Volume 40, Number 4, 2006

Analog Dialogue

A forum for the exchange of circuits, systems, and software for real-world signal processing

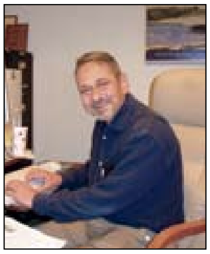
In This Issue

40 years of Analog Dialogue 1967 2006

www.analog.com/analogdialogue

ANALOG DEVICES

Editors' Notes



At the close of two-score years in print, we look back … heck, we can *all* look back at every issue[*] that ever rolled off the presses, just as they appeared at the time—including Volume 1, Number 1 (1967)—thanks to scanning and the miracle of PDF. Moreover, a more portable physical embodiment of the totality of *Analog Dialogue's* 40-year substance through 2006, a CD version, will soon be available, replacing the four bulging binders that are currently needed to contain the paper-and-ink version.

When it arrives, we will recommend the CD to our fans, to history lovers and reference librarians and their clientele everywhere, as a private refuge from the crowded, noisy, crime-ridden, sometimes dangerous highways and byways of the Internet.

Dan Sheingold [dan.sheingold@analog.com]

NEW WEB FEATURES FOR 2007

As our screens got bigger and our eyes get weaker, we chose to stop catering to the small-screen crowd at the expense of the overwhelming percentage of readers who are using screen resolutions of 1024 × 768 or higher. Please let us know if you like the new online format[†]—or think we should revert to the original. We also added a new feature, the *Back Burner*, which is sure to become one of your favorite spots. It will include teasers, design and test tips, tutorials, and other information of interest to designers. Please let us know of any topics that you would like to have covered in future issues.

IN THIS ISSUE

Mechanical buttons, switches, and jog wheels have long been used as interfaces between users and machines, but their many drawbacks have led designers to look for more reliable solutions. Capacitive sensors, which can be used in place of buttons, can also add versatility. Available ICs can measure the capacitance of up to 14 sensors, compensate for environmental changes, and provide a digital output.

The picture quality available from cell phone cameras is constantly improving. Autofocus is standard in many high-resolution cameras, and optical zoom, shutter control, and image stabilization are becoming common. These features require the lens to move rapidly. Lens drivers power the motors that move the lens in response to digital signals.

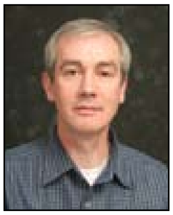
New isolation capabilities—including integrated, isolated power and truly bidirectional isolation channels—are greatly simplifying the design of isolated systems. Fueled by a shift from LED-based optocouplers to chip-scale microtransformer technology that is compatible with standard CMOS processes, they fit more functionality into a single package.

As always, your comments are welcome.

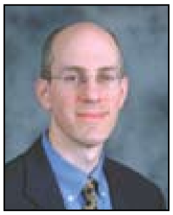
Scott Wayne [scott.wayne@analog.com]

AUTHORS

Gary Casey (page 10) is a staff engineer with the DAC Applications Group in Limerick, Ireland, providing support for lens-driver products. Gary graduated from the University of Greenwich, London, with a BEng (Hons) degree in electronic engineering in 1991. He joined Analog Devices in 1996.



Mel Conway (page 10) is a product marketing manager for lens-driver products, based in Limerick, Ireland. In 2000, Mel joined DAC Marketing at ADI after having worked in applications-, design-, and marketing roles at other electronics companies. His global responsibilities in Germany and Ireland are well-served by his experience with mixed-signal- and power devices—and software. Mel has many interests, but his wife and daughter are his top priorities.



David Krakauer (page 13) is marketing manager for ADI's *i*Coupler isolation products. Previously, he was the product manager for *i*MEMS gyro products in ADI's Micromachined Products Division and strategic marketing manager for Mixed-Signal DSPs. Prior to joining Analog Devices, David was a device and reliability engineer at Digital Equipment Corporation, and was also product development manager for DEC's graphics-accelerator ICs. He holds four U.S. patents and has authored or co-authored 10 papers on solid-state physics and reliability. He holds BS and MS degrees in electrical engineering and computer science from MIT and an MBA from MIT's Sloan School of Management.

