13µm SOI — **Luxtera**
- Intel's 5520 I/O Chipset for Server, Workstation, and High End Desktop — **Intel**

***Parallel Computing Centers***
- The Berkeley Parallel Computing Laboratory — **UC Berkeley**
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***Client Processors***
- Moorestown: The Innovation Platform for Next Generation MIDs — **Intel**
- Architecture and Development of the OMAP 4430 — **TI**
- ION: A Single Chip that Energizes Balanced PC Architectures — **NVIDIA**
- Intel Nehalem and Westmere: Transitioning into the Mainstream — **Intel**

***Panel*** **Technology Scaling at an Inflection Point: What next?**

### Tuesday August 25

***Computing Accelerators***
- Sun's 3rd generation on-chip UltraSPARC Security Accelerator — **Sun**
- Hybrid Computing - Xeon Socket-Compatible FPGA Architectures — **Nallatech, ArchES**
- Instruction Set Innovations for Convey's HC-1 Computer — **Convey Computer**
- SPARC64 VIIIfx: An Octo Core Processor for PETA Scale Computing — **Fujitsu**

***Keynote 2*** ***Rich Hilleman, Chief Creative Officer*** **Electronic Arts**
- ***Computers Making a Big Difference in the Games Business***

***SoCs and Clocking***
- PNX85500: A Single Chip LCD TV System with 120Hz HD Frame Rate — **NXP**
- IMAPCAR2: A Dynamic SIMD/MIMD Mode Switching Processor — **NEC**
- Car Navigation SoC With a 53.3 GOPS Image Recognition Engine — **Hitachi**
- New MEMS Oscillators for High Speed Digital Systems — **SiTime**

***FPGAs***
- Virtex-6 and Spartan-6 FPGAs — **Xilinx**
- Ultra Low Power FPGAs Fuel Mobile Application Features — **SiliconBlue**
- Stratix IV and Arria II FPGAs — **Altera**

***Server Systems II***
- Sun's Next-Generation Multi-threaded Processor - Rainbow Falls — **Sun**
- POWER7: IBM's Next Generation POWER Microprocessor — **IBM**
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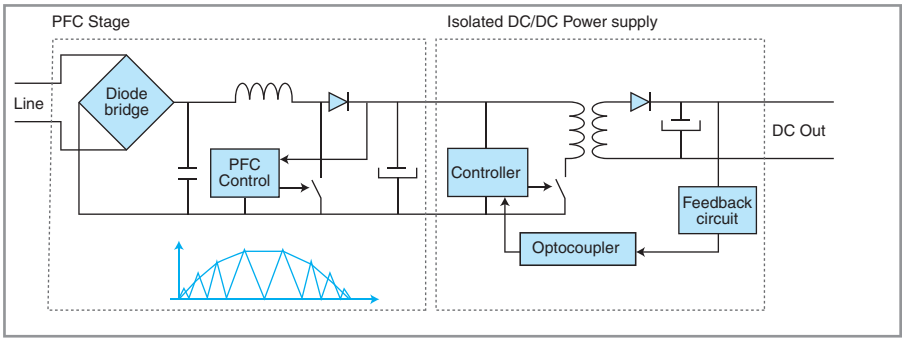


**Figure 6**—A PFC replaces the direct connection to the large ballast capacitor with a smaller capacitor followed by an intelligent boost converter, which then charges the ballast capacitor. The PFC controller modulates the switching element to mimic a resistive load, ensuring that the average current is proportional to the line voltage.

of this virtual resistance if the capacitor's voltage is too low or too high. Figure 6 depicts the overall architecture.

I'm sure you want a demonstration. STMicroelectronics offers dedicated PFC chips like the L6562A, which is an 80-W preregulator PFC single-chip solution. I bought the corresponding evaluation board and connected it to the aforementioned AC/DC board. I simply connected the PFC board's 400-V DC output to the output of the diode bridge on the AC/DC power supply board. That way the line voltage is first transformed to a high DC voltage, thanks to the PFC board, and then converted back to a low DC voltage through the AC/DC supply board used as a DC/DC converter. Photo 3 shows the setup. Switch on the line with a 15-W load on the output and the resulting waveforms are now a far cleaner pseudo-sine wave (see Figure 7).

The numbers are interesting. With the addition of the PFC stage, the real power increased from 19.2 to 22.8 W. This 18% increase is due to the PFC stage's efficiency which isn't 100%, especially with a low 15-W load on the output. The loss would be around 5% with a more typical 40- to 80-W load. However, this little increase in real power is counterbalanced by a drastic reduction in the apparent power—from 44 VA

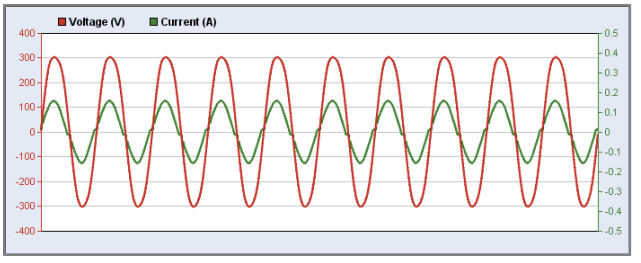


**Figure 7**—With the PFC circuit, the current wave form is drastically improved and very close to a pure sine. Some distortion is visible at the zero-crossing, but this is nothing compared to Figure 4.

without PFC down to 23.5 VA with PFC. Similarly, the power factor increased from 0.45 up to 0.97! Of course, the harmonic distortion also improved impressively.

## SHUT DOWN POWER

You won't need PFC in all your projects. However, you will definitively need to look at these solutions when you will build a power supply above 75 W. There are no other solutions to comply with the IEC regulations. Moreover, you will definitively need to optimize your line-powered devices in order to satisfy your customer, your regulator, and even the planet. I'm sure that linear AC/DC power won't exist is a couple of years.

I hope that you have a better understanding of line power issues, measurements methods, and constraints. Don't hesitate to play with these converters. High-voltage electronics is fun too. But once again, please be careful: 220/240 V is definitively dangerous, but 110 V is lethal too. And don't forget: capacitors stay loaded a long time.

*Robert Lacoste lives near Paris, France. He has 18 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.*

## RESOURCES

European Parliament and the Council of the EU, "Directive 2005/32/EC of the European Parliament and of the Council," *Official Journal of the European Union*, July 6, 2005, www.energy.eu/directives/l_19120050722en00290058.pdf.

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## SOURCES

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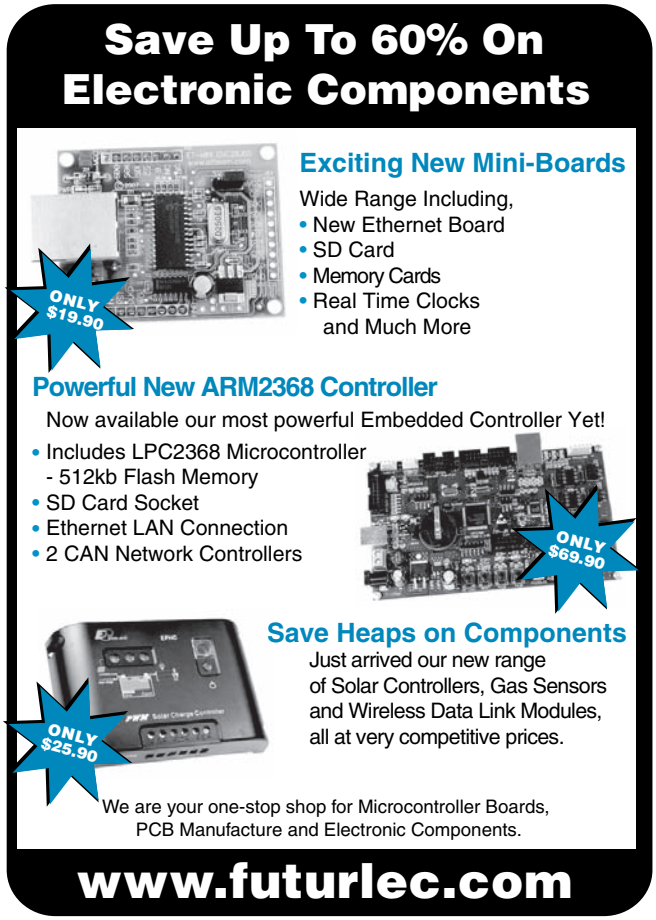
ALCIOM | www.alciom.com

**Fluke 43B power analyzer**
Fluke Corp. | www.fluke.com

**EVL6566B-40WSTB Board, L6562A PFC preregulator, and L6566B flyback controller**
STMicroelectronics | www.st.com



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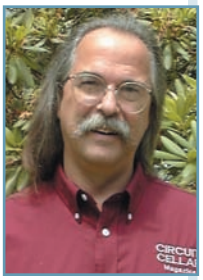

# Threat-Level Indication System

## Implement a Simple USB-to-Parallel FIFO Interface

Need an effective way to move data in and out of an embedded app? Check out how Jeff uses a USB FIFO IC to move information in his "threat-level indication system." It picks up information, sends it through the interface, and displays it via a parallel connection to color-coded stacking indicators.

When USB technology began to take hold, engineers were scrambling to learn how to use the new interface in their designs. With the legacy serial and parallel ports on the verge of extinction, any design that required them would soon be left without a mate. A few companies foresaw the panic and designed USB legacy interfaces. One of the first companies to do so was Future Technology Devices International (FTDI). A sigh of relief was heard from designers because this new design assured them that their equipment's lifespans would be extended without the need for in-depth knowledge of USB operation. The focus was on the serial interface, while the lowly parallel interface took a back seat—and it remains in the shadows even today. Thus, in this article, I'll shed a little light on the serial port's sibling, the USB parallel port. After covering some of the basics, I'll present an interesting design: a threat-level indication system (see Photo 1). You may not need a threat-level indication system of your own, but you can definitely put the technology and design techniques to good use. Get creative!

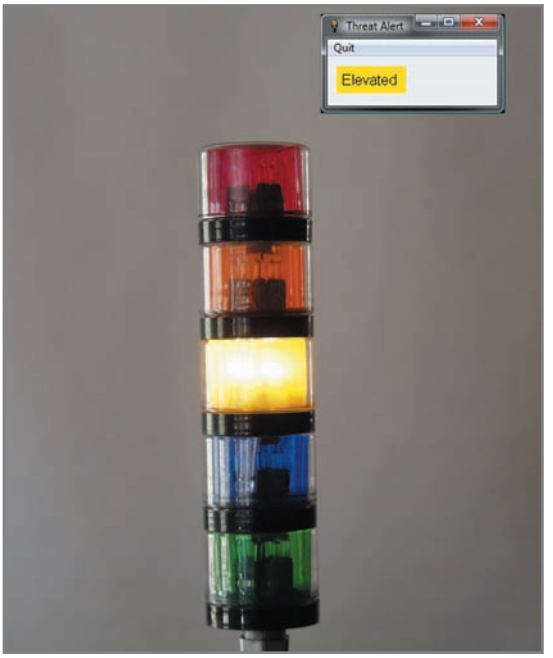


**Photo 1**—Since I started this project, the threat level has remained "Elevated." The small inset in the upper-right-hand corner is the application running in Liberty Basic on my PC. It queries the DHS web site to determine and display the present threat level (and it updates the project's interface via USB).

### USB-TO-PARALLEL FIFO

The FTDI FT245R is a USB-to-parallel FIFO interface that features the new FTDIChip-ID security dongle. Both asynchronous and synchronous bit-bang interface modes are available. A USB-to-parallel design using the FT245R has been simplified by fully integrating an external EEPROM, a clock circuit, and USB resistors onto the device. A unique number (the FTDIChip-ID)—burnt onto the device during the manufacturing process—is readable over USB, thus forming the basis of a security dongle, which can be used to protect customer application software from piracy. The FT245R is available in Pb-free (RoHS-compliant), compact, 28-lead SSOP (good for us prototypers) and QFN-32 packages.

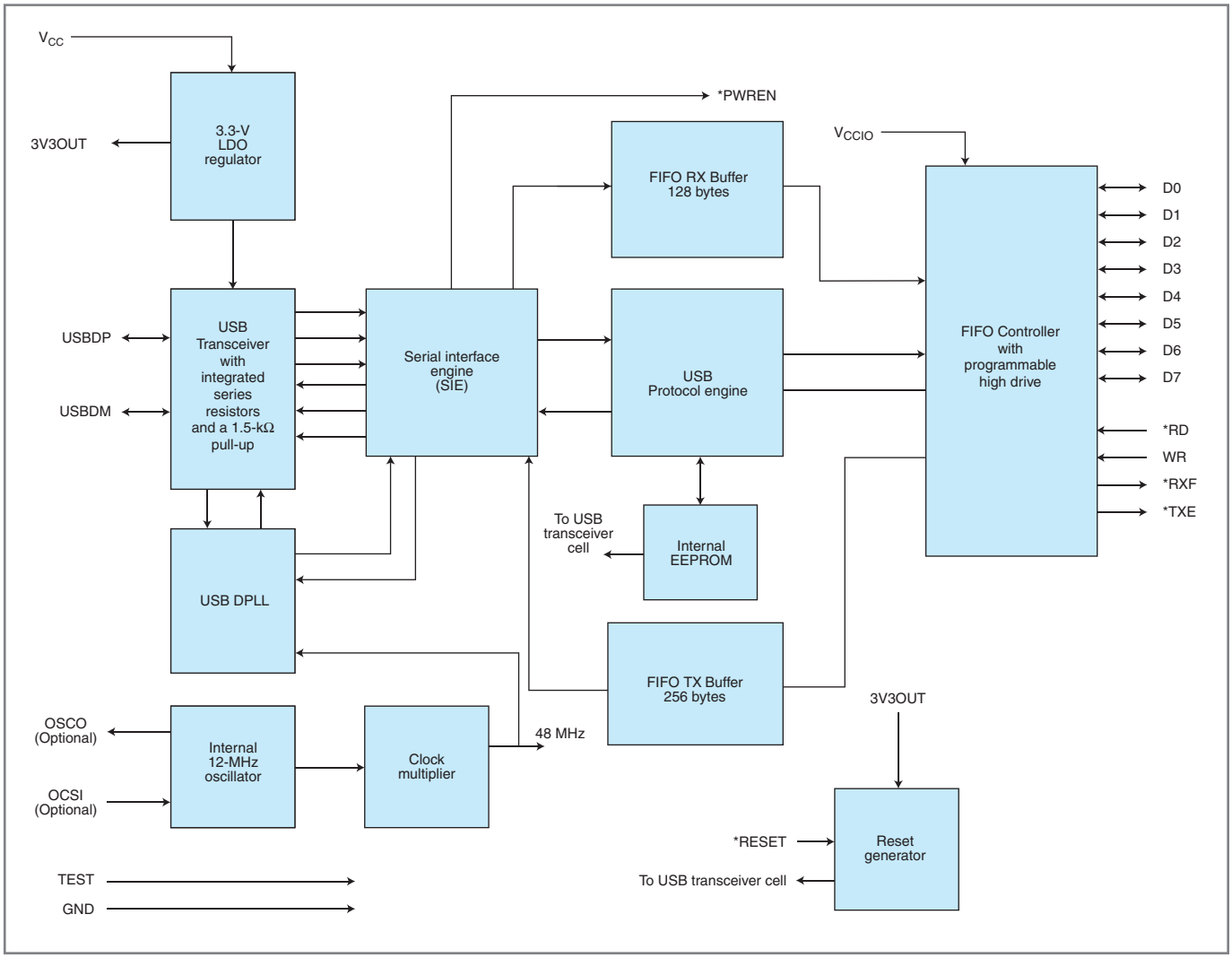


**Figure 1**—The FTDI245 has a few key components that are used to provide a USB interface to a peripheral device.

Just like with any USB device, you can get power directly from the USB bus, 100 mA maximum at power-up, or be totally self-sufficient using an external supply. You can use the FT245R in either mode with only a small number of peripheral support components for the interface support. While there are specialty drivers available to allow the interface to be used without connection to a higher authority (a microcontroller), adding a microcontroller enables you to use the standard COM driver available in Windows.

