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Innovation in MOTOR CONTROL

ARM Cortex IC Family **Delivers Smarter Motor Control** at an Affordable Cost

By Suribhotla Rajasekhar, Tim Menasveta

The 10 billion electric motors sold each year are about to get a face lift. Ubiquitous brushed motors, introduced in the early 19th century, rely on mechanical commutation of electric current in stator coils used to drive rotors. Now, innovation in software commutation algorithms and lowered costs of embedded microcontrollers are breathing new life into a generation of brushless DC motors, high-voltage AC motors, and permanent magnet synchronous motors (PMSM). These motors can provide significant power and performance benefits to a range of applications, including household appliances like refrigerators and freezers, washers and dryers, heating and cooling systems (HVAC), and power tools for home and garden. By integrating a 32-bit ARM Cortex-M0 processor core, as well as sophisticated configurable analog and power management, the Power Application Controller™ (PAC) family of integrated circuits from Active Semiconductor enable this wave of innovation by delivering smarter motor control at an affordable cost. The highly integrated solution not only reduces system component count and increased energy efficiency, but also enhances safety through automatic fault mitigation systems.

MARKET CONSIDERATIONS

The electric motor market can be segmented in multiple ways. A typical segmentation is of AC against DC (with typical control method), with some examples shown below in Table 1. Popular control methods range from simple voltage control to more sophisticated electronic commutation including volts-frequency (V/f), pulse-width modulation (PWM) control, 120-degrees trapezoidal control, or field-oriented control (FOC). Other ways to segment the market are by horsepower, which is often relevant for enforcing energy-saving considerations, or by end application, which can have significant implications on system considerations such as sensor or sensorless operation, speed control, torque control, and initial position detection.

AC MOTORS (Typical Control Method)	**DC MOTORS** (Typical Control Method)
Induction Motor (V/f)	Brushed (Voltage control)
	PMSM (FOC)
	BLDC (Trapezoidal)
	Servos (PWM), Steppers

Table 1. Segmentation of popular motor types based on AC versus DC operation, along with the typical control method employed.

As with any electronics system, consideration must be taken to ensure there is a balance between performance, design footprint, cost and energy efficiency. Owing to the sheer number of motors employed across the world, energy efficiency has become one of the strongest driving forces behind traditional motor technology replacement. In recognizing this need for energy savings, several governmental agencies have started to mandate energy saving targets for electric motors, especially those above certain power ratings. For instance, the Energy Using Products (EUP) directive (EC640/2009) in Europe mandates strict requirements for energy efficiencies in motors, with compliance enforcement by 2017. In addition, consumers are beginning to demand energy-efficient motor control systems in order to lower their overall energy consumption and the associated costs.

Better system performance and overall system size are also driving motor selection and use of control algorithms. Refrigerators, for example, are typically rated for their energy efficiency, while new ceiling fan designs are chosen for being quieter, more efficient and even with smaller form factors. These user benefits are possible with migration from traditional AC induction motor usage to high-voltage BLDC motors.

MARKET TRENDS AND CHALLENGES

Traditional brushed motors and AC induction motors constitute the majority of motors employed in the industry today. Trends have changed as a result of the drive for lower power consumption, better system performance and reduced costs.

Some common changes include:

- Migration from brushed motors to brushless DC (BLDC) motors
- Migration from AC induction motor to PMSM and BLDC motors
- Migration from sensor to sensorless motor control
- Increased use of variable frequency drive algorithms and sensorless FOC

This transition, however, has faced some headwinds. Traditional motor technology enjoys well-amortized manufacturing costs. Developing and deploying new motor control technology incurs research and development costs for motor control hardware platforms and for motor control software. Moreover, the design footprint may not fit the smaller form factor due to an increase in bill of material (BOM) count as a result of the additional functionality.

Despite these headwinds, the trend to migrate to newer motor technologies is here to stay. The demand for more energy-efficient and higher performing motor-based equipment is driving down development cost. In addition, highly integrated solutions such as the PAC IC help simplify overall system design, lowering the cost to develop, build and sell such equipment.

MOTOR SOLUTIONS WITH CORTEX-MO-BASED POWER APPLICATION CONTROLLER (PAC) FAMILY

Power Application Controllers (PAC) are a family of ICs that integrate an ARM Cortex-M0 core along with sophisticated analog and power management peripherals, solving many design problems and offering single-IC hardware solutions for running complex field-oriented control for variable frequency drives and other control algorithms in a small design footprint. Figure 1 shows the general block diagram of PAC ICs.

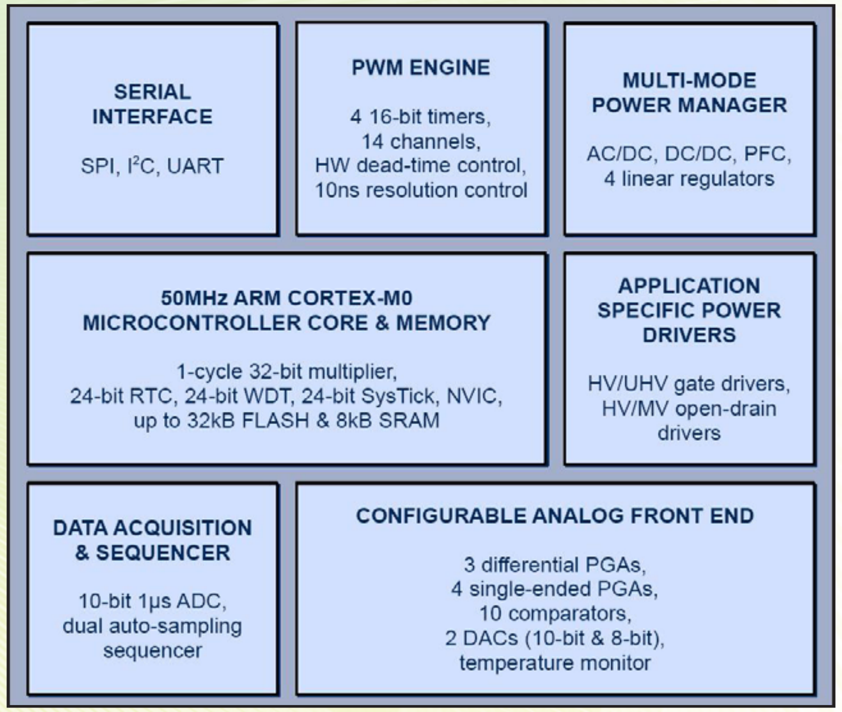

Figure 1. General block diagram of Power Application Controller (PAC)™ IC Family

Energy efficiency has become one of the strongest driving forces behind traditional motor technology replacement.

With only twelve thousand gates in its minimal configuration, the Cortex-M0 processor combines a range of benefits including ultra-low-power performance and low silicon cost. The core features a 32-bit programmable processor with very short interrupt latency, easy programming model, and built-in fault exception handling that has proven itself in over a billion field-deployed devices.

The Cortex-M0 core is augmented by multi-mode power management (MMPM), configurable analog front-end (CAFE), data converters, auto-sampling sequencers, and a 100 MHz PWM engine, amongst other hardware peripherals. These factors coalesce to provide the Cortex-M0 processor with better performance capabilities. For instance, MMPM enables PAC ICs to manage both AC input power (in an AC-DC flyback configuration) or DC input up to 72V (in buck or boost modes). In addition, the four onboard LDOs contained in MMPM offer system power rails, thereby eliminating the need for additional ICs to manage system power.

The Cortex-M0 processor includes a number of built-in features that enables software developers to create reliable systems. The fault detection features enable a number of error conditions to be detected which can then enable rapid recovery, or to provide diagnostic information to help debug the situations. The safety functionality is further enhanced with the powerful CAFE block. This block enables programmable gain amplifiers (PGAs) to detect system faults, which could be caused by the current condition through a motor phase and would be responded to by shutting down the gate drivers, interrupting the Cortex-M0 processor and enabling further software action to be taken.

One of the key features enabling PAC to run complex FOC algorithms for variable frequency drive motors is the patented auto-sampling sequencer block. Figure 3a shows the operation of PAC which frees up the Cortex-M0 processor to focus on application code, while Figure 3b shows a typical MCU that has to monitor the data acquisition process, thereby tying up the MCU core.

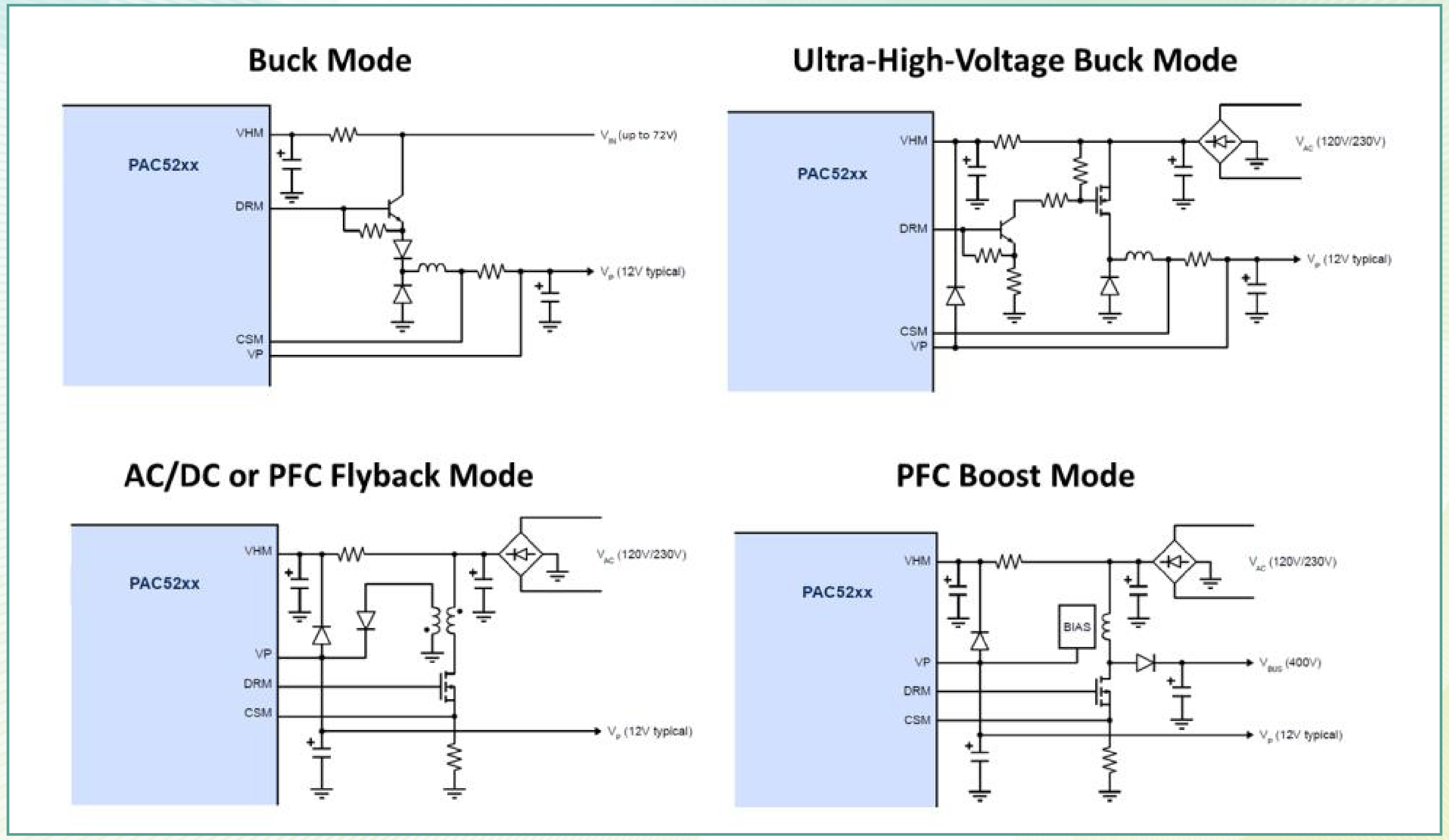

Figure 2. Cortex-M0 based PAC™ ICs can work with AC or DC input owing to integrated Multi-mode Power Manager