Mark Murphy (page 10) is a senior engineer with the DAC Applications Group in Limerick, Ireland, providing support for lens-driver products. Mark holds a BSEE from Merrimack College and an MBA from the University of Limerick. He joined ADI in 1988.

Susan Pratt (page 6), a senior applications engineer with responsibility for ADI's resistive and capacitive touch controllers, graduated from the University of Limerick (Ireland) with a BEng in electronic engineering. She joined Analog Devices in 2002 and is based in Limerick.

Analog Dialogue

www.analog.com/analogdialogue **dialogue.editor@analog.com**

Analog Dialogue is the free technical magazine of Analog Devices, Inc., published continuously for 40 years—starting in 1967. It discusses products, applications, technology, and techniques for analog, digital, and mixed-signal processing. It is currently published in two editions—*online*, monthly at the above URL, and quarterly *in print*, as periodic retrospective collections of articles that have appeared online. In addition to technical articles, the online edition has timely announcements, linking to data sheets of newly released and pre-release products, and "Potpourri"—a universe of links to important and rapidly proliferating sources of relevant information and activity on the Analog Devices website and elsewhere. The *Analog Dialogue* site is, in effect, a "high-pass-filtered" point of entry to the **www.analog.com** site—the virtual world of *Analog Devices*. For history buffs, the *Analog Dialogue* archives include all regular editions, starting with Volume 1, Number 1 (1967), plus three special anniversary issues.

If you wish to subscribe to the print edition, please go to **www.analog.com/analogdialogue** and click on **<subscribe>**. Your comments are always welcome; please send messages to **dialogue.editor@analog.com** or to these individuals: *Dan Sheingold*, Editor **[dan.sheingold@analog.com]** or *Scott Wayne*, Managing Editor and Publisher **[scott.wayne@analog.com].**

---

[*] See http://www.analog.com/library/analogdialogue/archives.html

[†] Take a look at http://www.analog.com/analogdialogue

ISSN 0161-3626 ©Analog Devices, Inc. 2007

D-Day (continued)
[The Wit and Wisdom of Dr. Leif—5]

By Barrie Gilbert [barrie.gilbert@analog.com]

Niku's Daedalus Day presentation began in Volume 40, Number 3. The complete series can be found online at www.analog.com/library/analogdialogue/leif1.html.

"This next study will show some results comparing the relative effects of mismatches and noise. Such comparisons can never be precise, for reasons I gave earlier. Not only are mismatches just *interesting cases*; the onset of strong oscillations—the start-up trajectory—also depends on such controllable factors as the rise-rate of the tail current, I_T; the overdrive beyond the critical value, I_{CRIT}; and the load resistance, determining the tank's effective Q. Once these have been chosen, we can compare start-up times, defined as the time from when the tail current crosses I_{CRIT} to the time the oscillations reach 90% of their final amplitude.

"I'm sure all of you appreciate that, frequently, the potency of simulation in gaining insights does not necessitate the use of accurate parameter values, or reliable process statistics, such as are essential in predicting the performance of a production microsym. Rich insights are to be gained from pursuing a well-planned set of comparative studies using relative values that are just as valuable as the *confirmation* of an original design using absolute parameter values …"

Dr. Leif raised his hand politely. Niku caught the gesture and invited his comments. "Yes, sir? Do you have a little song for us?" she teased.

"Perhaps we ought to say '*far more* valuable,' since we should never forget that learning is as much a part of an engineer's job as getting new products to market—and this is as important for our Fusers as for Originators. We must always set aside time in our busy lives to think about those Fundaments, and ceaselessly ask ourselves those vital questions: 'What If?', 'How About?', 'Why does *that* Happen?'. You need to be acutely aware that, while your latest, thoroughly robust, high-yielding, and trend-setting product, which you have managed to get to market in a competitive time-frame, and yet meets every one of its highly challenging performance specifications and goes on to make us all fabulously rich …" (Leif grins as the audience groans, and he takes a brief sip from his water glass) "… while all that is very important, it is the *new insights* that you gained throughout the experience, as well as from the time you put into facing up to *independent*, *self-assigned* challenges—of the sort that Niku is urging you to undertake—they will be the *foundation stones* of your career. New product development frequently requires the use of several distinctively clever ideas. But that is a one-time event. On the other hand, the *new insights* that opened to you, during the experience, become the precious gems you'll add to your own unique treasure trove of tools. These diamond-hard gems of insight will never be far from you, waiting in your subconscious to illuminate and inform the creative work of a long and productive career. I …"