There are FIFOs for both receiving (128 bytes) and transmitting (256 bytes) paths. The serial interface engine (SIE) handles the internal USB transceivers and FIFOs. An internal 12-MHz oscillator and PLL create the necessary 48-MHz clock for full-speed USB connections. An internal 3.3-V regulator can supply 50 mA if your external circuitry will operate 3.3 V. Figure 1 shows what makes up this powerful little device.

Each of the FIFO buffers has handshaking to help keep the data out from interfering with the data in. On the output side, a low on the *RXF output indicates when the RXFIFO data is available from the buffer. You can read a byte of data from the buffer by pulling the *RD input low and then reading the value placed on the D0:7 before releasing the *RD input. On the input side, a low on the *TXE output indicates the TXFIFO can accept data. When you want to write a data byte, the WR input should be high when data is placed on D0:7. Lowering WR reads the data from D0:7. There is only 1 data port (8 bits), so this port must be shared by both input and output functions.

Let's take a look at the port's real interactions. The RXFIFO is read on the falling edge of the *RD input. As long as the *RD input stays low, D0:7 are driven outputs (up to 2-mA source or sink). Once *RD is released, the outputs are tristated and have light pull-ups (approximately 200 kΩ) to $V_{CC}$. D0:7 are sampled by the falling edge of the WR input. If this is done while *RD is low, you can essentially read back the data that just came out of the RXFIFO.

## OUTPUT DEVICE

To use the device as a byte-wide output device, you can program a Microchip Technology PIC12F508 microcontroller to handle the handshaking lines automatically. At about

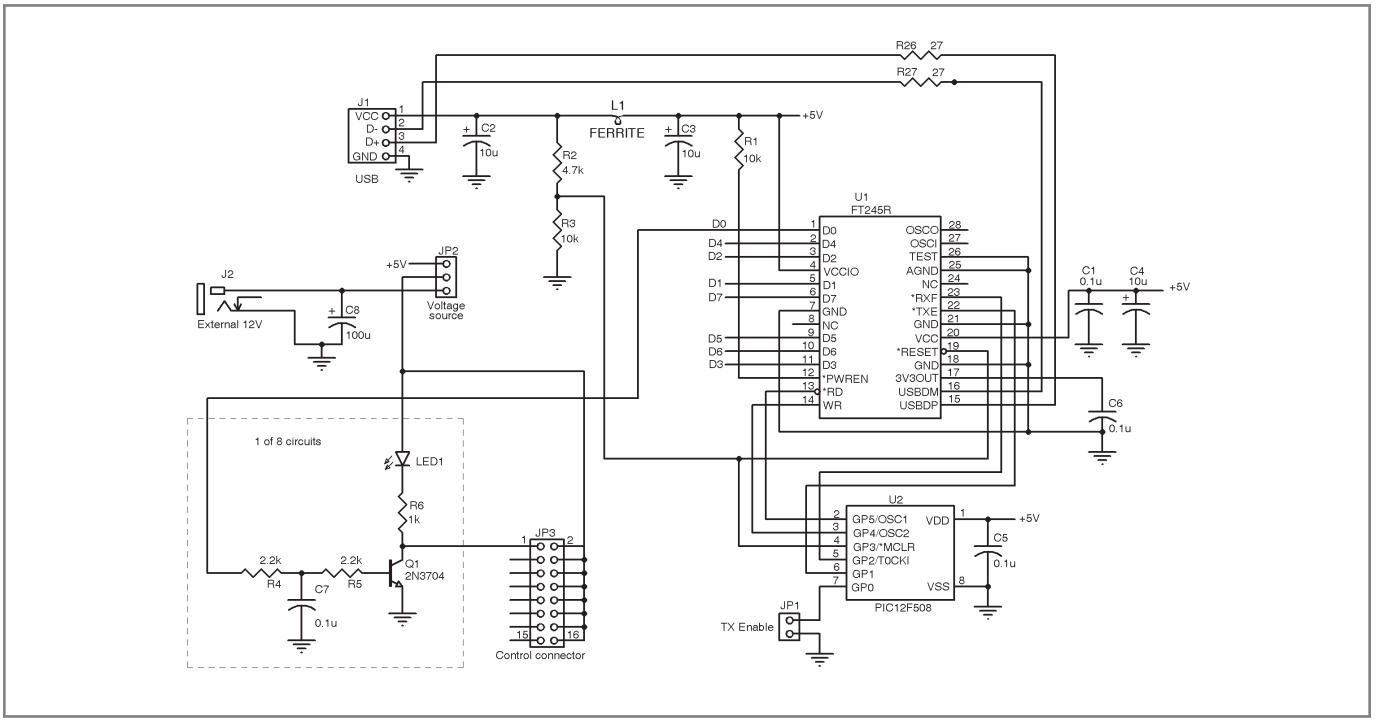


Figure 2—This minimum circuit allows control of eight output devices via a USB port. The digital output states can be read back as inputs through the USB port as well. Open-collector transistor outputs allow control of higher voltage devices such as relays or incandescent bulbs (used in this project).

$1 apiece, it doesn't make any sense to do this with discrete parts. Although you can use a PIC10F200 (four I/Os) for this application, the PIC12F508's extra two lines allow for some flexibility.

As you review the application in Figure 2, you'll notice only a single output circuit that has a small output filter before the drive transistor. While an LED is shown as a load, this might be a relay or other high-current device (higher-current devices may require an external power supply). If you remember the previous discussion, the output is not latched—that is, when the next byte is read (*RD goes momentarily high), the output tristates (and is pulled up). Although this might be less than 1 µs, you don't want any low output momentarily going high! So, the filter eliminates any really fast switching. Figure 3 shows this simple application.

## INPUT DEVICE

To use the design as a byte-wide input device is a bit more difficult because of the nature of the event. If the event is periodic, or if it has a singular point of request like a push button, it can be accomplished with the same circuit. The configuration jumper can be used as a push button input if that is the requesting element. Periodic sampling can be achieved with an internal timer that's used to initiate a sample at a fixed rate. The configuration jumper can enable/disable the function. As far as any data being received, it can be handled or just tossed out if it is not required. Note that you cannot use a split port—that is, some bits as output and some as input—without additional circuitry, which I'll cover later.

The inputs D0:7 connect to your circuitry through a series resistor to drive the data port high or low. The series resistor protects the port from trying to drive the same point with two sources—the external circuit and the output pin (when *RD is low). If your circuitry has a separate output for sample triggering, it should be connected to the configuration input. This application keeps *RD high (most of the time) so the data port is held tristated (with pull-ups). External circuitry drives D0:7 and the application takes care of sampling this data and transferring it to the TXFIFO either periodically or from an external request via the configuration jumper (determined by the application). Figure 4 shows the simple input application (with an optional timer for periodic samples).

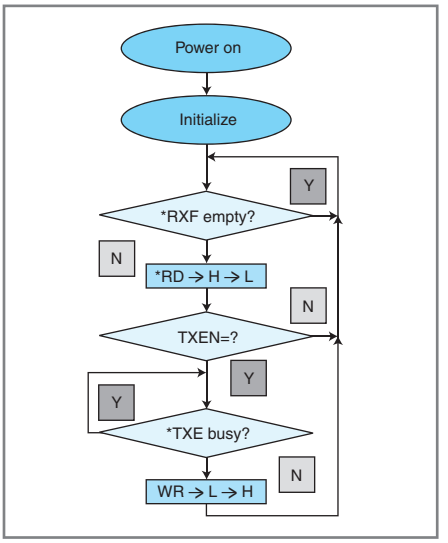


Figure 3—This application waits for data to arrive in the RXFIFO, transfers the data to D0:7, and holds the output drive active. If the configuration jumper calls for a read back, data will be transferred to the TXFIFO as soon as it's free. Otherwise, just skip transferring data into the TXFIFO.

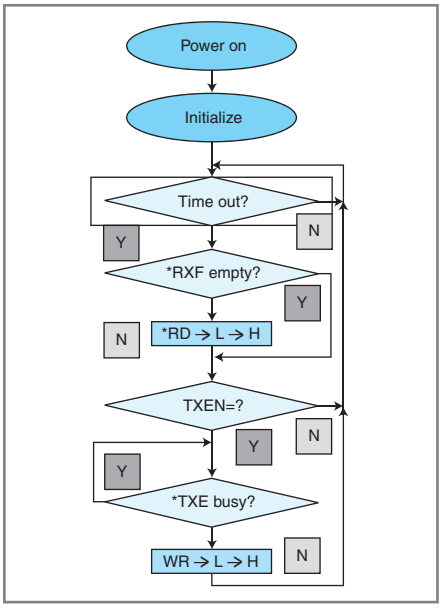


Figure 4—This application is for inputting data. The optional periodic "Time out" is necessary for circuits that cannot provide a sample trigger and must sample data on a periodic and continuous basis. Input data is sampled if received, but not used. This just keeps the RXFIFO from overflowing. The *RD strobe is such that the data port is kept tristated (except while *RD is low). Otherwise, if the configuration input (TXEN) requests data, it is sampled and transferred to the TXFIFO when the *TXE isn't busy.

## SEPARATING I/O

For more complicated applications requiring both input and output bits/bytes or multiple input triggers (e.g., many push buttons), it is necessary to add a larger microcontroller. The 40-pin PIC16F59 microcontroller (about $2 apiece) is adequate to break the I/O into multiple functions. Figure 5 is a general circuit that enables you to connect external circuitry in many configurations. Although the circuit divides the D0:7 of the FTDI245 into an 8-bit input port and an 8-bit output port, you have the flexibility to divide this any way you see fit.

Earlier I mentioned the necessity for a more complicated circuit when using multiple push button inputs. That's because each push button input needs to be monitored separately for a press and release (unless you're sending periodic data, but that requires the PC application to busy itself with a continuous stream of incoming data). With eight push buttons, the input byte's value can reflect the simultaneous status of all the buttons. You can use more than eight inputs; however, the sent byte will be defined as a separate value for up to 128 buttons (i.e., with push values of 0x00-0x7F and release values of 0x80-0xFF).

You can handle output data the same way—either with an output bytes value latched to a port directly or the value is interpreted as a change to one of the (up to 128) output bits. Note that this 40-pin part offers less than 30 I/O bits after the connection to the FTDI245. Larger or multiple parts would be needed for 128 I/Os.

When you design with a microcontroller instead of discrete logic devices, you end up with a flexibility that you can't get with individual logic devices. You can change how the circuit functions internally by reprogramming the firmware. Although there are small delays in the functions due to the in-line processing nature of microcontroller code, you won't notice it in most real-world applications.

## THREAT-LEVEL APP

Prior to September 11, 2001, global terrorism was not a major concern to most people living on U.S. soil. Things are a bit different today. We still welcome legal immigrants with open arms, but we pat down each traveler as he or she arrives. Another precautionary measure the government uses is to alert the public of threats by adjusting the national threat-level indicator to the present situation. (I have to admit that I like this approach much better than the government sounding a warning siren so people can hide under their desks.) The Homeland Security Advisory System involves a five-level, color-coded, "threat condition" indicator. There are five colors, ranging from green (low risk) to red (high risk). Each

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threat condition is meant to elicit an appropriate response from the government, industry, and public in the face of danger. When the risk is low, people should remain relaxed yet aware. When the risk is high, emergency response personnel and specially trained state and federal employees are dispatched to protect the public.

You can check the current threat level at the Department of Homeland Security's web site (www.dhs.gov). I recently combined this information with my new ability to control external objects via the USB port to create what I call "The FTB Threat-Level Indication System." I've already covered the control portion of the technology, so let's focus on the input and output portions of the project.

## THREAT LEVEL I/O

The Department of Homeland Security presents five threat-level choices (www.dhs.gov/xinfoshare/programs/Copy_of_press_release_0046.shtm). The sentence structure remains the same for every announcement: "The United States government's national threat level is XXXX, or YYYY." For example, XXXX can be the word "Elevated" and YYYY can be the word "Yellow." I use this fact to automatically determine the threat level by searching for this text in the HTML page. While I would like to create a widget or customized notification icon for this, I'm leaving it for another column (based on your input). Let's just focus on building a quick application using Liberty Basic.

One of the handy commands available in Liberty Basic is the ability to use Internet Explorer to go to a web address and save things like files and graphics. For this project, the application periodically captures and saves the HTML page that displays the threat-level announcement. The application searches through the page and looks for the text of interest. In this instance, the file search is for the string "Threat level is." The text following this string should be the word of interest: Low, Guarded, Elevated, Severe, or High.

Once the application determines a threat-level change, it sends this change as a byte value to the USB port. The first 5 bits are used to indicate the current threat level with the least significant bit (D0) as the lowest threat and bit 4 as the highest threat level. Although this could be handled with only 3 bits, it makes more sense to treat each output as a separate bit. This reduces any extra computing for the USB device and also allows more than one output to be enabled at a time for testing purposes.

## THREAT LEVEL INDICATION

After acquiring the present threat level, I send data through the USB interface. Data might be displayed as text on an LCD or a value on a large seven-segment display. Instead, I used a more identifiable interface: a stack of colored lights. Since the colored stack matches the color codes used in the threat level, this is easily identifiable from both a color and position point of view. You've seen this kind of light used in supermarkets and industrial environments.