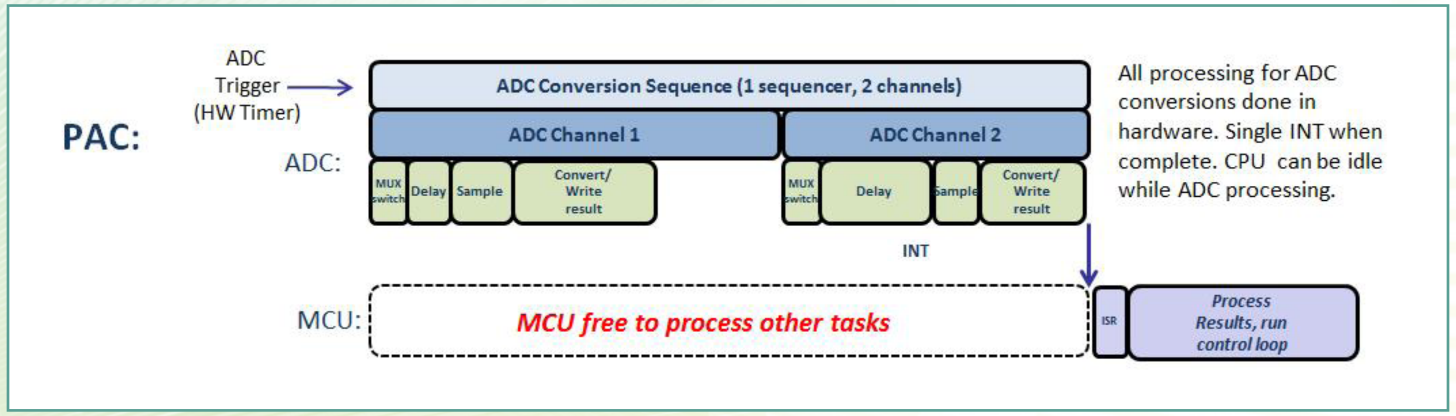

Figure 3a. Typical ADC data acquisition cycle on 2 channels on PAC ICs. Thanks to the auto sampling sequencer, the Cortex-M0 processor is free to process other tasks during the data acquisition phase

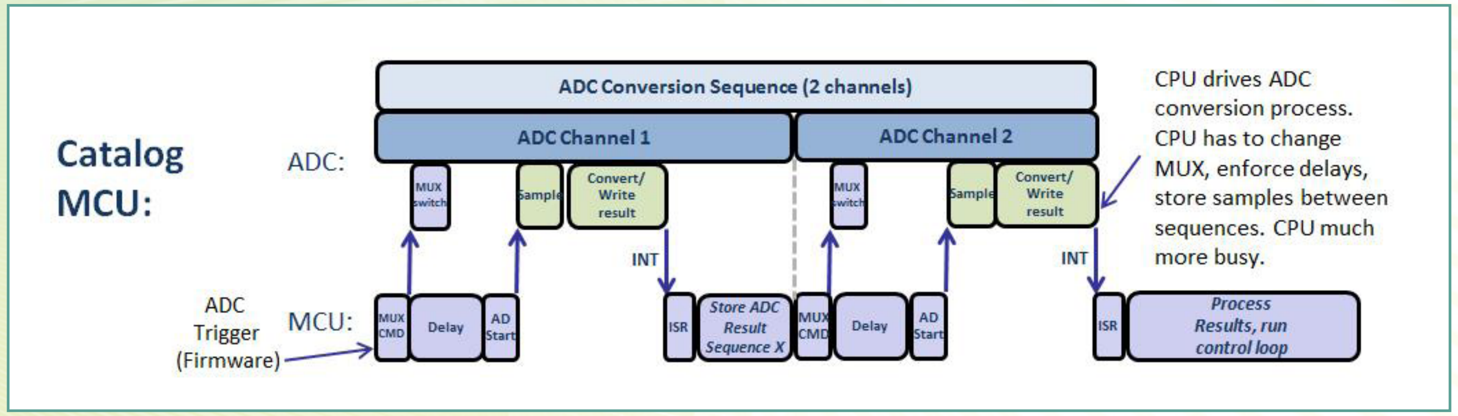

Figure 3b. Typical ADC data acquisition cycle on 2 channels on a catalog which typically does not have bandwidth to run any application code during the data acquisition phase

Highly integrated solutions such as the PAC IC help simplify overall system design, lowering the cost to develop, build, and sell such equipment.

MOTOR CONTROL SYSTEM SOLUTIONS

PSMS motors commonly used in industrial automation for traction, robotics or aerospace equipment require greater power and heightened intelligence. On a system level, this demands a motor control hardware solution that offers a small footprint with higher level of integration, lower BOM count, and hardware performance to run complex algorithms. The PAC5250 simplifies system design by integrating 600V gate drivers and the ARM Cortex-M0 for FOC. As shown in Figure 4, systems based on the PAC5250 only require additional passive components, thereby significantly reducing overall system BOM count.

For BLDC motors, the PAC5223 is able to drive gates up to 72V and can operate with or without external sensors. The ability to run accurate control algorithms on the Cortex-M0 enables BLDC motors to operate without any sensors, further reducing the number of required external components.

MOTOR CONTROL FIRMWARE / SOFTWARE

In some applications where the motor is encased, a sensor-based solution is impractical due to the cost of getting the feedback wires through the casing. This is where sensorless FOC systems offer designers the information through processing signals already available on the controller. Software models to estimate back electro-magnetic field (EMF) waveforms and to sense any slip become critical for synchronized and asynchronized systems. Whatever the technique, the process of producing a stable software sensor is extremely challenging. Applications that require the use of FOC will find features in a PAC52XX motor, which offer the optimal balance between cost and programmability for FOC applications.

As more and more applications rely on BLDC and PSMS motors such as medical equipment, home appliances, building controls, industrial automation and robotics, there is pressure to deliver more intelligence control and improve efficiency. Microcontroller-based electronic commutation for motor control can also help meet government agencies' and consumer's demand for lower power consumption and higher efficiency. Highly-optimized PAC family of ICs powered by the ARM Cortex-M0 processor combined with highly sophisticated, configurable analog and power management peripherals offer solutions that meet the processing needed for implementing complex algorithms for variable frequency drives. In addition, fully developed motor solutions including hardware platforms and firmware IP for sensor-based and sensorless motor control can significantly help to reach cost parity while developing with BLDC and PMSM motors. EE

Applications that require the use of FOC will find features in a PAC52XX motor, which offer the optimal balance between cost and programmability for FOC applications.

ABOUT THIS ARTICLE AND ITS AUTHORS

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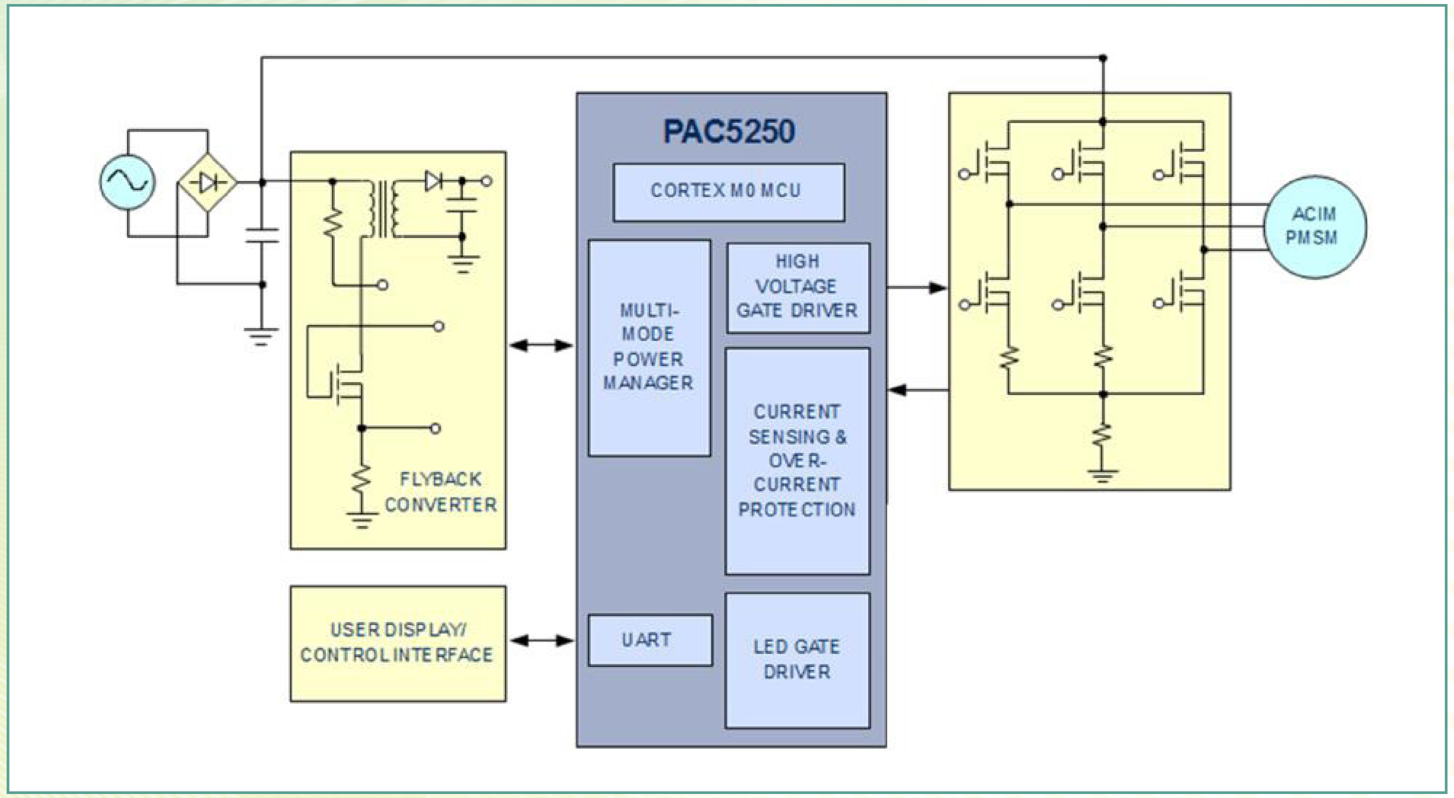

Figure 4. Integration of all major functionality into the PAC5250 offers enhanced performance and limits the additional BOM to passive components, hence reduces cost and PCB real estate.

How To GaN

Generation 4 eGan FETs

Improving Electrical and Thermal Performance

Alex Lidow
CEO of Efficient Power Conversion (EPC)

The previous column in this series demonstrated the benefits of the 4th generation of eGaN FETs in low voltage point of load converters. The 4th generation of eGaN FETs is keeping Moore's Law alive with significant gains in key switching figures of merit that widen the performance gap with the power MOSFET in high frequency power conversion. In this installment we will discuss the benefits of the 4th generation eGaN FETs in 48 V_{IN} applications and evaluate the thermal performance of the chipscale packaging of high voltage lateral eGaN FETs.