Leif stopped abruptly, as suddenly as he had apparently felt the need to make these interlineal observations. Returning to his front-row seat, he seemed uncharacteristically self-conscious. What next thought that he decided to suppress was in his mind?

"*War das eu'r lied*?" Niku again teased, with a little quote from *Die Meistersinger*—as asked by Hans Sachs, the humble cobbler, of Sextus Bessemer, the town clerk of 16th-century Nuremberg who was attempting to serenade the heroine Eva. From the chats they frequently enjoyed over at Galaxybux, Niku knew that Leif would be in on the joke, and both smiled together at its poignant appropriateness. But the bulk of the audience was perplexed by this unfamiliar four-word exchange, yet increasingly aware of the unusual rapport and the spirited give-and-take between these two. Had they been more informed about widowed Hans Sachs and the young Eva, the parallel would have been evident.

Breaking eye-contact, and seeming to suddenly remember she was in the middle of a lecture, Niku blushed deeply and visibly for the second time in an hour.

"Thank you, Dr. Leif. So … uh, back to our little friend, Oscar. A few minutes ago …" (Or was it a week? Or a century?) "I showed that its internal noise—and the enormous noise-amplification factor—reduce this time to just a few cycles. So, comparisons of start-up time are much too close to be of any use as a source of insight. In fact, for even tiny amounts of [stochastic] noise, the very notion of a *start-up trajectory* becomes moot. Rather, the modulation envelope during startup, which can be seen in this slide" (Micha-2, which had remained frozen on the screen) "is determined by the particular L, C, and R of the tank.

"However, to complicate matters further, the *effective* loading of this tank, embedded in the active circuit—the *in-situ* value—is *not* the value that is conventionally deduced from measurements of the tank alone—the *ex-situ* value. And here, I'm not referring to any incidental, parasitic effects, for example, as caused by the shunt loading imposed by the incremental output resistance of the differential pair. In fact, as I believe I mentioned earlier, to remove all such complicating factors, the transistors are assigned Early voltages (VAF and VAR) of 10^9 volts, and the classical dc beta-modeling factors (BF and BR) are similarly 10^9.

"This is not as fanciful as it might at first seem, because the core properties of the BJT do not depend on these parameters having moderately low values. Indeed, they represent *defects*—rather than *assets*—of the transistor. We long ago gave up thinking of the BJT as a current-controlled current source (CCCS); rather, just like field-effect devices, they are more properly viewed as voltage-controlled current-sources (VCCS). The finite output resistance of a VCCS never did anything *useful* for it; neither does the base current of a BJT, unless you were foolish enough to actually depend on the need for some finite base current.

"Likewise, the depletion capacitances (CJE, CJC, CJS) are just useless baggage, as are the ohmic resistances (RE, RB-RBC, RC), and should not be *depended on* for any specific circuit behavior. Between them, they only increase the *inertia* of a circuit, and the ohmic parts contribute *thermal noise*. They are defects of a BJT. By the way, don't confuse the diffusion capacitance with those parasitics. It is a *direct measure* of the base charge needed to establish a given collector current.

"This perspective—and the practice of stripping the BJT model of all nonuseful attributes during preliminary investigations of new and unfamiliar topologies—is called 'Foundation Design' by Dr. Leif. When every nuance of the cell has been thoroughly understood and accounted for, using what he calls this 'Level 0' model, it is permissible to move forward to a 'Level 1' model, which, for example, might first add in more realistic values of the dc betas and Early voltages, the consequences of quasistatic depletion-layer modulation by the terminal voltages …"

Some in the audience, listening to what was beginning to sound more like philosophy, were manifesting spaced-out expressions; but most were working hard to follow the convoluted contour of Niku's thinking. Leif again wanted to comment and again was polite enough to signify this by raising his hand.