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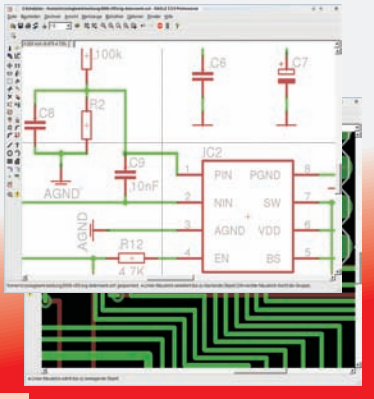

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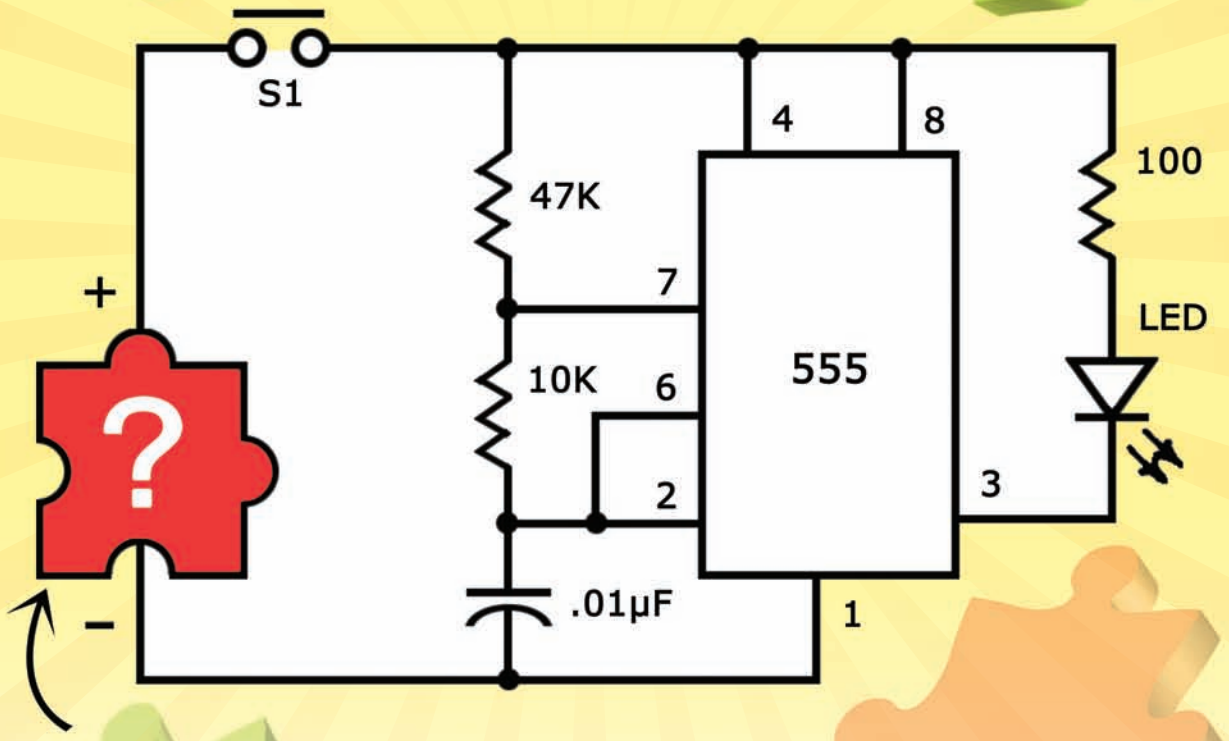


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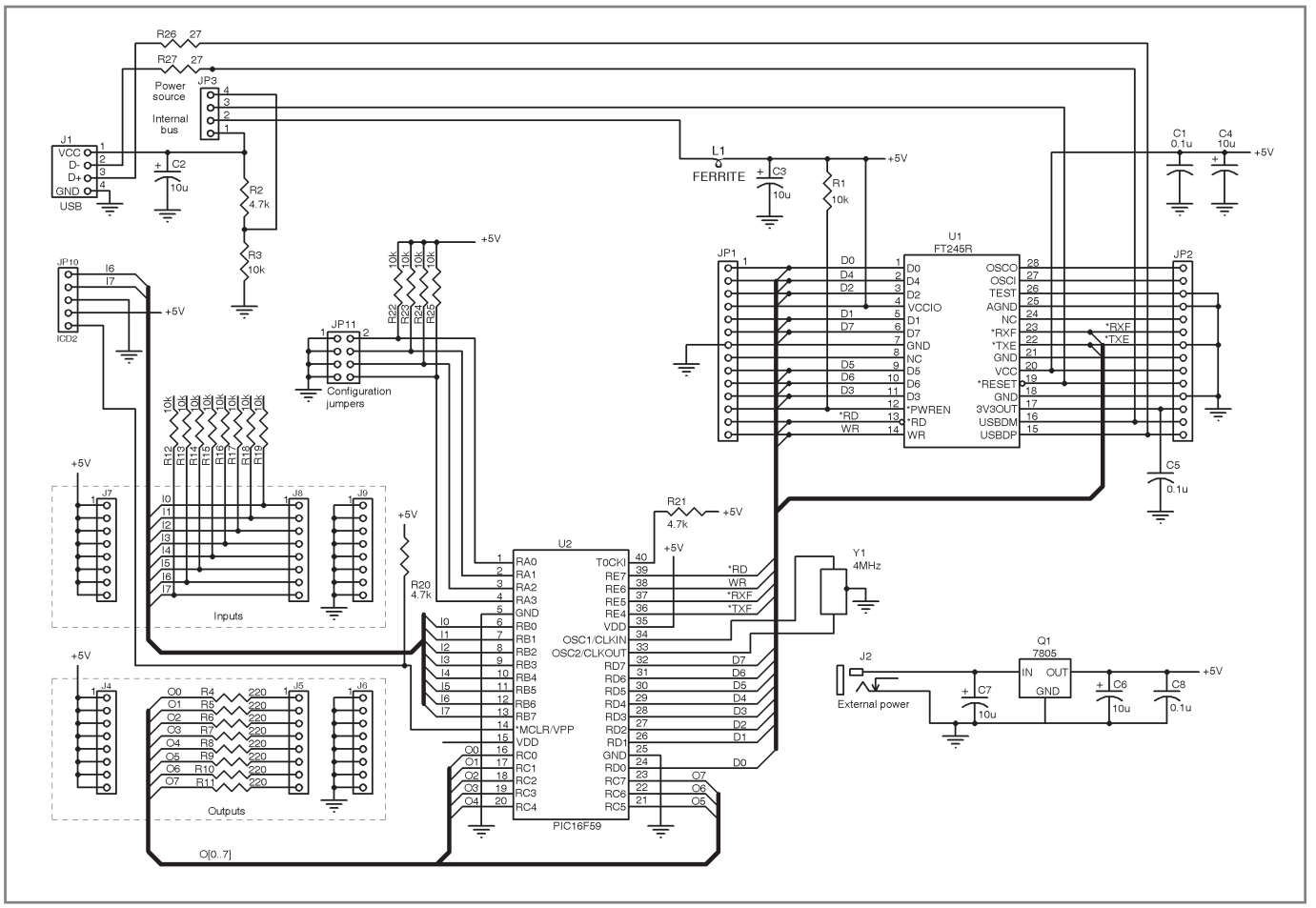



**Figure 5**—Using a larger micro (more I/O pins) allows the input/output data to be directed to and from discreet I/O pins. This general-purpose circuit provides eight input and eight output bits. Advantages of this circuit include the ability to trade-off additional inputs for outputs and vice versa. In addition, the microcontroller can monitor inputs for change of state, which can then trigger an input data exchange.

I gathered a number of useful items available from various local establishments. An electrical conduit connector is shown in the center-left portion of Photo 2. It came in a bag of five, and I cut off the conduit flange on four of the pieces (seen center-right). I found the easy-to-stack plastic jars in the spice aisle at the supermarket. Along the front is a piece of transparent colored vinyl (the five colors I needed were available). I bored 0.75″ holes through each jar's bottom and lid. The threaded conduit connectors hold the bottom of a jar to the top of a cap. I attached the fifth flanged connector to a lid and it became the bottom of the stack. I cut a strip from each piece of vinyl to line the inside of each jar to provide tinted light output. I simply screwed each jar upside down to the previous cap to create the stack and the stack mounts to the top of a piece of conduit (cut to an appro-

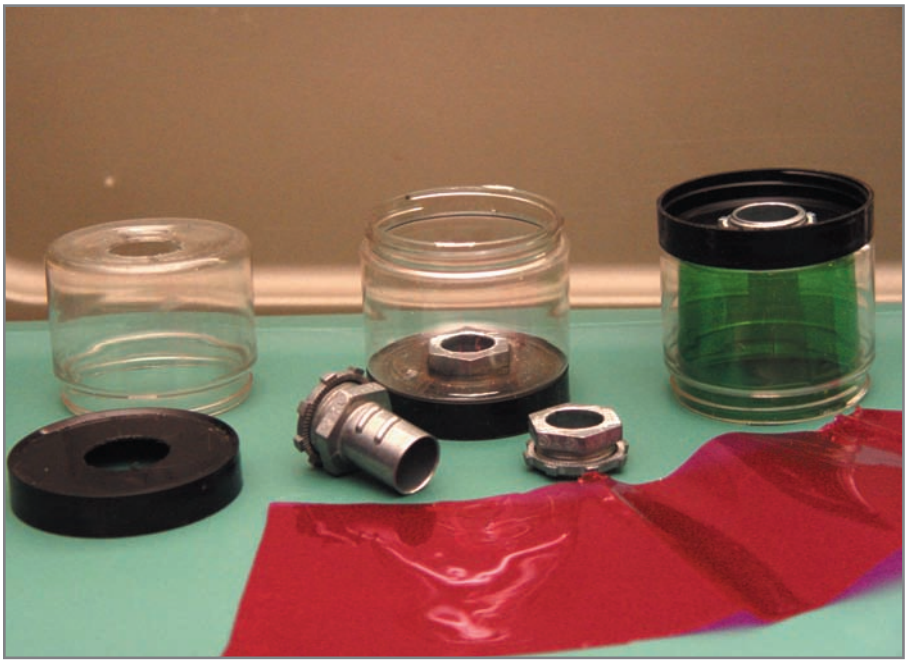


**Photo 2**—You can stack large color indicators to reflect the threat levels. As you can see, I used ordinary containers I found at the supermarket. I chose these herb containers for their size and stackability.

priate length).

Now for some lights. Merry Christmas! Nearly every string of holiday lights has at least one that doesn't work due to a blown lamp. Most people just toss them out instead of trying to locate the bad bulb. Fortunately, I saved my last string, which had 4-V incandescent lamps. I ran these with 12 VDC, so sets of three worked well and could be paralleled for higher output levels. Refer to the center-left portion of Photo 3 to see a conduit connector with a short piece of plastic inserted into its hole. This is a 0.5" plastic water pipe union. I used this union as a base in which to hot glue nine lamp sockets. The leads of each of three sets of three sockets are soldered together (with heatshrink tubing on each joint) along with a long pair of color-coded power leads and fed through the center of the plastic union. The union fits back into the conduit connector, which was previously assembled to a cap (and jar). The finished assembly (one of five) is located on the far right. The power leads from each assembly are fed down through the center as you assemble the stack beginning with the top of stack (red). All of the color-coded power pairs extend out the bottom of the conduit (pole) and can be connected to the aforementioned transistor drive circuitry.

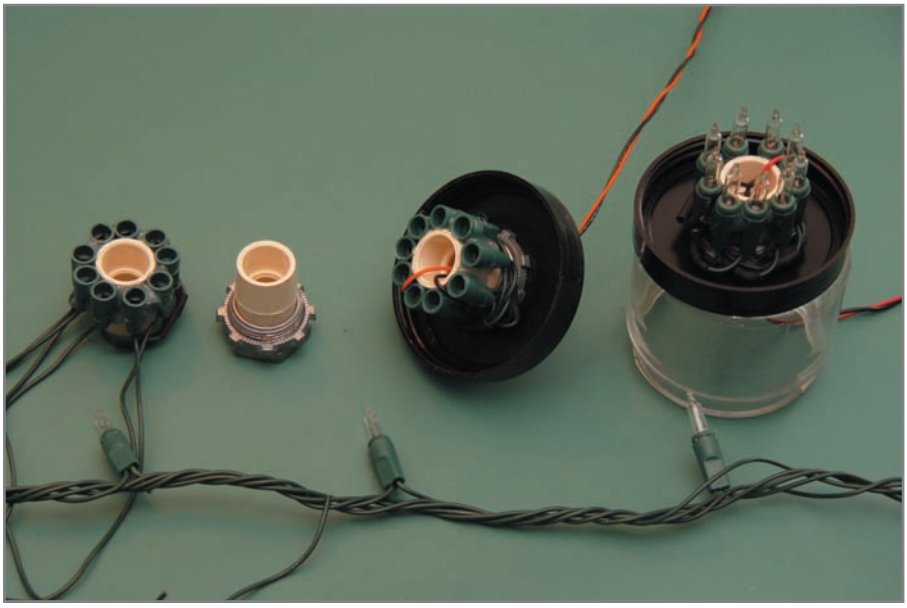


**Photo 3**—A broken string of 4-V holiday lights became the source of light for the 12-V indicators. I used hot glue to tack nine of them around a plastic union. A pair of wires from each module is fed down through the center of the unions to the interface located at the bottom of the mounting conduit.

## ON GUARD

Now that the project is finished and working as my own vigilant sentry, I feel like I am an active participant in the Homeland Security Network. So now it's your turn to add the FTDI245 to your library of interfacing tools. You never know when a bit of stored knowledge might be just the piece required to simplify a new app.

While building this project, I couldn't help but think of alternatives to the original design. Colored bulbs would eliminate the need for colored filter material or even replacing the incandescent devices with solid state LEDs. After hand-wiring the strings of bulbs and gluing them into modules, it became apparent that a PCB would be a labor-saving improvement.

The DHS also has a separate threat level for domestic and international air flights. This information is available on the same web page as the national threat level. You can easily change the search criteria and use this application to reflect that information if you desire. One of the links on this site lists luggage restrictions, a good thing to review before any air travel. Of concern is a ban on items such as gel shoe inserts and snow globes. Go figure.

While we cannot prevent terrorist activities or natural disasters, it helps to acknowledge that they exist and how they might affect the public as well as our infrastructure. Raising public awareness also spearheads reaction plans that can help minimize the effect of a disaster and quickly return us back to normal. This project proves a regular citizen like me—who just happens to have an interest in embedded design—can use his creativity to contribute to this effort.