To read the previous installment, click the image above.

INCREASED VOLTAGE AND FREQUENCY CAPABILITY

As the voltage across the transistor increases, so too do the switching related losses, including the voltage and current commutation losses, P_{SW}, and output capacitance losses, P_{COSS}:

$$P_{SW} = \frac{V_{IN} \cdot I_{OUT} \cdot (Q_{GD} + Q_{GS2}) \cdot f_{SW}}{I_G} \quad (1)$$

$$P_{C_{OSS}} = 0.5 \cdot C_{OSS(ER)} \cdot V_{IN}^2 \cdot f_{SW} \quad (2)$$

Where V_{IN} is the input voltage, I_{OUT} is the device current, Q_{GD} is the gate-to-drain charge, Q_{GS2} is the gate-to-source charge from the device threshold voltage to plateau voltage, IG is the gate driver current, fsw is the switching frequency, and $C_{OSS(ER)}$ is the energy related output capacitance which is determined from the non-linear output capacitance [1].

In the previous column the reduction of the charges, $Q_{GD}+Q_{GS2}$, determining commutation losses, P_{SW}, were compared. The 4th generation family of eGaN FETs reduces the commutation charge by 4.8 times, 8 times, and 5 times respectively for 40V, 100V, and 200V devices when compared to the best state-of-art Si power MOSFETs with the same on-resistance. This significantly reduces the commutation losses in the power device, which dominate loss at lower input voltages.

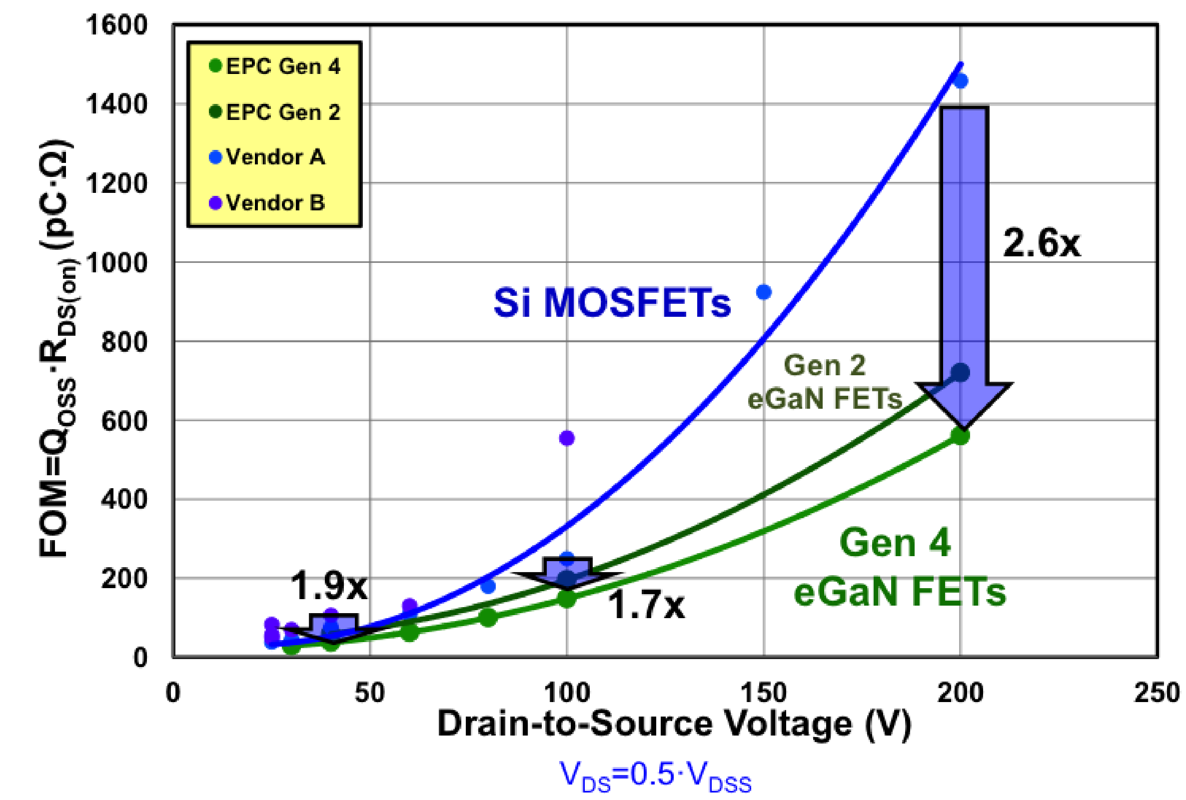

Figure 1. Output Charge FOM comparison of 2nd generation and 4th generation eGaN FETs and state-of-the-art Si power devices.

When moving to higher voltages, the output capacitance loss, P_{COSS}, is often a major source of switching loss. Described in equation (2), they appear to increase as a function of the device voltage squared. In power semiconductor switches, capacitance is not linear and decreases as a function of voltage. The energy related capacitance $C_{OSS(ER)}$, which represents the output capacitance losses, is not common in datasheets, but can be calculated as described in [1]. The output charge, Q_{OSS}, which is commonly provided in datasheets, takes into account the non-linearity of the output capacitance and gives a more accurate estimation of the effective output capacitance than a single capacitance value from the datasheet. The 4th generation family of eGaN FETs reduces the output charge, shown in figure 1, by 1.9 times, 1.7 times, and 2.6 times respectively for 40V, 100V, and 200V devices when compared to the best state-of-art Si power MOSFETs with the same on-resistance, significantly reducing the output capacitance losses in the power device.

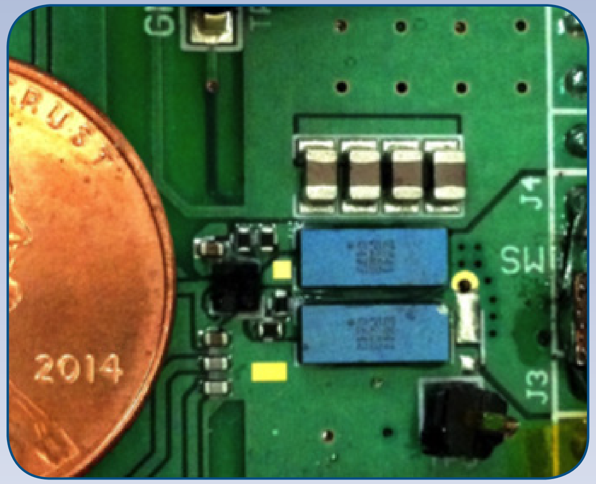

Figure 2a.
EPC9034 4th generation half-bridge development board.

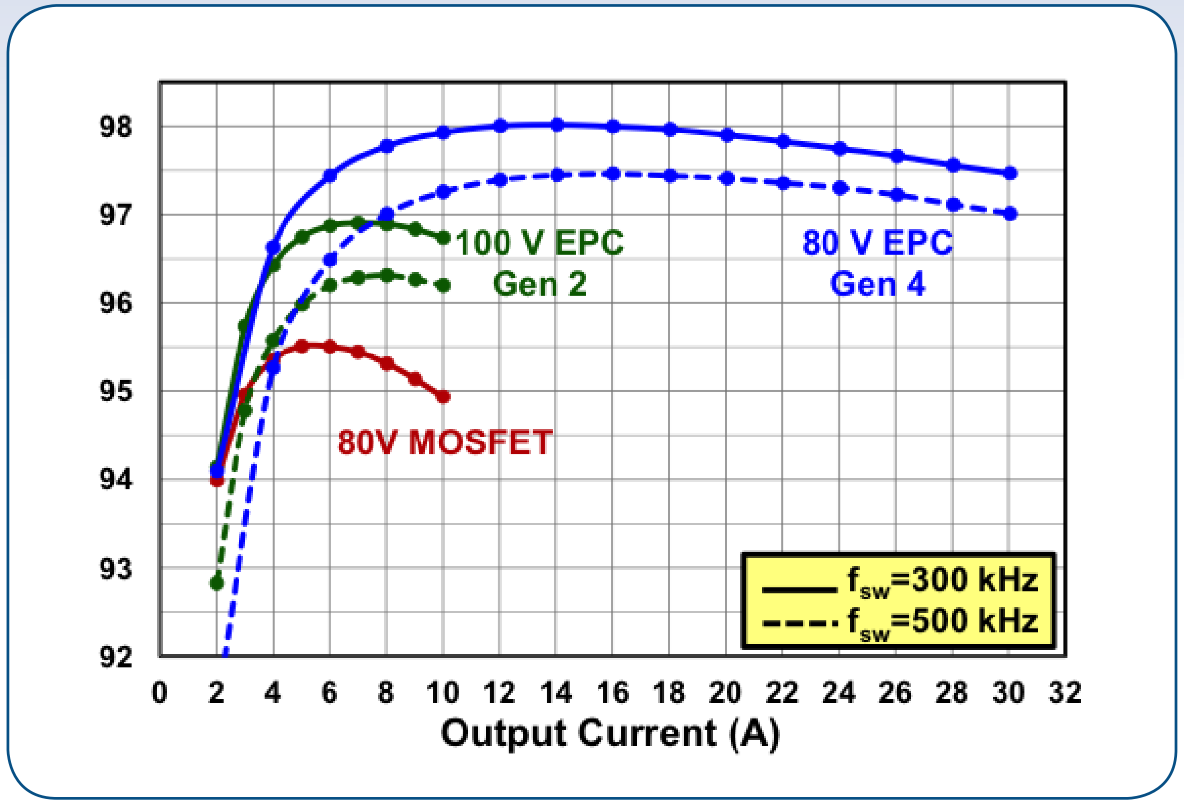

Figure 2b.
Experimental efficiency comparison between GaN and Si based non-isolated buck intermediate bus converters, V_{IN}=48 V to V_{OUT}=12 V, 300 kHz and 500 kHz (blue: 4th generation 4 eGaN FET curve, Top:EPC2021, Synchronous Rectifier:EPC2021, L:Coilcraft SER2915L-472KL; green: 2nd generation eGaN FET curve, Top:EPC2001, Synchronous Rectifier:EPC2001, L: Coilcraft SER1390-103ML; red: Si MOSFET curve, T: BSZ123N08NS3 G SR: BSZ123N08NS3 G, L: Coilcraft SER1390-103ML).

Figure 2 shows the experimental system efficiencies of the 48V to 12V, 30A non-isolated buck intermediate bus converters operating at a switching frequency of 300 kHz. The 4th generation eGaN FET-based design achieves efficiencies above 98% demonstrating the superior in-circuit performance of the 4th generation eGaN FET power devices compared to the 2nd generation of eGaN FETs (shown in green), and Si MOSFETs (shown in red). At 300 kHz and 10A, the eGaN FET design can reduce the system power loss, which includes the inductor and driver, by 60% when compared to the MOSFET design. With the improved performance provided by eGaN FETs, higher frequency can be achieved without significantly sacrificing efficiency, shown in figure 2(b) are the efficiencies of the 48V to 12V buck converters operating at switching frequencies of 500 kHz.

IMPROVING THERMAL PERFORMANCE

Combined with the increasing current density and switching speeds, power devices must be accommodated in an ever decreasing board area and therefore must also become more thermally efficient. A high-density power device must not only be more electrically efficient by generating less heat, but also enable superior heat conduction properties.