"Dr. Leif?"

"Ah, well, let's see now. First, if you'll forgive me Niku, you're running a little short on time, and I know you have some really interesting discoveries to share with us, about Oscar. I suspect you didn't plan to digress so deeply into these peripheral ideas at the expense of the main theme, did you? Secondly, neither the term 'Foundation Design' nor its principles are mine, although I admit I am a passionate advocate of them. They go *way* back to the last century, and the lectures given by a long-departed ADI Fellow, of whom we hear very little these days. When I get back to my office, I'll issue a cy-mail, and include a reference to his lectures, for the engineering community. Okay. That's it."

"Oh, yes; now I recall, you did tell me that Foundation Design came from a long time back. I'm sorry I got that mixed up. And you're right: I got a bit carried away with some incidental ideas. I was about to explain that another approach to tracing the start-up trajectory is to disable the modeling, and run the simulations in the old SPICE-like mode, when they *didn't* model noise as a time-process. Then, using a variety of representative mismatches we can simply observe how the start-up times compare to the noise-driven case.

"In fact, now that we have seen how very short this delay can be, provided that noise mechanisms are fully modeled, we need to extract some other insights from these studies. To be candid, that was the only reason for starting down this path. I was pretty sure from the outset that noise had to be the driver—in both senses: 'was bound to be' and 'had better be,' and that in all cases where this wasn't so it would be due to unplanned mismatches. But never due to *glitches*! Any oscillator that needs to be started by such gross influences is, as a matter of practical definition, a poor design, since this very sensitivity is almost bound to degrade the phase noise after it reaches its periodic steady state."

"Dr. Yeng?" It was a rather mature lady's voice from two rows back. "That's not quite true. There are times when one wishes to preserve a very high effective *Q* in a different class of oscillator, which would indeed eventually start up because of noise, and in a certain sense *right away*, but would reach its cyclostationary state only after perhaps tens of thousands of cycles; whereas its services are needed immediately following a logic edge that defines t = zero. So one needs to introduce a particularly well-managed start-up strategy to do this; and with it, the oscillator not only starts up instantly, but at exactly its final amplitude."

"That's really interesting!" said Niku, clearly genuinely pleased to learn of something that sounded so close to her own recent discoveries. "Can you say a little more about this?"

"I can, although I don't wish to steal too much of your time. I have a couple of visuals prepared. By the way, I'm Hjørdis Björklund. May I open my Michaday channel to the screen?"

"Oh … yes, of course," said Niku, slightly flustered by having forgotten that her own access to the GE°E had been suspended, in its capacity as a surrogate presenter.

"Michaday, this is Björklund. Show 101.37.01.255."

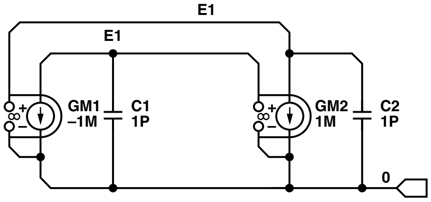


Figure 1. The mysterious Dr. Björklund's first visual.

With no chummy banter, of the sort that Niku always expected from Micha, but just a curt "Certainly, Dr. Björklund"—which suggested to Niku that this lady was no newcomer to Solna and was all business—a simple schematic instantly appeared. She wondered why she'd never met this individual; and why Dr. Leif was apparently suppressing his mirth. What was going on?

"This is just an illustrative example I prepared. It's nothing more than two ideal *gm*/*C* integrators in a loop, forming a sine/cosine oscillator, of the sort one might need in an *I*/*Q* demodulator. The rapid start-up is essential because such a subsystem is shut down between active time-slots, until valid data is available. When this happens, the phase-locked loop, of which this is a part, needs to acquire the carrier within a few cycles. On the other hand, a high effective *Q* is essential to minimize phase noise; and normally that would result in the oscillator's start-up process being far too sluggish. So it appears there's a basic conflict, here.