*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 code, go to ftp://ftp.circuitcellar.com/pub/Circuit_Cellar/2009/229.

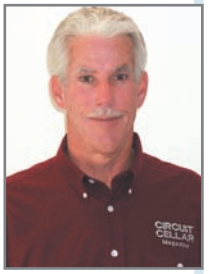
## SOURCES

**FTDI245 USB FIFO IC**
Future Technology Devices International | www.ftdichip.com

**PIC12F508 and PIC16F59 Microcontrollers**
Microchip Technology, Inc. | www.microchip.com

**Liberty BASIC IDE and language**
Shoptalk Systems | www.libertybasic.com

by Tom Cantrell



# Thin Is In

## High-Profile Energy in a Low-Profile Package

Tom returns to the topic of energy harvesting with a focus on new "micro-energy cells." Get ready to learn how the convergence of advanced battery technology, alternative energy, and nanopower silicon will change the way you design forever.

It's true the latest and greatest silicon is so power-efficient that a disposable battery can last months or even years. But with all the talk of "smart dust" networks comprising thousands of nodes, the prospect of having to replace the batteries, ever, is simply a nonstarter.

This month, the energy-harvesting saga continues courtesy of a new startup, Infinite Power Solutions (IPS). They've been painting the town red (er, green) and generating a lot of buzz with their "Thinergy" lithium batteries. Oops, IPS says what they offer is no mere "battery," but rather a "Micro Energy Cell" (MEC). Marketing machinations aside, read on and I think you'll agree that whatever they call it, IPS is definitely bringing something to the party.

### POWER STAMP

The IPS MEC might best be described as a power "stamp"—that is, at just 1" on a side, it's about the size of a postage stamp, as is apparent in Photo 1. What's less apparent, but more impressive, is the thickness, or rather lack of it, at just 170 µm (less than 0.01"), little more than a paper postage stamp. That means you could stack two or three MECs and still have headroom on a typical surface-mount PCB. Indeed, IPS offers just such two and three cell stacks, and half-size versions (i.e., 0.5" × 1.0") of the MEC cell/stacks as well. I suppose you could even laminate MECs inside credit cards, PCBs, solar panels, and so on for the ultimate in permanent power.

Capacity is impressive at up to 1 mAH (700 and 500 µAH units also available). But besides cramming a lot of energy into a little space, what sets the MEC apart is that it delivers said energy with gusto. Even the "standard" MEC can deliver a whopping 30 mA continuously while a "performance" version boosts that spec all the way to 40 mA.

As usual with battery specs, there are caveats only uncovered by a closer look at the datasheet. Referring to the discharge graph in Figure 1, you can see higher currents reduce both capacity and the output voltage. The headline specs (e.g.,

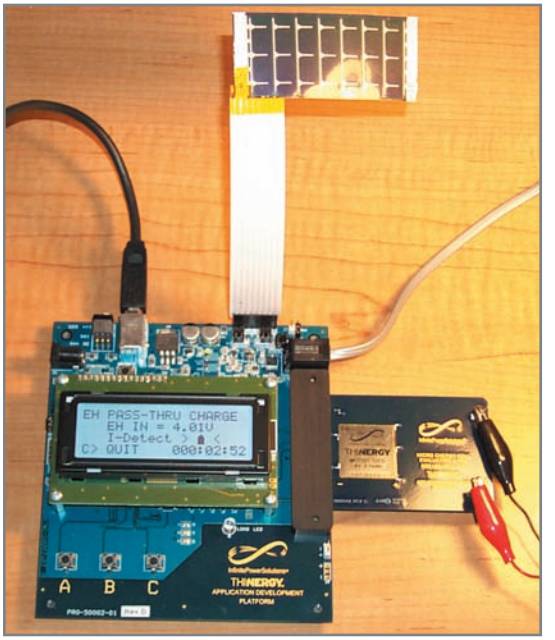



**Photo 1**—Here you see the ADP kit in action with the amazing IPS "Micro Energy Cell" soaking up some rays, and electrons, from the attached solar panel.

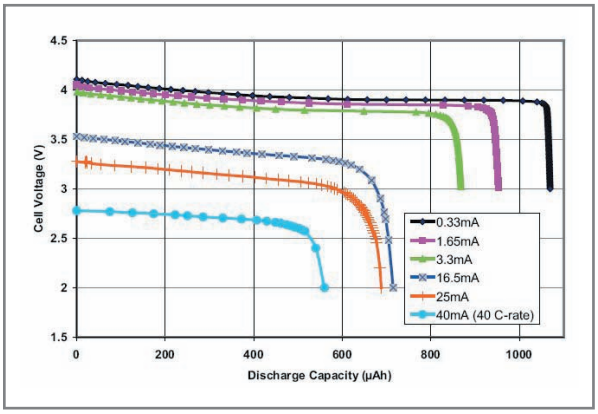



Figure 1—The IPS "Micro Energy Cell" can deliver up to 40 mA continuous, more than enough to power-up the latest generation of nanopower silicon.

3.9 V and 1 mAH) are only guaranteed for discharge at a "C/2" rate (i.e., capacity divided by 2 is 500 µA for a 1-mAH MEC). The voltage drop associated with higher currents would seem problematic, but the selection of low-voltage MCUs grows day by day. It's common to find 3-V devices with a wide (e.g., 2.4 to 3.6 V) operating range and parts that run at even lower voltages (down to 1 V and less) are becoming available. However, like other lithium batteries, you don't want to run the MEC down until the gas gauge is resting on "E." The datasheet advises that you should cut off the load once the cell voltage falls below 2.1 V lest problems (i.e., reduced performance or battery damage) occur.

Perhaps more significant is the influence of temperature. The good news is that the MECs are specified to operate over a full –40° to +85°C temperature range, which is wider than the "commercial" temperature spec (e.g., 0° to 70°C) of many batteries. The bad news is that output current is severely limited at lower temperatures (see Figure 2). This is a challenge, and opportunity, for designers to get creative. Are there ways to capture and utilize ambient or generated thermal energy to heat the battery? How about a goose-down comforter for your circuit board?

Anyway, as long as the MEC is kept above freezing, it's clearly feasible to pull tens of milliamps—a power budget which goes quite a ways these days. For example, rough calculation shows a 1-mAh MEC can run a 25-mA, 3-V load for a minute or so (at 25°C). These days, many MCUs consume a mere 1 mA/MHz or less. Running a 25-MHz MCU for a minute gives you 1.5 billion clock cycles to play with, more than enough to do something useful.

Charging the MEC is simply a matter of providing 4.1-V constant voltage, with a recharge taking maybe 10 minutes or so. According to the datasheet, the MEC can draw up to 10-mA peak during charging, and you don't need to otherwise current-limit the charging source. The datasheet points out how eagerly the MEC will gobble up even the tiniest scrap of energy you toss it (e.g., as little as 1 µA at any voltage above the cell voltage).

The MEC is good for up to 10,000 recharge cycles under favorable (temperature, discharge rate) conditions. It also ages very gracefully with standout self-discharge and capacity loss specs of just 1% per year. The MEC is truly capable of delivering a lifetime of service measured in decades.

And what with "exploding laptops" and all, lithium battery safety concerns always lurk in the background. The datasheet speaks directly to the issue when it says there is "no possibility for chemical leakage, thermal runaway, or fire."

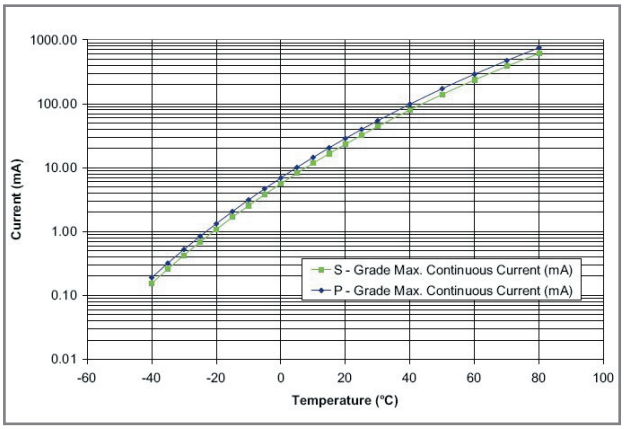



Figure 2—One caveat for extended temperature applications is that output current capability is very dependent on temperature, varying by a factor of 1000 over the –40° to 85°C operating range.

## CHARGE CARD

Being a high-falutin journalist and all has its privileges. Like the writer for a car magazine who gets to drive a Ferrari, right now I'm playing with the loaner IPS Application Development Platform (ADP) shown in Photo 1. Few of you will ever have the chance given the unit's $3,000 (!) price tag. Not that there's anything that special about the hardware itself. Rather, the premium price tag reflects the reality of a starting up a new company by helping to offset up-front engineering costs and keeping the focus on serious customers willing to pay to play. If you've got $3,000 burning a hole in your pocket (or your use-it-or-lose-it department budget), the ADP kit is a quick and easy way to get started.

Maybe later, once the ball gets rolling, IPS will cut the ADP price tag. But even if you never get your hands on an ADP, it's worthwhile to follow along as I put it through its paces. Seeing it in action yields insight on the challenges of going green and will give you some ideas for moving forward with your own "Batteries Included" design.

The ADP block diagram in Figure 3 shows an MCU fronted with an LCD and button user-interface that controls and monitors on- or off-board loads and charging circuits. There's a USB connector, but it's just used as one of the options (the other being a wall-wart) for powering the board. Instead, data monitoring and logging is supported via an RS-232 connection (e.g., a PC COM port and terminal emulation program). Sure, it seems a little goofy. Why not use the USB port for both power and COM port emulation? On the other hand, the dedicated RS-232 port could be useful for monitoring activity with something other than a PC (e.g., an MCU or SBC).

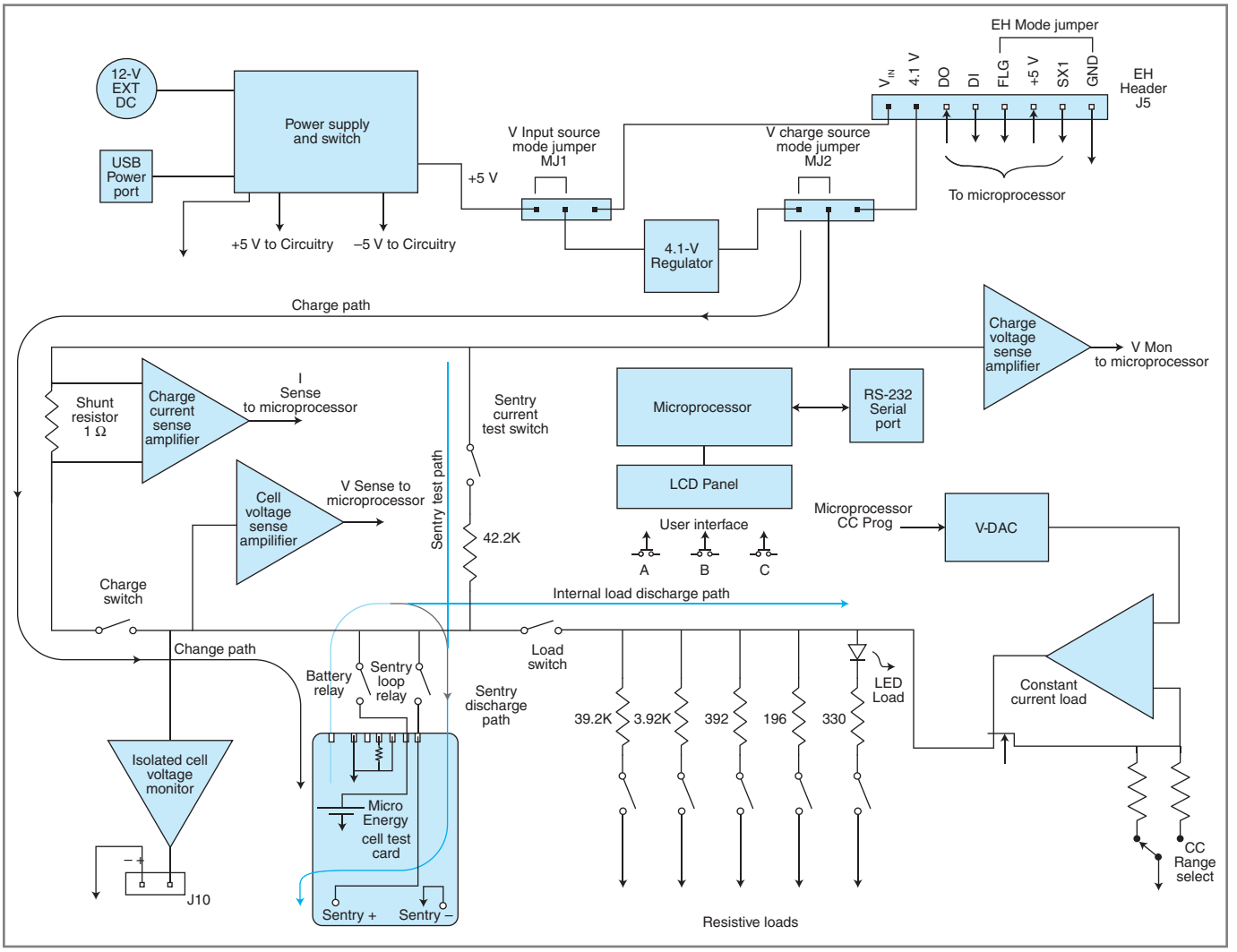



Figure 3—The ADP kit features integrated test loads, short-circuit and over-discharge protection for the battery, and an RS-232 port for monitoring battery status.

The MEC's thin-is-in, tin-foil-like construction requires a steady hand and good eye to solder properly to a PCB. There's just a tiny, and I mean really tiny (0.5 mm, 0.020″), lip along either side for + and – connections. IPS offers MECs with lead wires preinstalled, a helpful option for prototyping.

The IPS kit takes MEC packaging one step further with the battery mounted on a credit card-sized carrier card that slides into the connector on the right side of the ADP board. The card makes it easy to swap batteries without fumbling around and shorting something out.

Actually, the MEC card is more than just a carrier. The battery isn't directly connected to the + and – pins on the end of the card where you attach your load. Rather, the ADP board hooks directly to the battery on one pair of connections and drives the load + and – pins with another. This allows the ADP board to act as a "sentry" to oversee and protect the battery. For instance, the ADP monitors the battery voltage at all times, and when it drops below 2.1 V, automatically disconnects the load to protect the battery from over-discharge. As an additional precaution, when an MEC card is inserted, the ADP first tests the load on the + and – pins to make sure nothing is amiss (e.g., it's not shorted) before bridging in the battery connection. Do note that excessive load capacitance (e.g., greater than 1 µF) can fool the ADP board into thinking the output is shorted.