The thermal efficiency of a package can be determined by comparing the two parameters, $R_{\theta jc}$ and $R_{\theta jb}$, normalized to the package area. $R_{\theta jc}$ is the thermal resistance from junction-to-case, defined here as the thermal resistance from the active part of the eGaN FET to the top of the silicon substrate, including the sidewalls. $R_{\theta jb}$ is the thermal resistance from junction-to-board, which is the thermal resistance from the active part of the eGaN FET to the printed circuit board (PCB). For this path the heat must transfer through the solder bars to the copper traces on the board. In Table 1 is a compilation of thermally related characteristics for several popular surface mount MOSFET packages as well as two popular eGaN FETs.

Device Package	$R_{\theta jc}$ (°C/W)	$R_{\theta jbB}$ (°C/W)	Area (mm²)
Blade [4]	1	1.6	10.2
CanPak S [5]	2.9	1	18.2
CanPak M [6]	1.4	1	30.9
S308 [7]	-	1.8	10.9
S308 Dual Cool [8]	3.5	2.7	10.9
Super SO8 [9]	20	0.9	30.0
Super SO8 Dual Cool [10]	1.2	1.1	30.0
EPC2001 [3]	1.0	2.0	6.7
EPC2021 [2]	0.5	1.4	13.9

Table 1.
Comparison of package area and thermal resistance components $R_{\theta jc}$ and $R_{\theta jb}$.

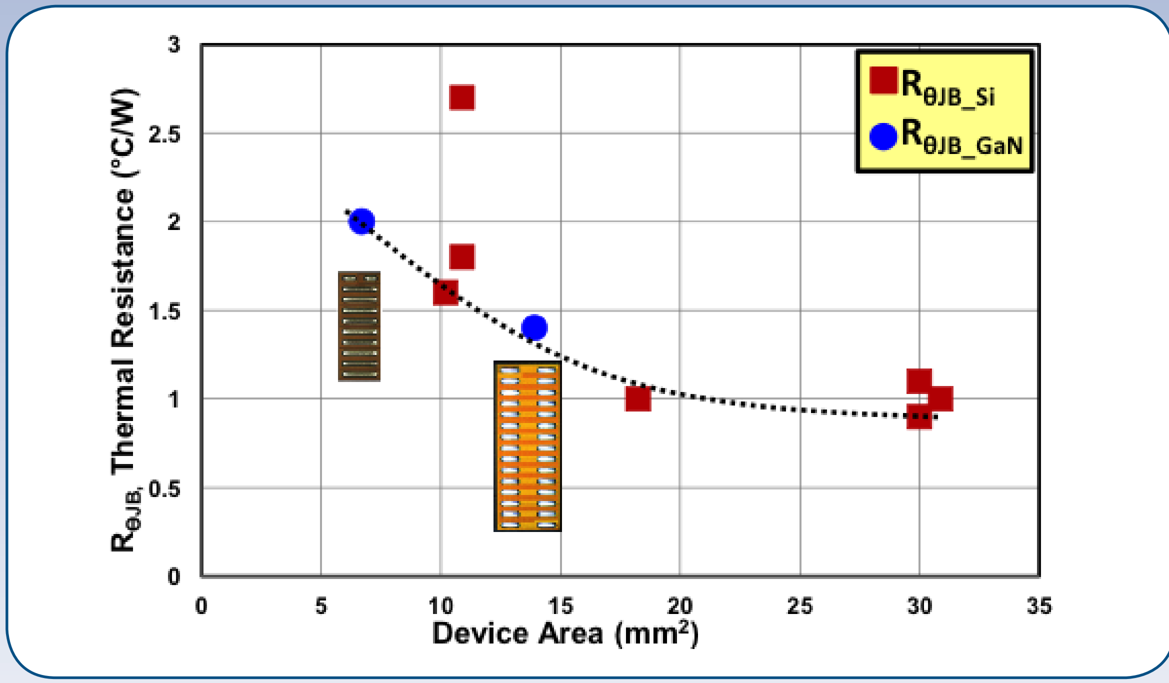

Figure 3.
$R_{\theta jb}$ *(Junction-to-Board Thermal Resistance) for several package styles listed in table I, eGaN FETs represented by blue circular dots and Si MOSFETs represented by red square dots.*

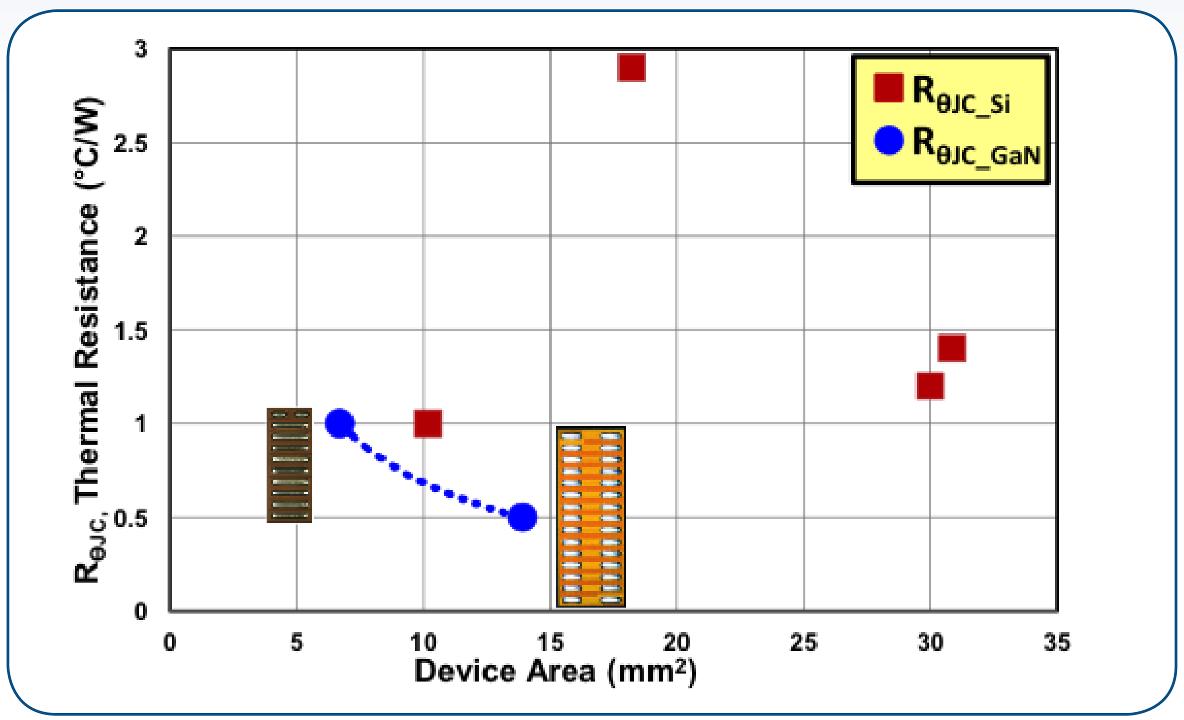

Figure 4.
$R_{\theta jc}$ *(Junction-to-Case Thermal Resistance) for several package styles listed in table I, eGaN FETs represented by blue circular dots and Si MOSFETs represented by red square dots.*

Figure 3 shows a plot of the junction-to-board resistance ($R_{\theta jb}$) for each of the packages given in Table 1. Red square dots represent the MOSFET packages, and blue circular dots represent the eGaN FETs. The majority of the sampled packages fall on a single trend line indicating that performance for this element of thermal resistance is determined primarily by package size, and not technology. In contrast, the plot in Figure 4 shows the thermal resistance from junction-to-case ($R_{\theta jc}$). The CanPAK and double-sided cooling SO8 packages are far less efficient at extracting the heat out of the top of the package than either the Blade package or the eGaN FETs. The eGaN FETs, however, are over 30% lower than even the Blade [4] when normalized to the same area. This makes the eGaN FETs the most efficient thermal package for double-sided cooling and most suitable for high density power designs.

SUMMARY

In this installment of the How to GaN series the performance of the 4th generation of eGaN FETs has been evaluated in a 48 V_{IN} to 12 V_{OUT} non-isolated buck converter achieving efficiencies over 98%. In addition to improved electrical performance, eGaN FETs also have a smaller footprint and superior thermal performance, making it clear that the aging power MOSFET is falling further and further behind GaN-on-silicon power transistors.

The EPC9034 demo board and the 4th generation eGaN FETs are available for purchase. Please visit epc-co.com for more information.

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MIXING SIGNALS: An Introduction to PID CONTROLLERS

{Part 4}

By Sree Harsha Angara
Cypress Semiconductor

To read the previous article in this series, click the image above.

CYPRESS
PERFORM

The PID Compensator

Compensating Second-order Systems

In the previous article, I showed how to compensate simple first-order systems. As a quick recap, a Proportional-Integral (PI) controller is all that is needed for compensating first-order systems perfectly. By perfectly, I mean that you can theoretically achieve any combination of crossover frequencies and phase margins. There is, of course, an entertaining mathematical proof for this, but it is not needed for the purposes of implementation.

We will now move to second-order systems, which constitute the vast majority of practical systems. At last, we come to unveiling the full Proportional-Integral-Derivative (PID) compensator and its implications.

The PID compensator

For the first example, I'll be picking the same second-order example I used in the previous parts of this series:

$$f(s) = \frac{50}{s^2 + 2s + 20}$$

For this example, we want the closed loop to have a crossover frequency of 5Hz and a decent phase margin of around 60 degrees. Before looking into the PID, we should ask ourselves why a PI compensator would not fit the bill. To understand this, let's begin with tuning the loop with whichever empirical rule set you're comfortable with. I ended up with a proportional gain (Kp) of 15 and integral gain (Ki) of 20 with the bode plot shown in Figure 1. In short, there is a horrible phase margin and no amount of fiddling can help. The time response of the compensated system is shown in Figure 2.

The key points to note from the frequency plot are:

1. As we added an integrator, the phase starts at -90 degrees.
2. Adding the proportional part added a zero (remember that PI is a pole-zero combination) and provided a phase boost of +90 degrees.
3. The system has 2 poles, so beyond the resonant frequency (0.72Hz for this example), the phase moves to -180 degrees.

Unlike first order systems, the compensator also needs some form of phase boost to make up for the natural -180 degree phase shift of second order systems. That's where the 'D' part comes in.

> There is an interesting point to be made here. If our requirement is a slower controller with a crossover frequency well below the 2 poles in the system (i.e., the phase never goes to -180 degrees in the region of our interest), we can get away with a PI controller alone—the phase margin won't be an issue. For many practical systems—although the true system may be second order or higher— lower-order compensators like a PI will be sufficient.