On the upper right of the ADP board is an 8-pin "Harvester" connector (see Figure 4) for you to experiment with your own energy scavengers. You have the option of supplying the 4.1-V MEC charging voltage directly on pin 2, or providing a higher voltage (pin 1, up to 7.2 V), which is regulated on the ADP board. Pins 3 and 4 aren't currently used, but they are reserved for a future digital serial "intelligent" interface between the ADP board and an external harvester. Pin 5, when connected to ground, is simply a flag that lets the ADP firmware know that an external harvester is connected. Pins 6 and 8 output power from the ADP 5-V supply. Pin 7 is an active-low trigger input that allows external logic (e.g., harvester electronics, mechanical switch) to tell the ADP board when to initiate a charging cycle.

## DEMO MEMO

Firing up the ADP kit and hitting the button for Demo, I found a variety of routines for exercising the MEC

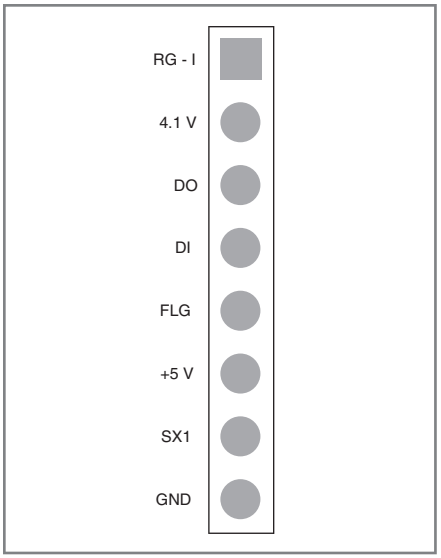



Figure 4—The "Energy Harvesting" port lets you test your green design ideas by adding external power sources, either regulated (pin 2, 4.1 V) or unregulated (pin 1, up to 7.2 V).

using the ADP's built-in dummy loads including variable current, resistance, and an LED. To mimic the intermittent activity of energy-harvesting apps, there's pulsed-load mode with variable period, but the duty cycle is fixed at 20%. That's pretty limiting and indeed not very realistic because many designs, notably wireless sensors, will have much lower duty cycles (e.g., wake up to do something for 100 ms every 5 seconds = 2% duty cycle). Of course, you can simulate a different duty cycle by changing the dummy load in proportion (i.e., reduce load by 10× to approximate 2% duty cycle). Just remember the actual capacity and output voltage varies depending on the load, so a simulated duty cycle isn't a perfect solution.

While the demos are running, the ADP dumps voltage and current readings out the serial port where they can be monitored and captured by a terminal emulator running on your PC. I'm no spreadsheet expert, but I was able to manhandle the data (i.e., use Notepad to strip the spreadsheet-unfriendly "V" and "µA" text from the numbers) in order to generate some illustrative graphs.

The "Rapid Recharge" demo highlights the willingness of the MEC to spew electrons and, just as happily, suck them back in. The discharge is accomplished with a healthy 10-mA load, which the MEC happily shouldered for a full 3 minutes. Let's see, that's one-twentieth of an hour at 10 mA, which means the 0.7-mAH MEC actually delivered only 0.5 mAH, a real life example of the relationship between capacity and discharge rate shown back in Figure 1.

When capturing and graphing the data during the recharge cycle (see Figure 5), I noticed the charge current peaked at less than 4 mA. This is nowhere near the up-to-10-mA spec in the datasheet, which probably applies to the worst case of a fully discharged or damaged battery. Or perhaps the current is actually limited by the ADP, but there is no mention of that in the documentation.

The tail end of the recharge curve yields an important application insight. You might be tempted to just use the MEC open circuit voltage to determine when to terminate the charge cycle. But that approach can leave a lot of milliamp hours on the table (i.e., unused capacity). Fact is, MEC continues to accept charge, topping off the tank long after it appears "full" in terms of output voltage.

The most accurate way to terminate a charge cycle is to look for low absolute charge current. Consider that even though the MEC cell voltage reached 4.1 V after just 5 minutes on the charger, the battery was still thirstily downing over 2 mA at that point! It took more than 10 more minutes to fully recharge the MEC during which time the charge current slowly declined. The ADP firmware finally terminated the charge cycle when the current dropped below 50 µA. Note that the datasheet calls for a 10-minute recharge time, but that's just to 90% of capacity.

After running through the various demos, I punched the key for Sentry mode (see Photo 2). As I described earlier, the ADP sanity checks the external load and, if it's deemed acceptable, bridges the battery to the power connections on the edge of the card. I hooked up a 10-kΩ pot as a variable dummy load and started Sentry mode. I noticed the data sent out only the serial port included the battery voltage, so I connected a meter to monitor the load current. Just for kicks, I cranked the pot down to induce an overload. As advertised, the ADP countered by refusing to connect the battery to the load. Similarly, once the battery was connected, an overload caused the ADP to disconnect the load, albeit with a misleading "MEC discharged" message. The battery wasn't really discharged, but the ADP interpreted the voltage drop from the excessive current draw as such (it tripped at about 40 mA). In any case,

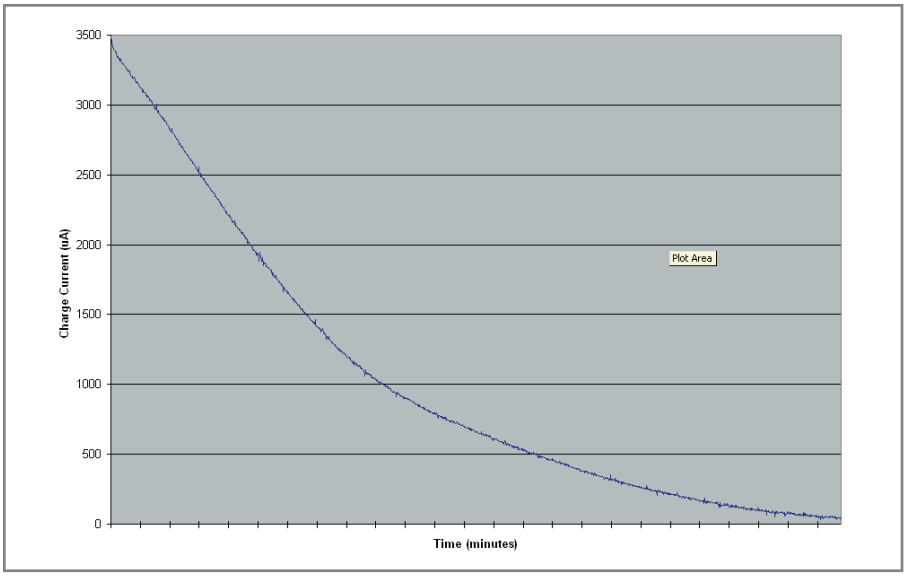



Figure 5—Like a sponge, a "dry" (i.e., discharged) MEC soaks up a lot of juice (i.e., current) at first. But don't make the mistake of cutting off the tail of the charging cycle prematurely. The datasheet recommends continuing until the charge current drops to 50 µA.

Photo 2—The MEC lives up to the claims in the datasheet. It delivers tens of milliamps without breaking a sweat—more than enough juice to power-up some pretty fancy silicon.

the "Sentry" did its duty to protect and serve.

Switch a jumper and plug in an alternative energy source and the ADP fires up in "Energy Harvesting" mode. Operation of the ADP doesn't change much in terms of the aforementioned demo routines, Sentry mode, and so on. The major difference is that now the power source for recharging the MEC is the external harvester rather than the ADP board's own power supply (i.e., the USB port or wall wart).

The folks at IPS kindly sent along the homebrewed solar panel you see back in Photo 1. I say "homebrewed" because they lined up some solar cells in series to get the proper voltage. You can also see the leak-stopper diode hacked into the flex cable near the eight-pin EH connector. Without it, the battery would leak down under low light conditions (i.e., when the battery voltage is higher than the panel voltage).

Using a desk lamp as a surrogate sun, I found the solar panel could deliver about 1.5 mA, enough to fully charge the 0.7-mAH MEC in less than half an hour. I captured the ADP serial port data log to generate a graph illustrating a hypothetical day in the life of a solar harvesting setup (see Figure 6). Overnight, the battery runs down, but as the sun rises, it begins to carry the load and the battery voltage stops falling. Around midday, enough surplus energy is generated to both run the load and recharge the battery for the next night's work.

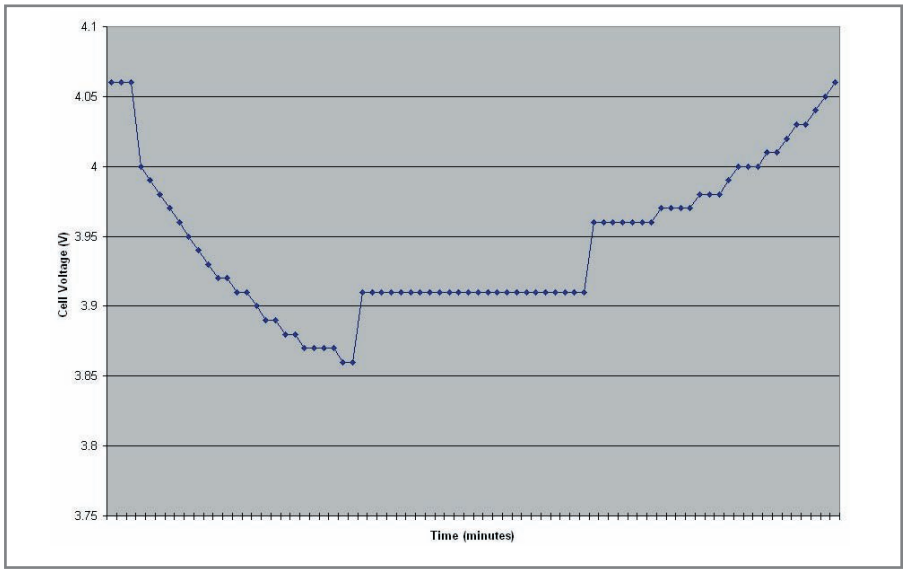



Figure 6—The classic solar energy-harvesting profile looks something like this simulation (i.e., run down the battery overnight, charge it during the day, and repeat … forever).

## POWER UP

The convergence of advanced battery technology, alternative energy, and nanopower silicon is a compelling one for designers. Obviously, it will spawn a dust storm of wireless sensor gadgets (I call 'em "wadgets"). Technology like the IPS MEC cries out for even more outside-the-box thinking. Or make that inside the box. Or laminated inside the PCB. Or, for that matter, why not buried inside the chip?

One of the most challenging design aspects is harvester electronics. Efficiency is critical since the power consumed by the harvester itself represents a fundamental limit for applications. At the same time, flexibility to handle a myriad of "crops" (i.e., energy sources) helps to boost volume and cut cost.

As I write this, IPS is getting ready to announce an integrated harvester and battery solution, the "Micro Power Module" (MPM). The MPM combines MEC(s) with an ultra-efficient "Passive Power Management Unit" said to accommodate a wide-range of sources (AC and DC) while consuming only 3-nA quiescent current. Make sure to check their web site for the latest on what's essentially a UPS for embedded apps.

The IPS technology represents an intriguing alternative for "Batteries Included" designs. The packaging options present both a challenge, and opportunity, for designers to get creative. Green is the new black, and thin is definitely in!

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

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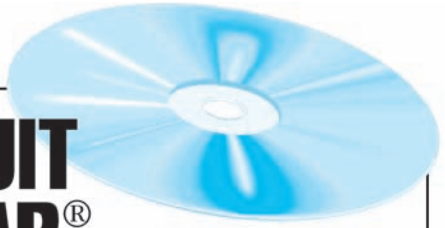

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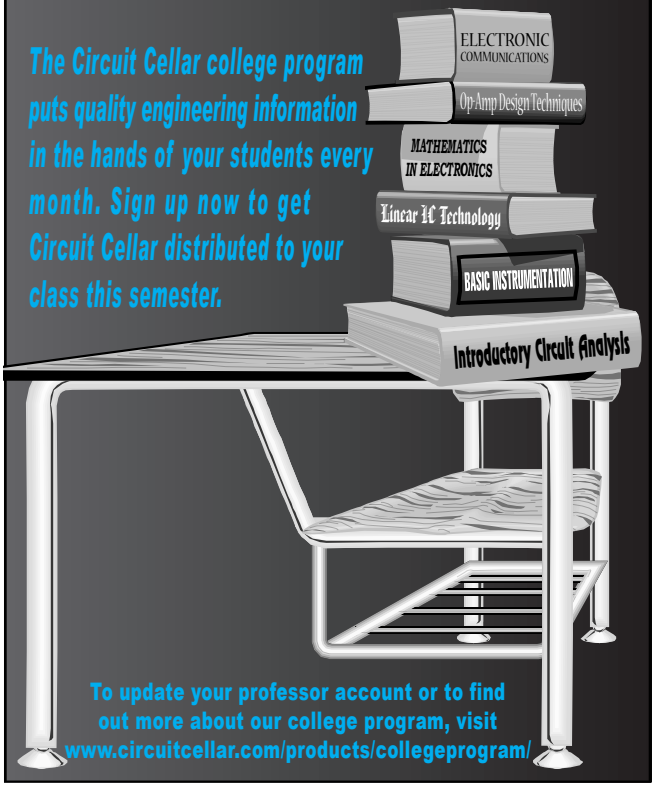


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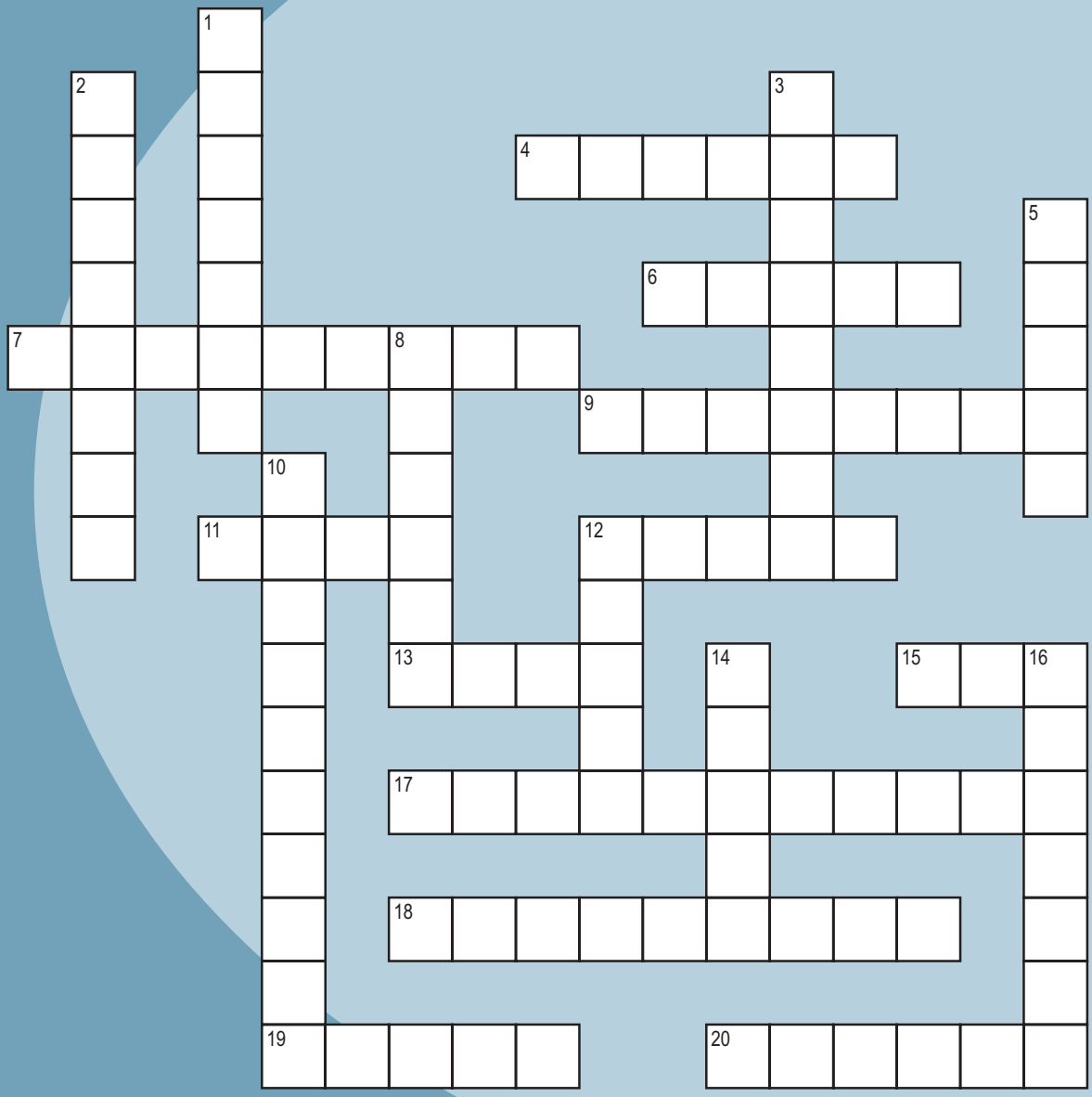

## Across

4. Cuprum
6. The engineer used ____ to secure the connections to the board.
7. C1 is the first
9. MS-DOS command lh
11. For overcurrent protection
12. Double word
13. Demonstration
15. Data pathway
17. Analog and digital on a chip
18. Spring-loaded clip with "jaws"
19. What is the "b" in $b^n$, where "n" is an exponent?
20. µ

## Down

1. Operators AND, OR, NOT
2. Ta capacitor
3. Remove solder for deconstruction
5. Test #1, in-house
8. Original message + reply + reply + reply …
10. Measures current, resistance, and voltage
12. Light emitting
14. 10,000 gauss
16. Jons Berzelius discovery (1823)

**The answers are available at www.circuitcellar.com/crossword.**

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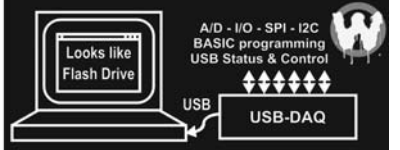

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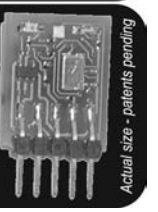
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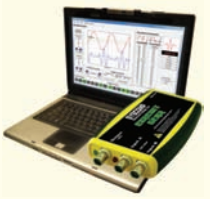
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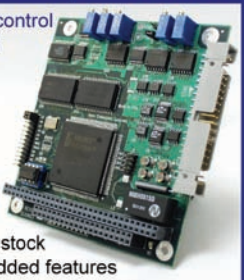
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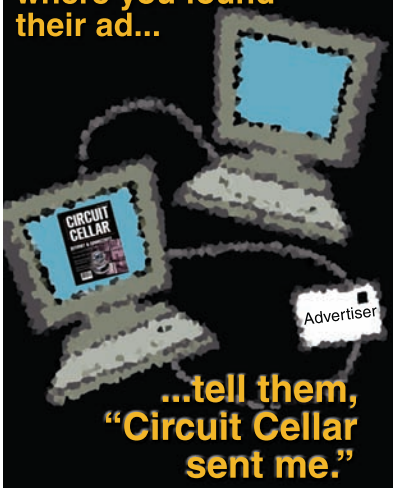

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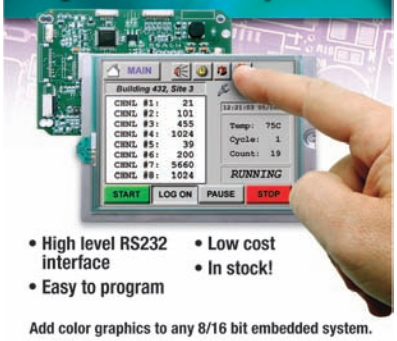

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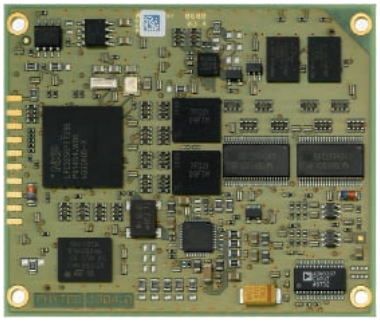

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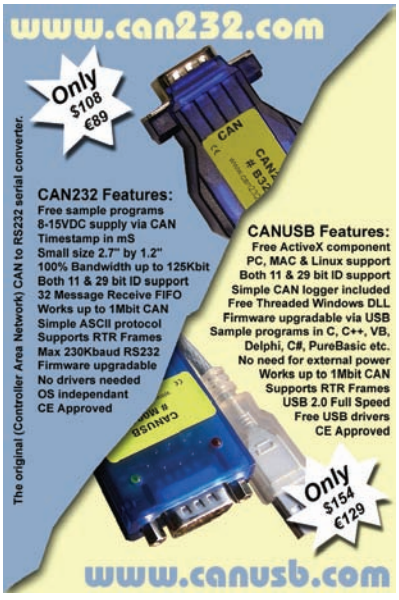

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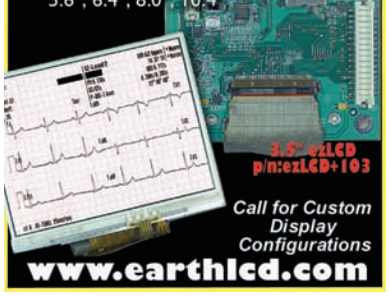

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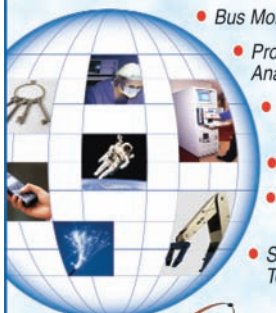

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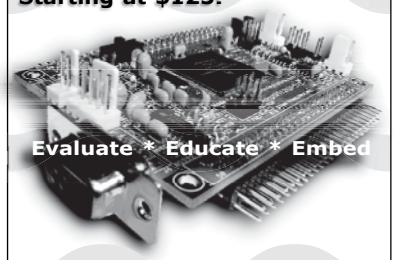


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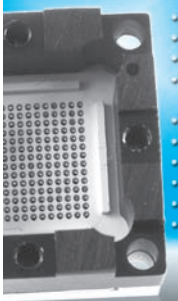

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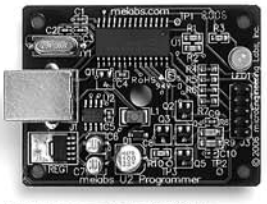

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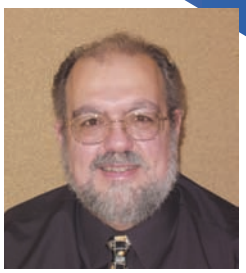
# PRIORITY INTERRUPT



by Steve Ciarcia, Founder and Editorial Director

## Swallowing the Pill

All right. I'll admit that sometimes I'm a stick in the mud when it comes to changing things. It's not that I have a radical adherence to the saying, "If it ain't broke, don't fix it." It's just that I'm very selective about dumping comfortable complacency simply to jump on the next technical bandwagon. Of course, my wife wonders why I can so readily discard this rational logic when it comes to buying cars that have to include turbo-charging, active roll stabilization, and a myriad of other gimmicks. I simply smile and say, "I'm an engineer. We all have to have our toys." ;-)

OK, you probably didn't need to know all that, but it's a nervous reaction I get when discussing anything Microsoft. I'm glad I'm not in Microsoft's marketing department because I don't know how you sell a new operating system when it appears that no one wants one. Let's face it: even lacking some cute Vista-unique features, XP is a fairly decent operating system. With proper browser updates, good audio/video hardware, security software, and a firewall, an XP box is a pretty long-term companion. Like me, I'll bet 95% of owners primarily use them to browse, e-mail, watch videos, write documents, collect and manipulate camera photos, print documents, download files, and burn a few CDs. The truth is that XP works just fine, and most of us see absolutely no reason to learn a new OS (and pay for it) just to do the same things.

I have to qualify my comments by saying that I haven't personally used Windows 7. The sum of my experience with Vista is helping my wife (mostly by looking for XP-like commands under all the extra crap) with her Vista-based laptop when she gets stuck trying to do whatever she's attempting to do—and that's the rub.

My personal distaste for Vista, and potentially my concern about Windows 7, has to do with the fact that Microsoft doesn't properly appreciate why people like XP. It's not some fetish thing. It's just that the Vista experience changes nearly every aspect of how you get things done on your computer. I don't mean in how it processes the information (heck, most people don't even want to know). I'm talking about the way you interact with the machine. XP is simple: find a recognizable icon, right click for info, and then intuitively follow some logical process.

My experience with Vista didn't seem the least bit intuitive. It just dumped me onto a complicated road where I didn't care to invest an extraordinary amount of time learning how to read a new map. All the text, all the icons, all the text with icons, icons replaced with text, etc, etc, were in different locations, different menus, different levels of menus, etc. Complicating that aggravation, we can add new rule changes about doing things with file names, deletions, and the Start menu. Heck, it took me 20 minutes to find the Off switch the first time! Certainly many professionals relished the technical challenge and now enjoy Vista, but Microsoft's failure in inducing more people onto the bandwagon happened because the upgrade experience was viewed as a 100% learning curve for virtually everyone else.

From what I'm reading, Windows 7 will be an improvement over Vista, but it will not be an easy upgrade path for XP users. XP users can't simply do an in-place upgrade where you apply a new OS on top of the existing one and it keeps all your old settings and programs (Vista to 7 is presumably easier). Windows Easy Transfer might still move your data, but you better start looking for all those original application CDs if you have to do a clean install from the bottom up. Arrgh!

Certainly we can hang on to our XP boxes, or even consider using XP Virtual Mode or XP downgrade under Windows 7. Of course, having to buy a more expensive OS 7 version in order to downgrade it leaves a bad taste in my mouth. Besides, virtual modes and downgraded OSs always seem like a kludge—and somewhere under all the onion layers running XP, it's Windows 7.

In the long run, the choice of how long we can keep our OS comfort may not be in our hands. It is the continued support of application and security software manufacturers that allows us to continue using XP. Today it is a no-brainer because 75% of the installed base is XP. What happens when you add a third OS to the mix and ask all these software vendors to support three different operating systems, especially when Microsoft has chosen to only support the last two?

XP has a few more years to live, and undoubtedly there will be extensions. However, at some point in the future, we may have to choose between a PC with a comfortable OS that risks its life every time it connects to the Internet and some new whizbang jack-in-the-box Maginot Line (and yes, I know it didn't hold) OS offering a new beginning and a new learning curve. The decision clock starts now.

P.S.—Stay tuned to *News Notes* for the latest in the "Critter Chronicles." The war continues!

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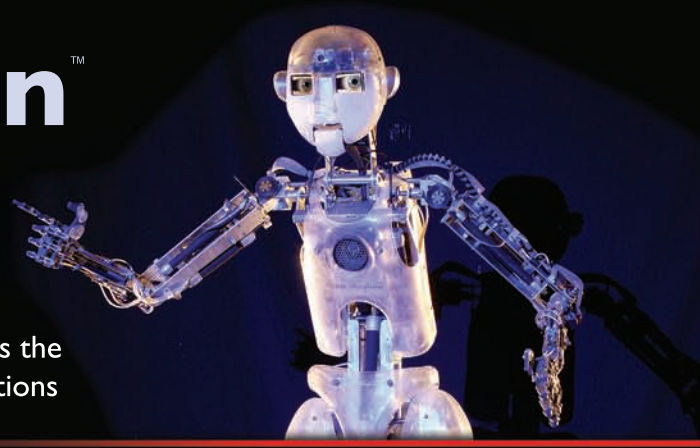

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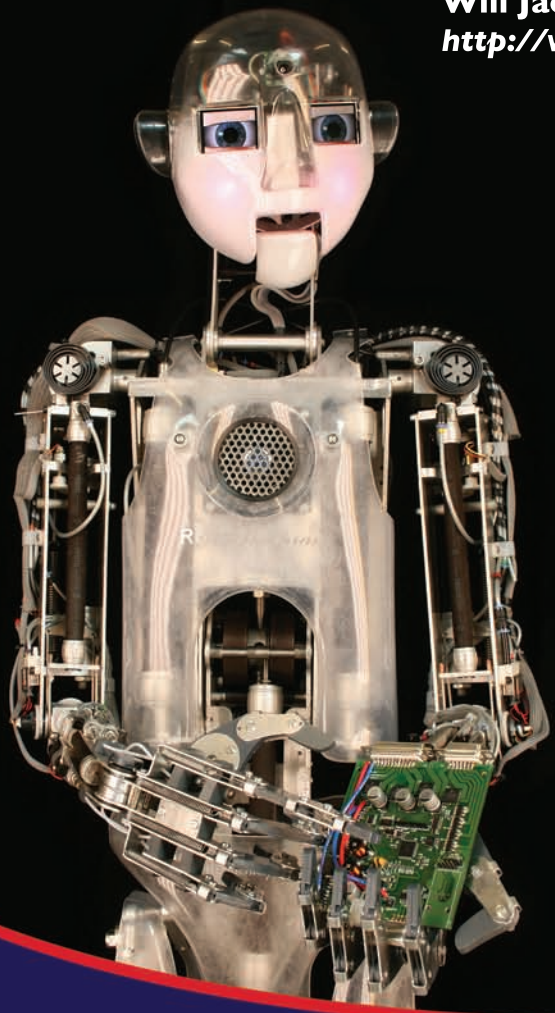

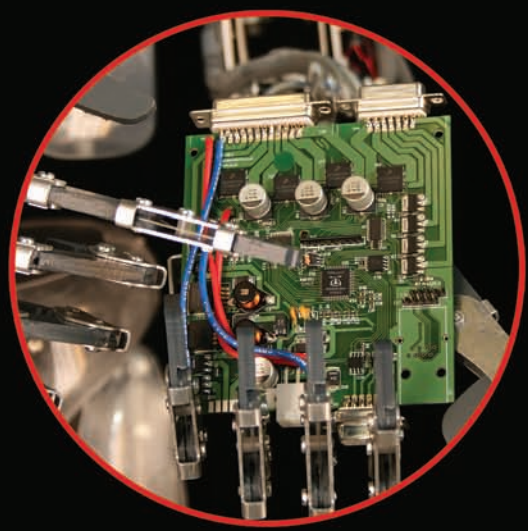

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BONUS ARTICLE

by Brian Millier

# USB I/O Expansion

Brian shows you how to build a USB link into a device without having to focus on the numerous complexities of USB technology going on in the background. He showcases the link as he describes a high-resolution data acquisition board.