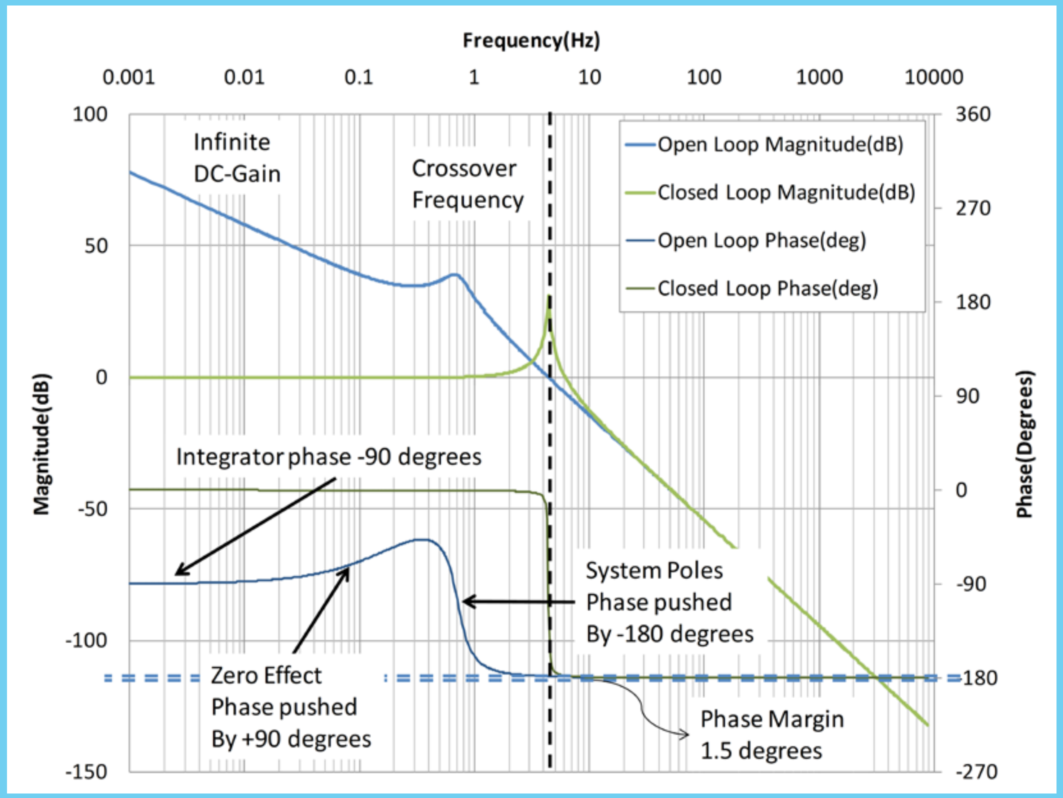


Figure 1. Effect of PI controller on loop characteristics.

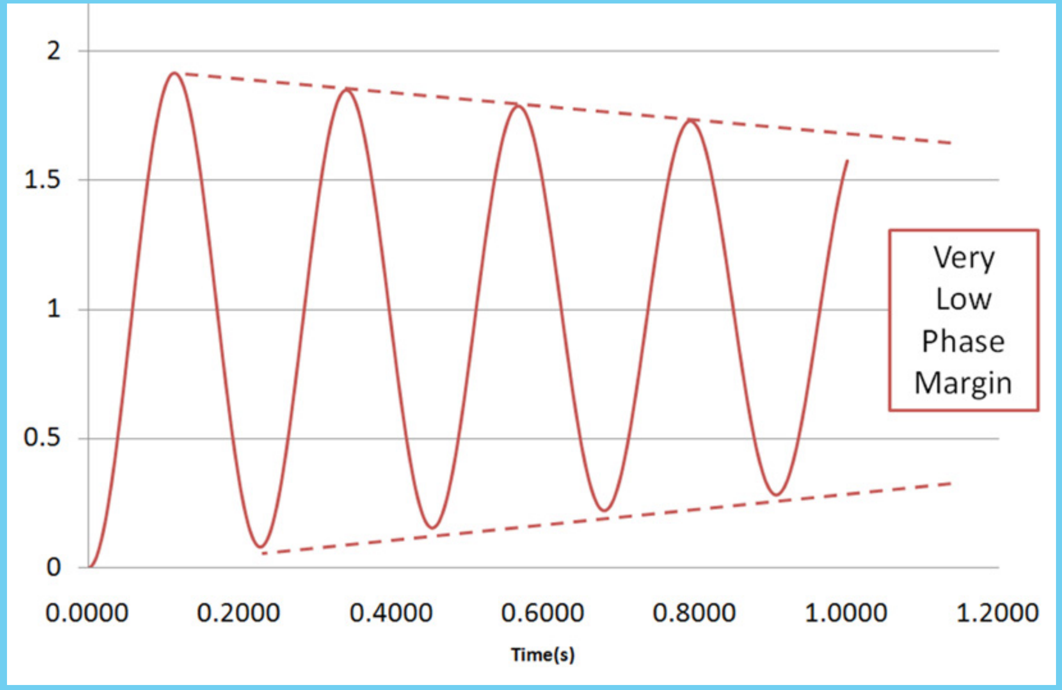


Figure 2. Effect of PI controller – time response.

Although “PID” implies that the final part is a derivative, it’s generally realized as a lead-lag compensator to cancel out the effect of the derivative gain at high frequencies. The lead-lag compensator is of the form,

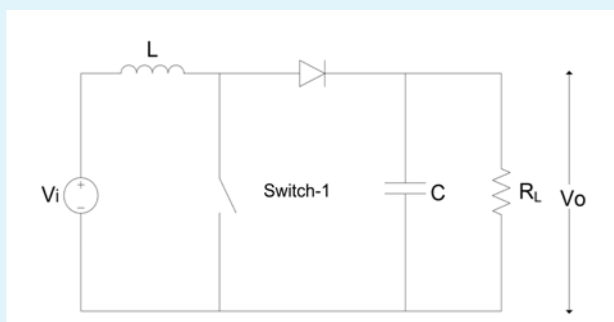
$$Lead\ Lag(s) = \frac{P_z}{Z}\left(\frac{s+Z}{s+P_z}\right)$$

The frequency response of this is shown in Figure 3.

If we add this to our previous controller, we get the response as shown in Figure 4. The key fact here is that the phase margin improves drastically to around 60 degrees without really affecting the crossover frequencies much.

The Boost Converter: A Difficult System

The boost controller in Continuous Current Mode (CCM) can be a notoriously difficult system to control because of its rather unique characteristics. A simple model of the boost converter is shown below:



On a high level, the boost converter boosts the input voltage as a function of duty cycle by pumping energy temporarily into an inductor and then pushing both the inductor voltage as well as the source voltage into the load.

The transfer function of power converter circuits is typically done by linearizing over a switching cycle and is a procedure described in great detail in most reference textbooks. I’ll be skipping straight to the transfer function of duty cycle versus output voltage. The expression is intimidating to look at, but the key point here is the additional zero on top of the two poles.

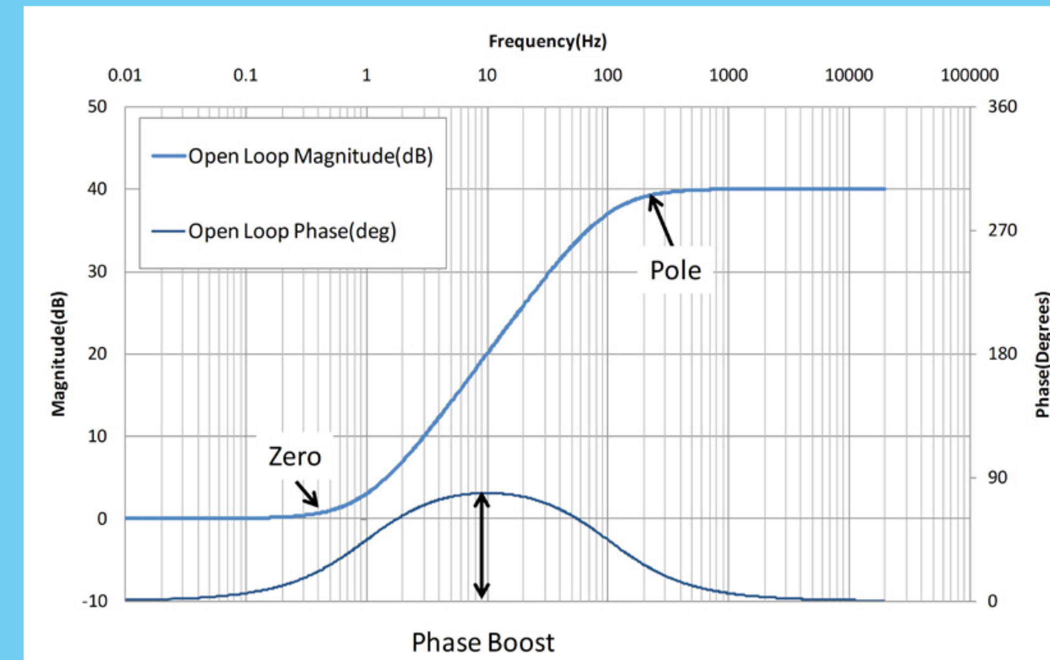


Figure 3. Lead-lag compensator frequency response.

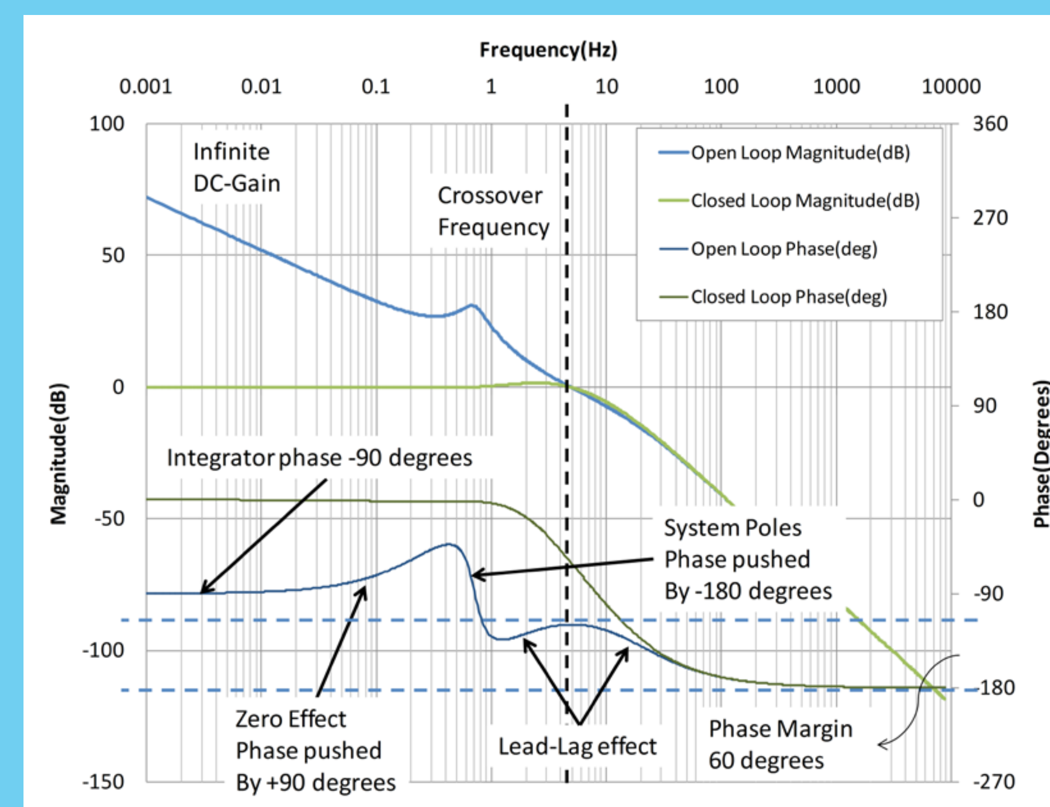


Figure 4. PI with lead-lag compensating a second-order system.

$$\frac{\hat{V_o}(s)}{\hat{d}(s)} = \frac{\frac{V_i}{(1-D)} * \left(1 - \frac{sL}{(1-D)^2 R}\right)}{1 + \frac{sL}{(1-D)^2 R} + \frac{s^2 LC}{(1-D)^2}}$$

Where,
V_i is the input voltage
V_o is the output voltage
D is the steady-state duty cycle
d is the small-signal duty cycle

Wait—if we are controlling the duty cycle, then why is there a steady-state duty cycle (D) term present in the transfer function as well? Here's the catch: for many power converters, the transfer function heavily depends upon the quiescent operating point (i.e., steady state duty cycle). For example, the step response variations between a 20% duty cycle and a 40% variation duty cycles are shown in Figure 5. So when designing loops for power converters, always know the operating point.