Although I'm as big a fan of flash memory drives as everyone else, I confess to dragging my heels when it comes to incorporating USB in my own PC-connected projects. While USB technology's many advantages are clear, it presents some roadblocks for those of us who are more adept at microcontroller hardware design than wading into the complexities of communications drivers. Interested companies have made progress in bringing down the complexity of the USB protocol to a level more understandable to many electronics hardware designers. Still, it is no cakewalk, particularly if your programming expertise is in languages other than C.

In this article, I'll introduce a tool that enables you to build a USB link into a device without having to focus on all the complexities of USB that are going on in the background. This product line is a small family of devices marketed by a partnership of two European companies: Hexwax in France and Firmware Factory in the United Kingdom. I will focus on one member of the family, the ExpandIO-USB device, which features SPI, I²C, USART, and parallel ports. It connects to a PC using a USB 2.0 port. To simplify the PC driver issue, this device appears to the host PC as a Microsoft-standard human interface device (HID). Later in the article, I'll describe a high-resolution data acquisition board I designed around this. The board is versatile enough to handle many different types of sensors.

## MINIMIZE "DRIVER FATIGUE"

Let's back up a bit. My first foray into USB connectivity involved using the USB/UART modules containing the now-ubiquitous FTDI USB-UART chips. Undoubtedly they are the most effective at insulating you from the USB protocol because they just end up looking like an additional serial port at the host PC end and the necessary driver has been incorporated in Windows since XP. At the microcontroller end, the FTDI chip looks like a UART, so it hooks up directly to the MCU U(S)ART port. Hand-shaking lines are provided, as well as small buffers in the FDTI chip itself, to accommodate the differences in processing speed between the host PC and the MCU peripheral. These are great devices, but they add an additional module to your design.

My next step was to consider MCUs containing a complete USB engine, preferably supported by USB driver code supplied by the MCU manufacturer. Both Atmel's AVR family (which I use almost exclusively) and Microchip's PIC family contain such USB engines. I found that the C language USB "Stacks" for both of these MCUs were rather hard to fathom, given that I use Basic almost exclusively on both the PC and for MCU firmware. It was at this point that I discovered the ExpandIO-USB family.

## ExpandIO-USB

Let's take a look at what is under the hood of the ExpandIO-USB devices. Basically these chips fall somewhere in-between a dedicated I/O co-processor and a ROM interpreter-based MCU (like the Basic Stamps). Their main purpose is to provide serial protocols such SPI, I²C, and parallel ports, all under the command of a host computer, via the USB port. All of the relevant parameters of the various serial protocols, as well as the behavior of the parallel ports, are configurable by the host, on the fly. Beyond the basic I/O functions, there are a number of other useful operations that can be performed that give the ExpandIO-USB some of the characteristics of Interpreter-based MCUs, such as Basic Stamps, except that they communicate via the USB port.

All the devices in the ExpandIO-USB family consist of a Microchip Technology PIC18F*xxxxx* USB-enabled MCU preloaded with firmware. The low-pin-count ExpandIO-USB devices use a PIC18F14K50 in a 20-pin DIP or SSOP packages. The larger ExpandIO devices are available in either

| Base PIC18F microcontroller | 14K50 | 24/4450 | 2455/4455 |
|---|---|---|---|
| I/O Pins | 12 | 21/32 | 21/32 |
| Interrupt on edge | 3 | 3 | 3 |
| Interrupt on change | 0 | 4 | 4 |
| Count/compare/PWM | 0 | 1 | 2 |
| UART (not buffered) | 1 | 1 | 1 |
| SPI/I²C (as master) | 1 | 0 | 1 |
| UNI/O (as master) | 12 | 21/32 | 21/32 |
| Comparators | 2 | 0 | 2 |
| 10-bit ADC | 9 | 10/13 | 10/13 |
| Timer 8-bit | 1 | 1 | 1 |
| Timer 16-bit | 3 | 2 | 3 |
| Product ID, low speed (hex) | 120 | 0121/0122 | 0129/012A |
| Product ID, full speed (hex) | 012D | 012E/012F | 0132/0133 |

Table 1—This is a peripheral feature matrix for the various members of the ExpandIO-USB family. Some of these features have dedicated commands, while others must be implemented by Register manipulation commands. (Source: Firmware Factory)

28/40-pin DIP or TQFP-44 packages, and they use the PIC18F2450/55 or PIC18F4450/55, respectively. All devices are available as either low-speed or full-speed USB versions. Since all PIC18F*xxxx* MCUs are capable of full-speed operation, I wondered why ExpandIO devices were even offered in a low-speed version. According to Firmware Factory, the low-speed versions are targeted at cost-constrained applications using a low-cost ceramic resonator in place of the quartz crystal needed to meet the full-speed USB timing specifications. The chips I received in the sample pack were full-speed devices, which suited me well because the extra cost of a crystal doesn't affect me.

To the user, these devices don't look like a microcontroller (i.e., you don't write any program code to run on them). What they do look like are peripheral devices preprogrammed to perform the following tasks: handle all of the USB enumeration and communications functions needed for a standard HID-class device; accept a series of commands from the PC host via USB, which are then parsed and used to configure and utilize most of the peripheral modules present on the particular PIC device being used; perform a few "high-level" functions, such as matrix keyboard scanning and multiplexed LED display generation; and respond (optionally) to various interrupt conditions arising from the use of the aforementioned peripheral functions, and report them to the host using USB reports in a reasonably timely fashion.

Given this functionality, it is relatively simple to connect an ExpandIO-USB device to a PC and gain access to most of the I/O modules found in the PIC MCU. Table 1 shows the various I/O modules that are available on each of the various family members. Table 2 is a list of the full set of ExpandIO commands, most of which are self-explanatory. The Execute UNI/O command handles Microchip Technology's new one-wire communication standard, which is now being used on some of their new serial flash memories (not to be confused with Dallas Semiconductor's 1-wire protocol, which has been around for some time now). The Stream Data command might best be described as a macro command. To use it, you assemble a group of ExpandIO commands needed to perform the desired operation and then send them out in a single packet (up to 64 bytes). You follow this by the Stream Data command in the very next packet. The stream Data command has a parameter to set the timing, and when it is invoked, it repeatedly runs this "macro" that you have defined at the rate defined in the Stream Data command. This macro type of command is why I consider the ExpandIO to be something more than just an I/O coprocessor. My only criticism here is that the range of timing intervals available is quite limited because it is based on an 8-bit timer in the PIC and has a maximum period of only 10.88 ms.

I already mentioned that ExpandIO devices use the common Microsoft USB HID-class to communicate with the PC. As its name implies, the HID class is not a high-speed protocol. It is intended to communicate human-generated I/O content with the PC. Full-speed ExpandIO devices communicate with the host using 64-byte reports or packets spaced no closer than 1 ms apart. Theoretically, this yields a 64-KBps maximum data transfer rate. If your application requires a higher data throughput, then the ExpandIO device is not for you. The low-speed devices are considerably slower than this.

The "timed packet" protocol, used by HID-class devices, is also used by modules containing the FTDI USB-UART chip, which I have also used. Some of my past project designs called for a fast PC response to short messages (1 to 3 bytes) coming in from the external device. In such cases, neither the FTDI device nor the ExpandIO-USB devices are suitable. Instead, I've stuck with the "legacy" PC serial port to handle the job; it is far superior in this respect.

As I looked over the ExpandIO datasheet for the first time, it seemed like it would be relatively easy to integrate it into a hardware design. Similarly, the available functions and their associated command set seemed straightforward enough. While I expected that HID-class USB drivers are part of most modern C compilers, I used an older Microsoft Visual Basic compiler (version 6). Native support for HID-class devices was not built into this version of the compiler. However, I had a custom OCX control that was part of a package supporting Atmel's USB MCUs. It worked well, but it was not something that the average reader would be able to access. When I contacted Firmware Factory about this, they sent me a beta version of a driver DLL, which communicates with the ExpandIO devices. Like anything new, it took me a while to figure out how to properly use it, but Firmware Factory's tech support was excellent and things

| | | |
|---|---|---|
| Get Register | Set register | Get register bit |
| Set register bit | Get port | Set port |
| Get port bit | Set port bit | Get analog (ADC) |
| Set serial | Execute SPI | Execute I²C |
| Execute UNI/O | Interrupt event | Wait on bit Change |
| Matrix keyboard scan | Multiplex out (LED) | Stream data |

Table 2—This is a list of the functions that the ExpandIO-USB handles. Most of the PIC18F*xxxxx* USB MCU's peripheral functions are implemented by the ExpandIO-USB.

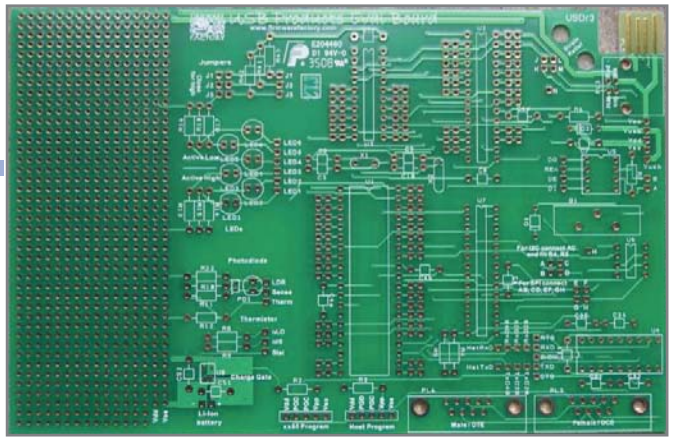

**Photo 1**—This is a picture of the unpopulated ExpandIO-USB evaluation board, as supplied by the factory.

worked out fine in the end. Due to the different ways that Visual Basic and C handle strings, this DLL is a somewhat awkward to use. But it works.

What initially interested me about the ExpandIO device was its availability in DIP packages, as well as the availability of a good evaluation board. This evaluation board has PCB footprints for the three DIP packages that the devices come in. If you decide to mount sockets, you can try your idea on the evaluation board and pop out the chip later to move to your target board. I also liked the 6 square inches of prototyping space and the headers for the MCU's I/O pins (all on 0.1" hole spacing). The evaluation board is sold as a bare board (see Photo 1). Instead of mounting a conventional USB socket, Firmware Factory laid out a USB Type-A "plug" pattern on the PC board itself. A USB extension cable is needed to use this. There is also a footprint for a conventional Type-B socket on the PCB, so I mounted one and used a conventional USB cable instead. One result of the decision to place the Type-A plug on the PCB is that the PCB is thick at 2 mm. They chose to extend the gold plating needed for this plug over the entire PCB. This makes the prototype area quite robust, which is great when you are developing your custom hardware circuitry. We all make mistakes, don't we?

## HI-RES USB DAQ

At about the same time that I was evaluating the ExpandIO-USB chips, I was asked to design and build a number of data acquisition modules for one of our teaching labs at Dalhousie University in Halifax, Canada. The intent was to replace 10 existing units consisting of custom external boxes containing some signal-conditioning circuitry connected to commercial ISA-bus DAQ boards. The existing computers were old and failing, and any new computers used to replace them would no longer contain ISA bus slots.

In an article titled "High-Resolution Data Acquisition Made Easy," I described a similar high-resolution DAQ module that I designed back in 2002 (*Circuit Cellar* 140). I successfully employed several of the devices back then. However, its RS-232 interface, while a sensible choice at the time, was no longer viable because new PCs no longer come with a serial port. I could have continued with the same design and used an inexpensive USB/serial port cable (which is now available). I also looked at several inexpensive commercial modules, but none of them had a resolution better than 12 bits, and most of them did not handle low-level signals directly. Therefore, decided to start fresh with a design featuring an ExpandIO-USB device. The final design was both smaller and less expensive to build than the older design, in part because no external power supply was needed for the USB version.

I built the prototype on Firmware Factory's evaluation board with lots of room to spare. Figure 1 shows the essential digital and power circuitry associated with the ExpandIO-USB device, as well as the ADC. Figure 2 and Figure 3 show two different analog front-ends—one of which can be used for any given application. Figure 2 shows a general-purpose, bipolar input module containing an instrumentation amplifier with true differential inputs and good input protection against stray overvoltage. Figure 3 shows another input configuration containing a zero-drift op-amp and a cold-junction compensation circuit designed to handle thermocouple sensors.

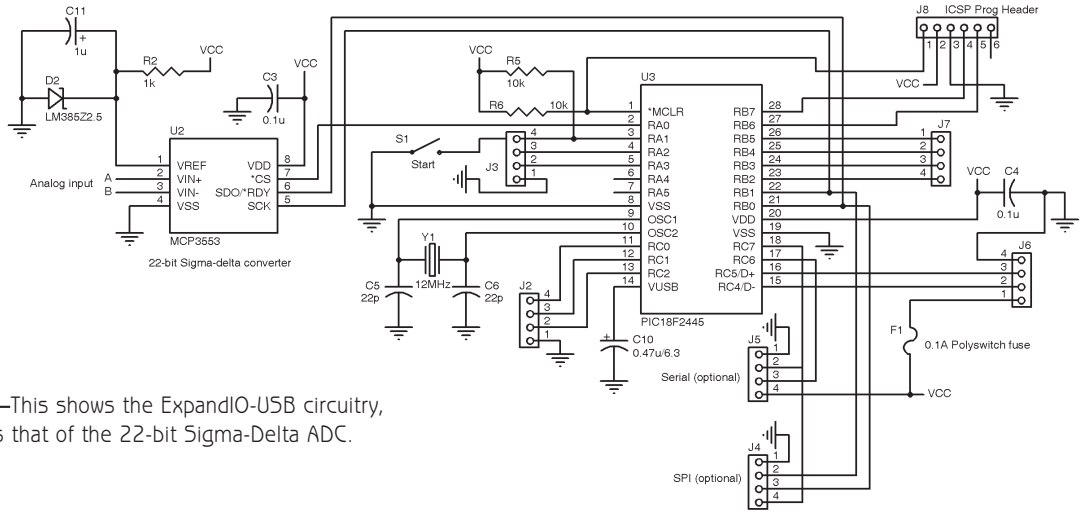


**Figure 1**—This shows the ExpandIO-USB circuitry, as well as that of the 22-bit Sigma-Delta ADC.

I designed a PCB for the project. I commonly use the low-cost "mini-board" format available from ExpressPCB. I found the 3.8" × 2.5" dimensions of the mini-board format were more than enough for the circuit. There was PCB space to spare, so I implemented the component footprints and jumpers needed for both of the aforementioned input configurations, even though I needed only one of the analog front-ends for this specific application.

As you can see in Figure 1, the ExpandIO device (U3) is directly connected to the USB port via J6. This is a USB bus-powered design, so it gets its 5-$V_{CC}$ supply directly from the USB power pins. When you get it, the ExpandIO-USB is configured to request a maximum of 100 mA from the USB host controller (but it can be configured for more current using Firmware Factory's HIDconfig utility). This is more than enough to handle the circuit's current requirements. Call me overcautious, but I also placed a 100-mA Polyswitch resettable fuse in series with the USB 5-V power line in case things went terribly wrong.

Although there are only a few passive components needed to operate the ExpandIO properly, you have to include C10. This capacitor is needed for the stable operation of the internal 3.3-V regulator contained within the ExpandIO. The USB engine in the ExpandIO requires either a 6- or a 48-MHz clock, depending on whether it is a low-speed or full-speed device. The PIC18F*xxxxx* USB MCUs come with a sophisticated internal clock module containing various dividers, as well as a PLL, so there are a lot of crystal frequencies you can use and still meet the USB requirements. As for ExpandIO devices, however, the PIC clock configuration bits are programmed to work with only a 12-MHz crystal (or resonator in the case of the low-speed versions).

I placed header footprints on the PCB for almost all of the I/O pins available on the ExpandIO, even though I didn't need most of them for this project. Note that J8 is a standard Microchip ICSP device-programming header. The ExpandIO firmware is protected against reading, of course, but you can erase and reprogram the chip if you want. I placed the programming header on the board in case I master Microchip's USB stack and later want to replace the ExpandIO with a "raw" PIC18F2445 containing my own C code. The fully populated USB-DAQ PCB is shown in Photo 2.

## CHOOSE THE ADC

A slow, integrating, high-resolution ADC was best suited to the signals involved in this project. I've used several different Texas Instruments (Burr-Brown) Sigma-Delta ADCs over the years and have been happy with their performance. More recently, I discovered the low-pin-count Microchip Technology MCP3551/3 Sigma-Delta ADCs, and I've been satisfied with their performance too.

The MCP3551/3 is a 22-bit Sigma-Delta ADC with a three-wire SPI, which easily connects to the ExpandIO. It requires an external voltage reference, which I like, because it enables me to choose the ADC's full-scale voltage anywhere from a fraction of a volt up to the value of the $V_{CC}$ powering the device. It has a fully differential input, and its common-mode input voltage range includes $V_{SS}$, so it's easy to configure it to measure bipolar voltages by biasing its $V_{IN}$- terminal at some voltage above $V_{SS}$. The MCP3551 and MCP3553 are basically identical, except the latter has a faster 60-Hz sample rate compared to the former's 13.75-Hz rate. The slower MCP3551 has better 50/60-Hz noise immunity and a bit better resolution. I used the MCP3553 in this application, although I have used both versions in the past. These ADCs are unique in that they incorporate an over-range capability of about 12% (i.e., they don't saturate at the 22-bit—2's-complement—maximum value). This feature isn't crucial to me, but it could be useful if they were being used in a closed-loop control system.

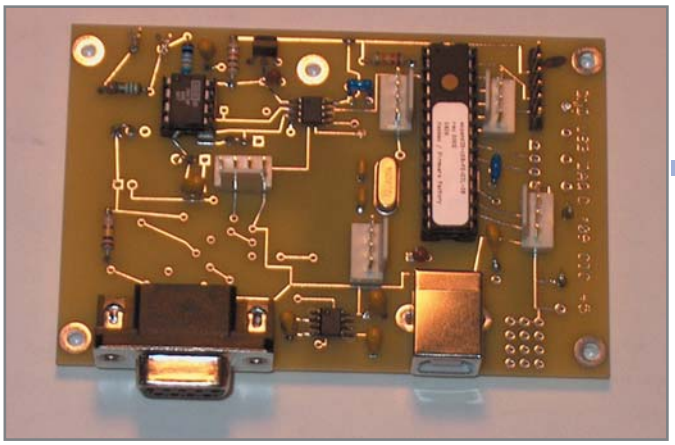

Photo 2—This is the finished project with components mounted for some options that were not used in this particular application.

Regardless of what analog front-end circuit I choose, the ADC is operated with a voltage reference of 2.5 V, provided by an LM385Z2.5 voltage reference. When used with the bipolar input front-end, this results in a ±2.5-V full scale range divided by whatever gain I choose for the instrumentation amplifier.

## ANALOG FRONT-END #1

Figure 2 shows the bipolar analog front-end. Here I decided to use the Texas Instruments (Burr-Brown) INA118 instrumentation amplifier, which I've used frequently in the past. At $10, it's an expensive part, but it does have certain advantages. It is internally protected up to ±40 V. And if that isn't enough, it is available in a DIP package, so I can mount it in a socket in case something really goes astray at the signal input terminals. However, I designed the PCB to also accommodate single-supply IA's such as the Analog Devices AD623, which is not so well-protected but works on a single 5-V power supply, eliminating the need for the LMC7660 negative supply charge pump. There are a lot of jumpers in this circuit that are used to accommodate the various choices of amplifier, as well as define whether the front-end will handle bipolar signals or not and how the two input terminals are referenced to $V_{SS}$. To enable the circuit to measure bipolar voltages, both the ADC's Vin- and the IA's output reference terminal are referenced to $V_{CC}/2$ by resistor network R14, R15.

To accommodate sensors that are commonly operated in a bridge mode (e.g., RTDs and strain gauges), there are PCB

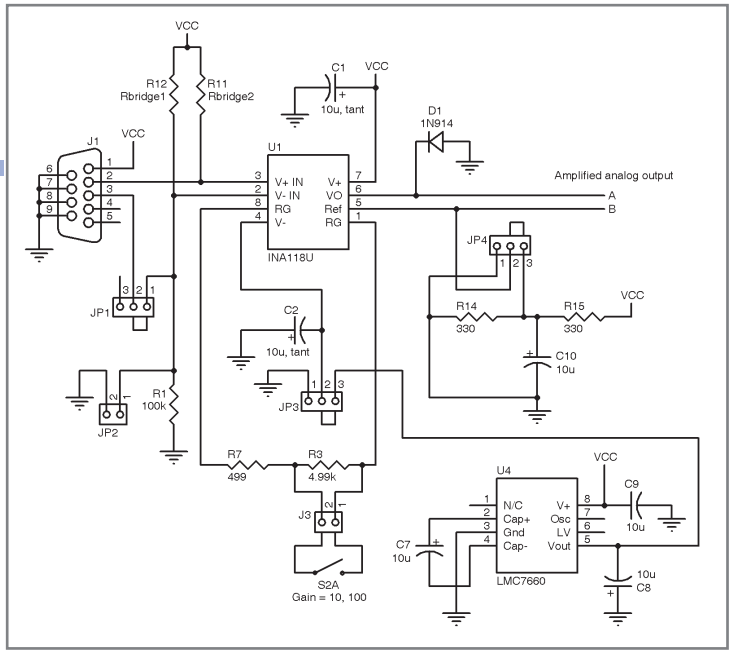


Figure 2—This is the project's the analog front-end.

footprints for bridge resistors (RBridge1 and RBridge2), and $V_{CC}$ is supplied to the nine-pin D connector in case it is needed for external bridge excitation.

## ANALOG FRONT-END #2

Figure 3 shows the second analog front-end, which is specifically designed for thermocouples. Assuming that the temperature range that you want to measure is always above ambient temperature, the thermocouple's output voltage will always be positive. Therefore, I did away with the instrumentation amplifier and the LMC7660 negative supply charge pump. In its place, I substituted an LTC2050 zero-drift, low offset voltage op-amp. To handle the cold junction compensation, I used an LM35 temperature sensor that I had on hand and divided its 10 mV/°C output down to the level needed for cold-junction compensation. Depending on the particular type of thermocouple you choose, you should adjust potentiometer R9 to match the offset voltage of that type of thermocouple at room temperature. A more elegant solution is to use a Linear Technology LT1025 cold-junction compensation chip. Given the ADC's 2.5-V FS range, you might also want to change the values of R1/R13 to provide a suitable gain for the temperature range that interests you.

The DAQ module is connected to the PC via USB, so it will share the same ground reference as the PC. To implement a simple cold-junction compensation scheme, using only a single op-amp for the thermocouple amplifier requires the thermocouple itself to be referenced above ground by the cold-junction compensation potential. Therefore, you would have to be careful to insulate the thermocouple-measuring tip from any electrical potential.

## SOFTWARE & DRIVERS

At the PC end, you must provide a USB HID-class driver for your compiler, unless USB HID-class support is native. The DLL provided by Firmware Factory is supplied in a ZIP file containing both the FwFhid.dll file and an Excel spreadsheet that demonstrates its use. Excel, as part of Microsoft Office, includes Visual Basic for Applications (VBA), which can be used to add custom VB code to an Excel spreadsheet application. In this case, Firmware Factory incorporated this DLL into a spreadsheet and wrote a bit of VBA code to demonstrate its use.

I was interested in using Visual Basic 6, so I imported the DLL's declaration lines into a VB program and used the VBA code in the spreadsheet as a guide. I encountered a few hitches. When using external DLLs with VB, my experience has been that as long as you place that DLL in the same folder as the actual VB program, VB will find and recognize it. Alternately, you can place it in Windows\system32, which is a huge storage house of various DLLs. With this DLL, I had to actually modify the declaration lines to point to the exact path of the directory in which I had placed the DLL. Otherwise, the DLL was not recognized. So, for example, if one puts the DLL into the root directory of drive C, a sample declaration would be:

```
Private Declare Function FwFhidCountDevices Lib
"c:\FwFhid.dll" (ByVal PID As Long, ByVal
Version As Long) As Long
```

This DLL uses a single, common array to buffer outgoing and incoming USB packets. When you send out any command to

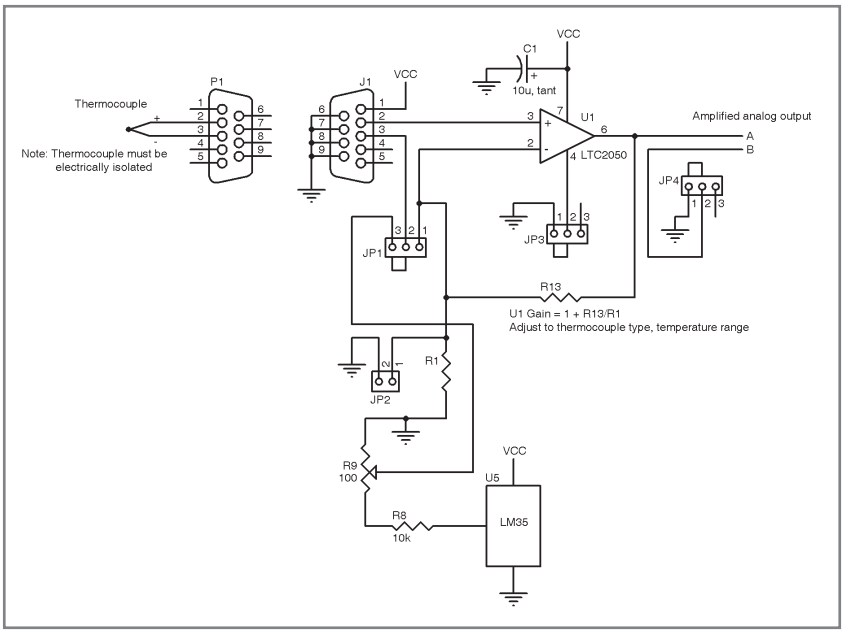


Figure 3—This is the analog front-end circuitry that needs to be populated on the PCB for a thermocouple sensor.

the ExpandIO, you have to ensure that the trailing bytes in the 64-byte packet are all set to zero (otherwise "stray" commands might be executed). The safest thing to do is zero them all out beyond the end of the command string. However, if you take any shortcuts based on the assumption of the length of your previous command, you can get into trouble if the incoming packets are longer than that command. I personally got caught by this and actually managed to "brick" an ExpandIO chip by unintentionally sending it "undocumented" commands. This modified the USB descriptor tables to the point where the chip was not recognizable as a valid USB device. I later realized that I could have "write-protected" the ExpandIO device using the HIDconfig utility and prevented any such mishaps.

## THE NEXT STEP

The VB source code and an ExpressPCB layout file for the project's PCB are available on the *Circuit Cellar* FTP site. Basically, the only real difficulties I ran into while designing this project had to do with getting familiar with the USB HID driver for the PC end of the USB link. The ExpandIO command set was well-documented in the datasheet, and it worked seamlessly with the ADC I used. My past experience has been that it is best to attack a new microcontroller chip, computer language, or protocol by starting out with something that already works and branching out from there. With this project under my belt, I plan to delve deeper into the process of writing my own code with the PIC USB MCUs.

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## PROJECT FILES

To download code, go to ftp://ftp.circuitcellar.com/pub/Circuit_Cellar/2009/229.

## SOURCES

**ExpandIO-USB chip**
Firmware Factory | www.firmwarefactory.com

**LTC2050 Op-amp**
Linear Technology | www.linear.com

**MCP3553 ADC**
Microchip Technology | www.microchip.com

**INA118U Amplifier**
Texas Instruments | www.ti.com