The step response also exposes the problematic aspect of the transfer function. The output swings in the opposite direction of the control initially. Physically, this can be understood as when we increase the duty cycle, the amount of ON time of Switch-1 increases. This means that initially the load is disconnected for a tad bit longer and the capacitor begins to discharge before the inductor supplies the extra energy. This also explains why the swing is larger at higher duty cycles (D = 0.4).

This transfer function characteristic is why most boost controllers are current controlled, which reduces the transfer function to a simple first order system. However, if you really want to control the boost with simple voltage mode control (to avoid current sense), the easiest approach is to make a slow compensator with a simple PI controller well below the resonant L-C poles as shown in Figure 6.

Now that we've seen all the mathematics involved in PID compensators, next time we'll explore how to implement these compensators in a real system. We'll also look at questions regarding analog versus digital, whether math helps in real systems, and how real life limitations affect these systems. EE

If you have comments or questions about the article, please click here to contact the author through his EEWeb profile.

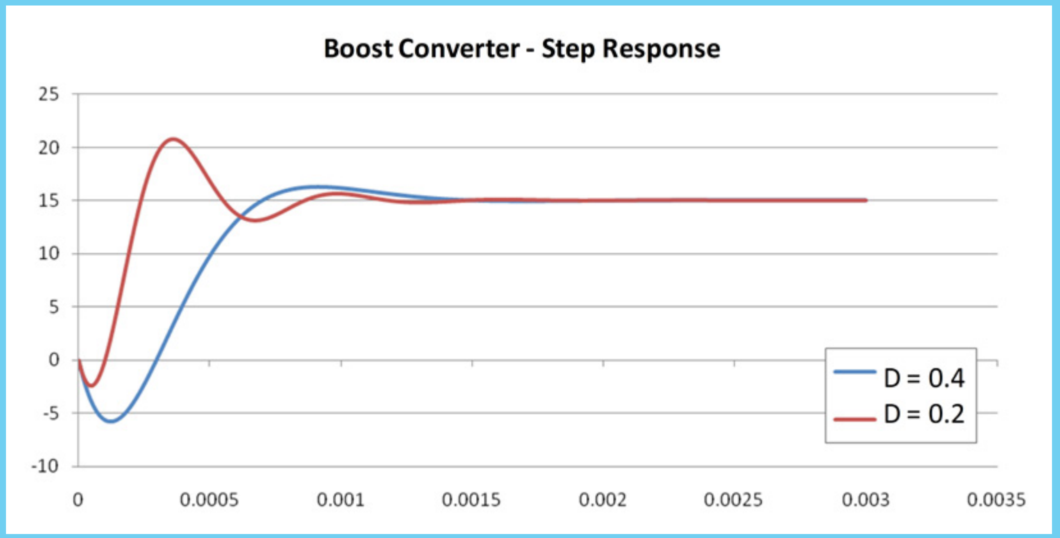


Figure 5. Boost Converter - Scaled step response with different operating points.

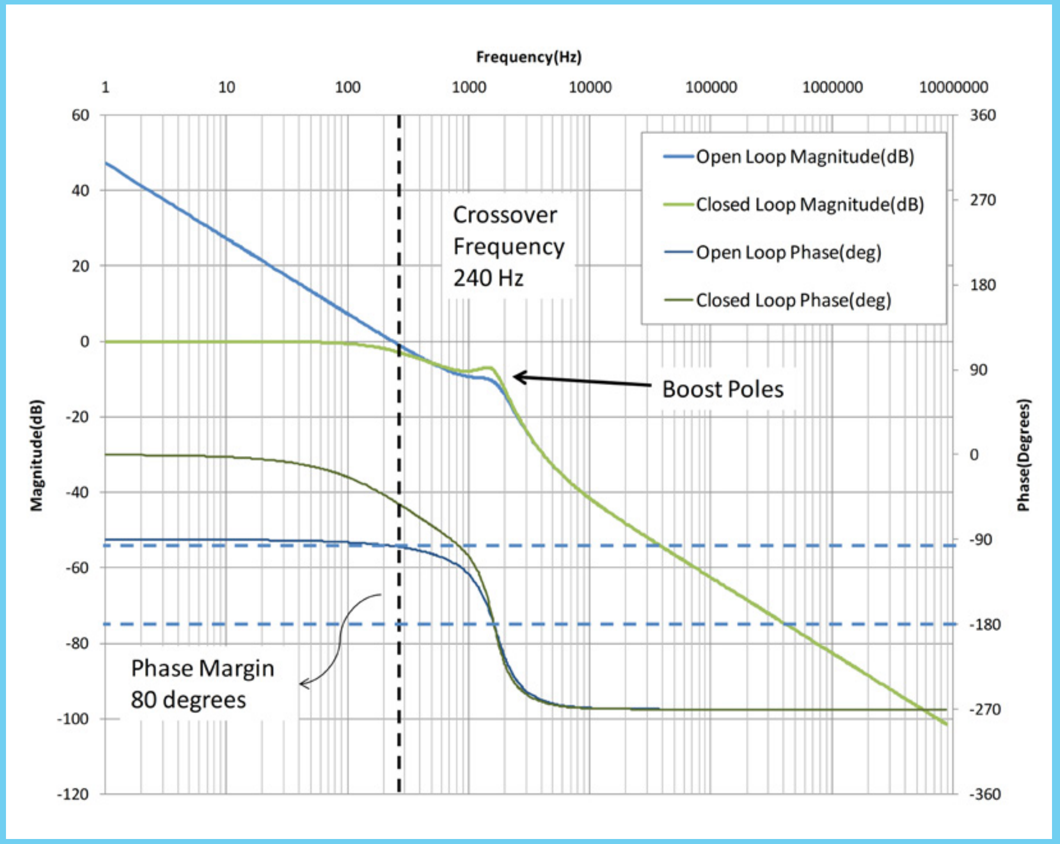
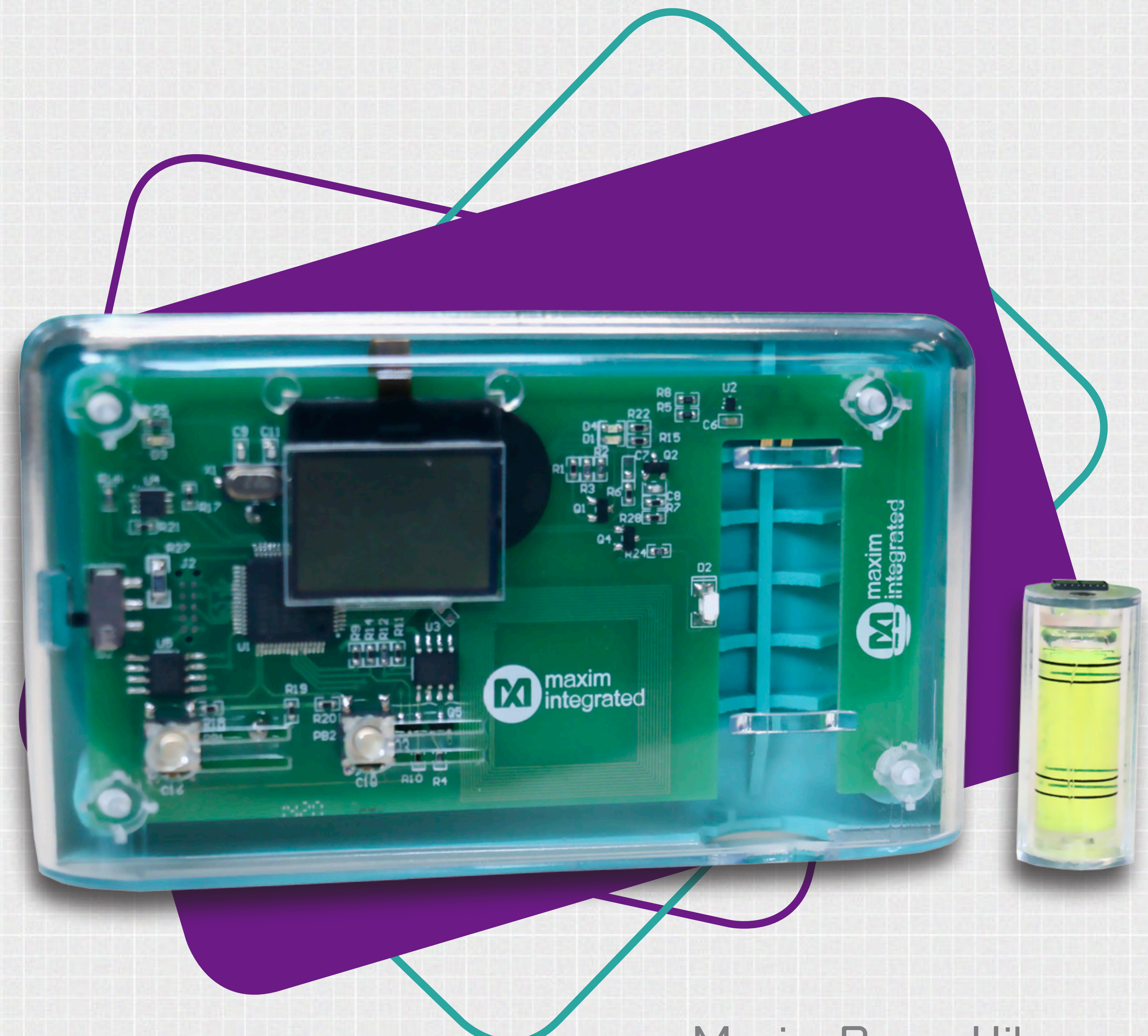


Figure 6. Compensated Boost Converter.



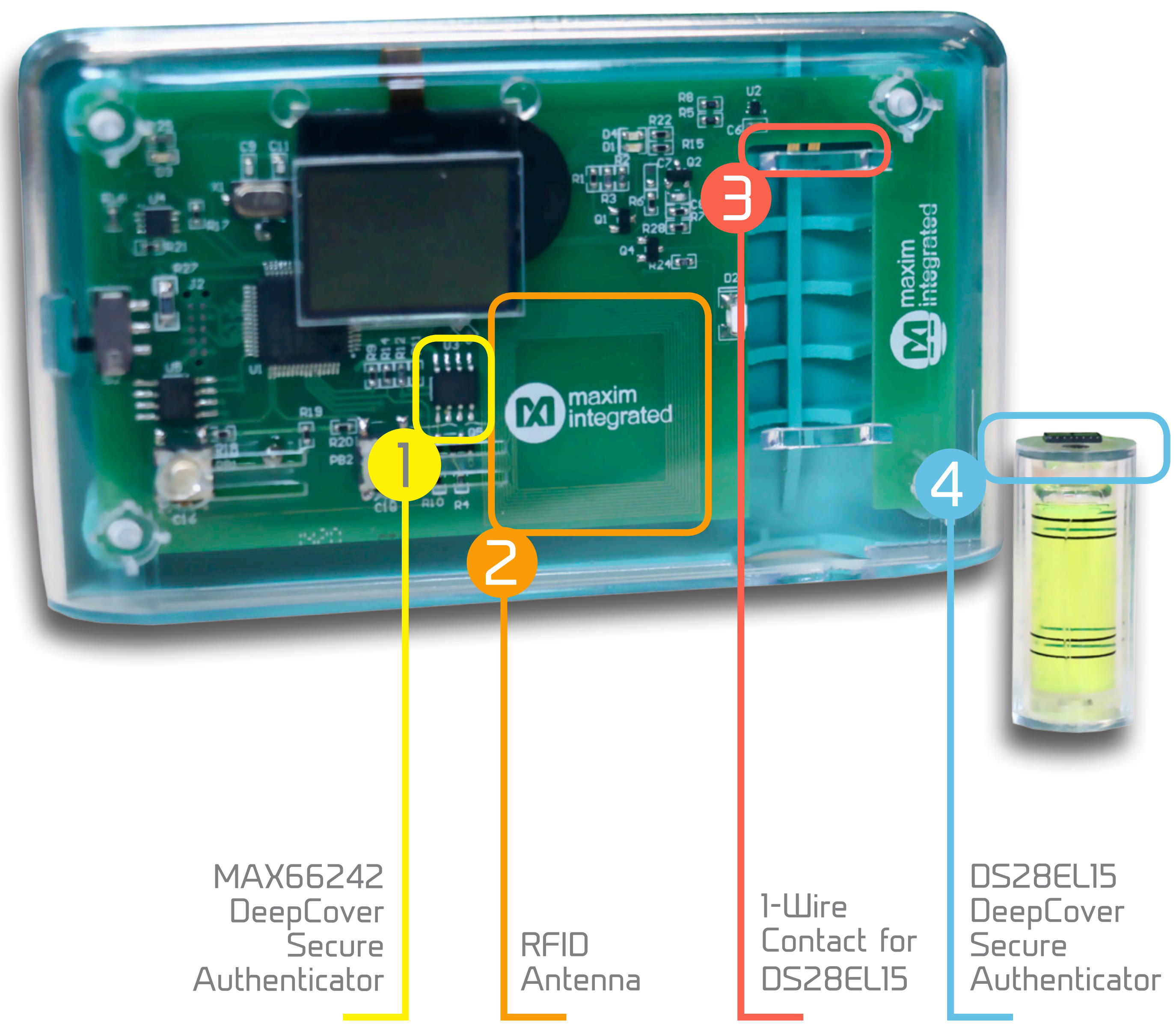
Maxim Demo Kit

Maxim DeepCover

Secure Medical Authenticator

There is a growing movement within the healthcare industry towards patient self-care—one that enables patients to manage certain aspects of their treatment, such as prescription drug delivery outside of the provider's guidance. Given the growing costs of some injectable biologic treatments, both doctors and insurance providers are posed with new concerns as to whether such costly treatments prescribed will be administered by the patient correctly or even whether the medicine itself is not counterfeit, diluted, or tampered with. Without safeguards in place, the convenience of self-care is likely to remain tarnished by these concerns. Luckily, Maxim has developed a demo kit based on their MAX66242 and DS28EL15 DeepCover® Secure Authenticators that will remotely connect the patient and doctor to quell these concerns.

Hardware



Specs

By Maxim's model, a patient would receive their vials of medication and insert them into the injector, which detects whether or not the medicine is genuine. To do this, each vial has a DS28EL15 authenticator with Maxim's 1-Wire® contact package on the end. Through an electro-mechanical contact, the vial is read by the host MCU when inserted, allowing the host to verify the drug's authenticity. If the drug fails authentication, OEMs could prevent it from being dispensed, or warn the user prior to dispensing. The patient can use an app linked to a mobile NFC-enabled device that authenticates the injector to the host network, which reports data back to the healthcare provider such as dates, times, dosages, and authenticity of the medication that was administered to the patient. This allows for verification back to both the healthcare and insurance provider that the drug administered is genuine and the treatment plan is being followed as prescribed.

Watch Video

To watch a video overview and demonstration of Maxim's medical demo kit, click the image below:

Mike Toutonghi
CEO and Founder
of Functionalize

Photo by Jiri Subrt

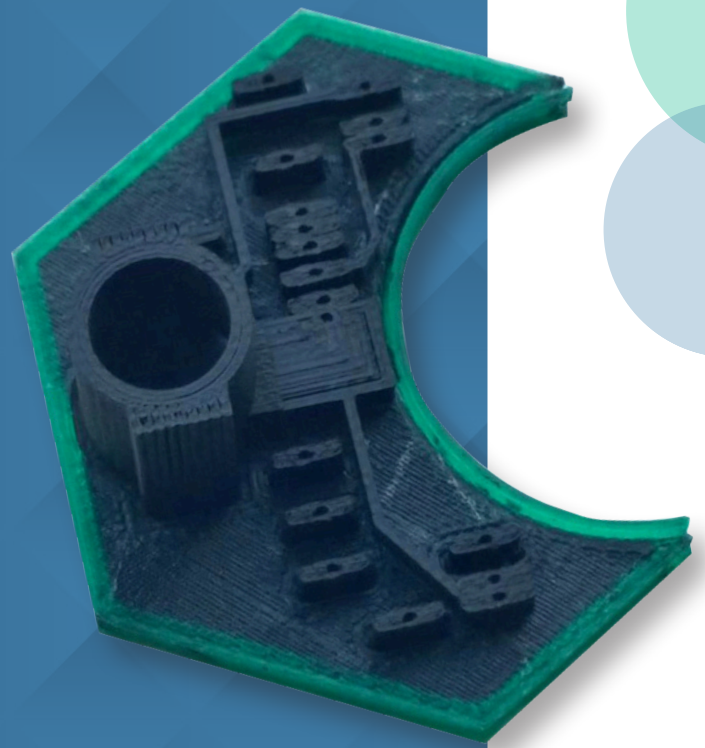
FUNCTIONALIZE Helms 3D Printing Revolution

Ultra-conductive Filament Enables Printable Electronics

The rise of the 3D printer has undoubtedly revolutionized the maker industry. With dozens of 3D printing startups popping up around the world, it is easier than ever to print anything from artifact replicas to eyeglass frames. These popular 3D printers utilize polylactide or acrylonitrile butadiene styrene filaments (PLA or ABS for beginners), which make for strong and durable 3D objects.

But for former Microsoft executive Mike Toutonghi, this was not enough. His most recent venture is Functionalize, a 3D materials and technologies geared startup that produces something not previously seen in the industry. Where 3D printers rocked the world by adding dimensionality to traditional printing methods, Functionalize aims to add another game-changing factor to the process: ultra-conductivity.

EEWeb spoke with Toutonghi about the boundless possibilities for this conductive material and the surprising origin for Functionalize: a grade school science fair.



The F-Electric material is the most conductive filament you can buy, boasting over 1,000 times more conductivity than any filament available today.

"It was a couple years ago on my birthday," Toutonghi began, "and I was talking to my son about an upcoming project fair at his school." The idea of working with his son was both new and exciting for Toutonghi—after years of working at Microsoft and various Seattle software startups, this certainly was a change of pace. The father son team sought to create an electromagnetic rocket ship and quickly got started on developing a circuit for the launch system. After a few iterations, they settled on a design that required a fair amount of soldering—a nightmare for novice engineers. Toutonghi already had the 3D printer for printing the launch pad, and assumed he could simply print the system circuitry using conductive filament. "I found no way to do it," Toutonghi said, "I even looked at higher-end printers and called conductive plastics companies for 3D printing filaments." The results were surprisingly sparse.

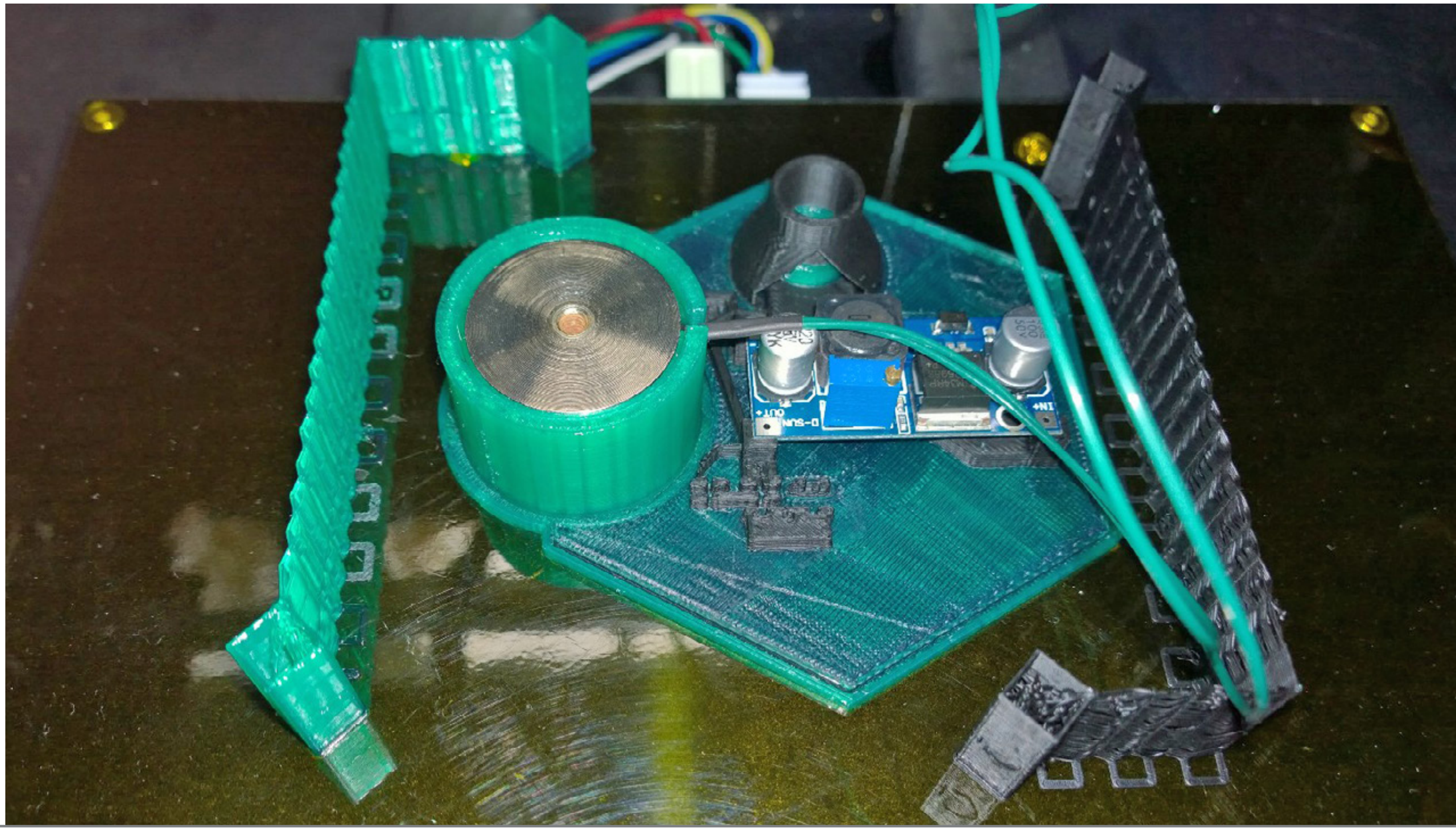
However, Toutonghi saw an opportunity in the unmet market demand for ultra-conductive 3D printable filament. He started diving into literature on how to develop a process to extrude a filament as a thermoplastic. This research eventually led to buying equipment to build a laboratory that would allow him to build nanomaterials and combine them with different polymers. "I was having positive results with my tests and I knew there was a lot more to do," he said. So months after his son's science fair, Toutonghi went part time as CTO of Parallels to start his new conductive filament company, Functionalize.

Toutonghi already knew there was a need for this material in the market based on his extensive research. He decided to harness this demand into a Kickstarter funding campaign with a few goals in mind. "Our first goal was clearly to get the message out," Toutonghi explained. "We really wanted people to know about the invention and to gauge how investors as well as Kickstarter supporters would respond." In that sense, the campaign has been a success. With a fairly modest goal of $100,000, Functionalize saw over 30-percent funding in one month, with a number of large investors in talks to eclipse the funding goals by an order of magnitude.

The Kickstarter funding campaign also reinforced Functionalize's goal of gearing not only towards industrial applications, but in academia and homemade, do-it-yourself projects. "We have had a major university reach out to us for a potentially huge collaboration," Toutonghi hinted—legally light on details.

The demand for this material is clearly there, and the Functionalize F-Electric filament has the specs to back it up. In addition to measuring a volume resistivity under 1-ohm centimeter, since announcing the Kickstarter, the Functionalize team has been doing frequency response measurements to measure its conductivity. "We have

"F-Electric is compatible with most popular 3D printers available today."



been seeing a bandwidth of almost 200MHz," Toutonghi explained, "with a flat RF response on a match terminator transmission line up to 600MHz."

So what do all these specs mean? Well for one, the F-Electric material is the most conductive filament you can buy, boasting over 1,000 times more conductivity than any filament available today. This means users can now print circuits, power connectors, and buttons right inside the printed objects. This poses huge potential benefits for the future of the maker industry. With wearable technology and interconnected devices on the rise, Functionalize's filament can enable users to print devices with embedded circuitry all within the 3D printing process, meaning smaller form factors and reduced production complexity. The F-Electric filament is also compatible with most popular 3D printers available today, meaning this game-changing material can seamlessly integrate with preexisting printing setups. Now, Toutonghi is looking past the Kickstarter campaign; "While F-Electric is a breakthrough in conductive 3D printing filament, the technology we employ to make it has much broader applicability. Functionalize has developed a patent-pending set of reactions to enable the creation of a variety of new functional materials in polymer matrices (including PLA, ABS, Nylon, Polystyrene, PMMA, and others), which makers and commercial businesses will be able to use to design, prototype, and build functional products." EE

The Open Source Movement Takes Flight

3DR's PERSONAL DRONES Offer New Insights from Above

Interview with
Chris Anderson
CEO of 3DR

There has been a lot of news coverage on drones the past few years. As part of a controversial defense campaign, the US military has been deploying armed drones in areas of conflict—replacing tens of thousands of American soldiers who are now returning home. These unmanned aircraft can carry out dangerous missions while being controlled from virtually anywhere in the world. But drones are not just changing the face of modern warfare—they are now changing the consumer and industrial robotics landscape.

At the helm of the personal drone revolution is 3D Robotics (3DR), one of the largest drone suppliers in the world. Founded by Jordi Muñoz and Chris Anderson, former editor-in-chief of *Wired*, 3DR has sold tens of thousands of drones and autopilots to customers worldwide. Now, the California-based startup is seeing some creative new data collection applications in a wide range of industries, from farm management to civil engineering projects. EEWeb spoke with Chris Anderson about the impetus behind starting 3DR and some of the challenges they face in mass adoption of both personal and commercial drones.

3DR

Where did the idea of a personal drone company come from?

I initially got into robotics in an attempt to get my kids interested in science. We bought a robotics kit and built a three-wheeled tri-bot and all it would do was roll slowly to the wall and back—the kids were completely unimpressed (they had seen Transformers, so it is hard to compete with CGI). So I started thinking; what would a more exciting robot look like? The answer was easy: something that could fly. We literally Googled "flying robot," which yielded a lot of results about drones. Drones are essentially flying robots, so I thought this would be an opportunity to take robots into the third dimension: the air. The recognition of the huge opportunity in the empty space between the ground and satellites was the starting point. The 3D element of robotics has not yet been explored, and drones were the way to do it.

What was the biggest technological challenge in developing 3DR's drones?

The easy part was implementing the parts that used to be hard, like the sensors, gyroscopes, accelerometers, and the GPS. All of these things are now easy additions thanks to the smartphone revolution. This started in 2007, back when MEMS sensors started becoming widely available because of sensor-driven devices like the Nintendo Wii controller and the iPhone. The industry saw different prototyping tools with 3D printing that came out that year as well, which prompted what is now known as the maker movement. If you were paying close attention, 2007 was the year where the hardware space got really interesting, all because of the smartphone revolution.

The hard part for 3DR was the software and the level of sensor fusion needed to get a drone flying well. Magnetometers are inherently difficult to operate reliably in the real world. Dealing with the signal noise issues in real world applications and dealing with sensor fusion across dozens of sensors is algorithmically challenging. Once we figured the software out, the next hard part was ramping up the traditional manufacturing in our state-of-the-art manufacturing facility in Tijuana, Mexico.

Ten years ago, did you ever imagine a world where there were affordable personal drones?

Technology speaks to us and tells us where it wants to go. The fact that I hadn't initially thought of working with drones and the technology it would enable is not abnormal. The technology at the time was just not ready. It is not surprising when big industrial products become cheap consumer products. The Internet did this to the telecomm industry, the PC did this to computing, and you could argue that the drone did this for the aerospace industry. The fact that you need to put the word "personal" in front of a traditional industry is completely normal—this is exactly what Silicon Valley does.

> "The 3D element of robotics has not yet been explored, and drones are the way to do it."

X8+ Copter in case (left) and assembled (right)

Is there a technology barrier right now that is preventing 3DR from achieving certain specifications?

The biggest area right now is something called "sense and avoid." Now that we have drones flying autonomously and inexpensively, we have to ensure they do so safely and responsibly. Once a drone gets into the air, it is in Federal Aviation Administration (FAA) territory. The FAA primarily deals with keeping vehicles apart through notifying pilots and air traffic control. The problem with drones is that there are no pilots and they are not on air traffic control's radar. These drones have to essentially look out for obstacles themselves, which is what sense and avoid is all about. The ability to identify a potential airspace confliction and avoid collision with another aircraft is a very challenging problem for us. We know it can be done because we have the technology, but we have to convince the FAA that it could work. Until we can prove that robots are significantly better than humans at always-on detection and avoidance, there will be continual resistance to allowing drones to get above 400 feet, which is the current limit.

What kind of impact do you think these drones will have on the average user over the next few years?

Right now, the industry has been selling between 500,000 to a million drones every year on a global level. The drones offer a unique user experience; the user simply pushes a button, the drone goes airborne, and it can follow them and keep the camera focused on them—it is essentially drafting off of the GoPro phenomenon.

The commercial side, which is currently limited by regulation, will be a much bigger market. It can focus on things like agriculture and farm management, construction and civil engineering projects, search and rescue, and countless others. The drones can be tools to bring big data to industries that don't currently have it. Agriculture is the biggest industry in the world, and construction after that, and both have yet to be transformed by data. Drones will bring the data to them.

What is else is needed to ensure mass adoption and acceptance of personal drones?

We have started to do very specialized embedded electronics—which is what our autopilots are—and as we continue this notion of surfing behind the smartphone industry and seeing what they do next, we will see a convergence of the other industries that are adjacent to smartphones. This can be seen with wearables, the Internet of Things, and robotics. What this means is that we are increasingly using the same chips, the same operating systems as these adjacent industries. As we move from writing code, to real time operating systems, and now on to Linux, we have moved from an ad hoc industry to more of a formal organization under the Linux Foundation and the Dronecode Foundation. We are basically on convergence with these other industries that are currently being transformed.

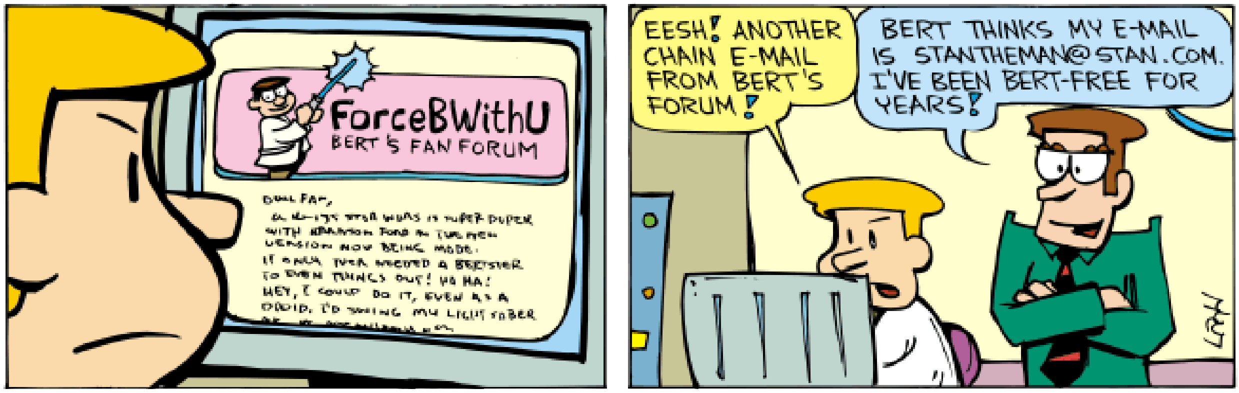
We are also aiming to align with Robot Operating System (ROS), which is an industry standard. We can then start to create standard processors and standard sensors to the point where we can turn it into an entire drone platform. That would be really powerful because we can stand on the shoulders of all these other industries by using the same software tools and libraries. Drones can move from a special category to something a part of a much broader transformation of the hardware space. EE

IRIS+ Personal Drone

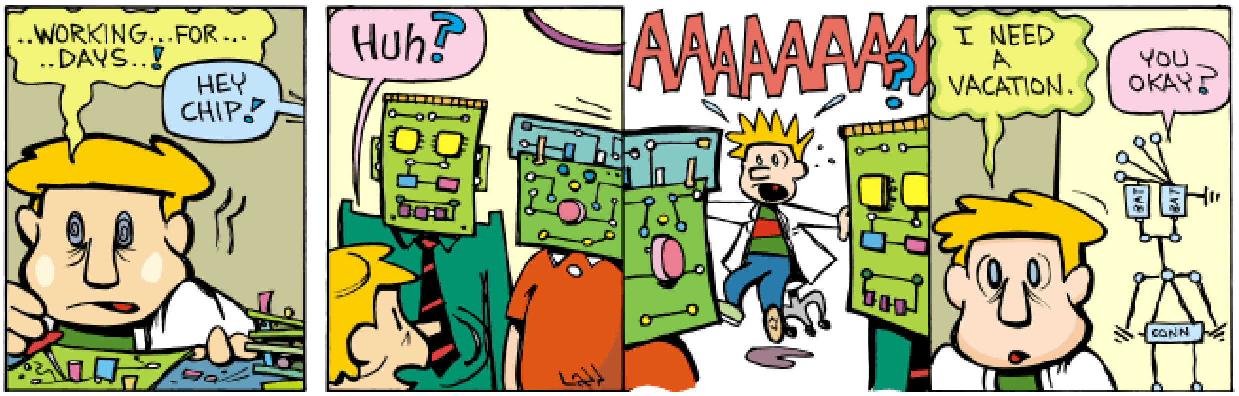
"Agriculture is the biggest industry in the world, and construction after that, and both have yet to be transformed by data. Drones will bring the data to them."

Return-to-ZERO

Spam Shield



Circuit Illusion



Circuits Quarterly