"Now, keep in mind," continued the mysterious Dr. Björklund, "that this is an *illustrative* circuit. Practical integrators used in a loop as basic as this will cause the amplitude of the oscillations to either decay—if their poles move off the imaginary axis into the left side of the *s*-plane, due to the shunting of the capacitors by the finite incremental output resistance of the *gm* cells—or the amplitude will rise exponentially when there is some additional hidden phase lag in the *gm* cells causing the resonant poles to move into the right plane.

"Such practical details are taken care of by regulating means on top of what I'm showing here. But they are not germane to the key idea that, sometimes, one does use a sort of glitch to get the ball rolling; though that would be a particularly inept description of the elegant way in which this start-up means is implemented. Michaday, show *.256."

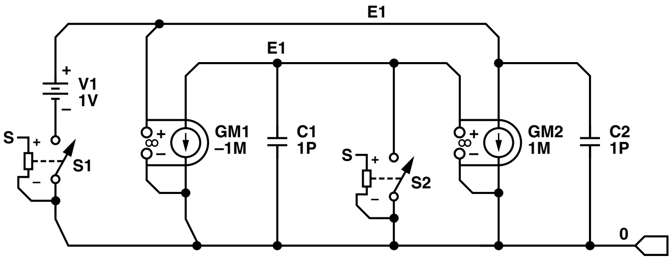


Figure 2. Dr. Björklund's second visual.

"Here's the key idea. Notice the two switches, one connecting a dc voltage source, which I am showing as 1 V, to the output E_2, while the other simply connects the output E_1 to ground. These switches remain closed right up to the moment we wish to start the oscillations. Now, Miku, what happens when we suddenly release the initial conditions of this describing function?"

$$\int E_1(gm/C)\,dt = -\int E_2(gm/C)\,dt$$

"It's *Niku*, ma'am." This was not fair! She had allowed this lady a moment or two, to show a sort of quick example of something or another that had admittedly sounded relevant to her own talk, and a bit interesting. But now, here was this … this *lady*, calling her 'Miku,' and putting her on the spot, in *her* time! Fortunately, while Niku might show her inexperience, and *was* perhaps being a bit too familiar with Leif, and *did* play cheeky with Michaday (Gosh! Can a GE°E get *embarrassed* in public, she suddenly wondered)—for all that, *she* was a warrior, too (for she knew that Hjørdis means 'Sword Goddess').

"Well, that's trivial ..." (whoa, *careful*, girl) "uh ... Dr. Björklund" (that's better; don't let her see you're rattled). "When the initial values are released this equation will execute a harmonic pair, of stable peak amplitude (E_1, E_2) = 1 V, at an angular frequency of $\omega = gm/C$, which, with the values shown, will be at 159.155 MHz."

"Yes … that's … right," said Björklund, who promptly sat down.

“Dr. Leif,” said Niku with a coy grin, “may I please have Micha back on my team?”

“He has been waiting for you for some time, Niku.” Was that a trace of empathetic tenderness in Leif’s voice, she wondered, now kicking herself for probably looking foolish in front of all those guys, or appearing to be angling for brownie points from the old fellow. Well, old is a matter of degree. Leif carried his 79 years remarkably well. His bronzed features, athletic form, white casual shirt and slacks, and the upscale gold watch gave him the appearance of one having just sailed up from Monte Carlo.

“Thank you, sir. Okay, Micha, you must have heard what was just discussed. Please take that equation and show us how this way of starting an I/Q oscillator plays out.”

That part of the GE°E currently servicing Dr. Björklund—her still-open channel—though operating within the one framework, was not in any sort of loyalty clash to the channel assigned to Niku. These machines shared at least that much with the old digital juggernauts. Micha probably had no idea what it meant to be “fair” or “even handed” in its dealings with those who used it. But, in the time since these latest models had arrived, it was becoming clearly evident—a surprise even to Neuromorphix, Inc.—that they developed a closer rapport with some users than others. It didn’t affect the speediness of their service, even less the accuracy of the results they produced. But it was almost as if they enjoyed working with some more than others. Leif had been made especially aware of this phenomenon during the past few minutes. It was evident that Micha was acting like … well, a *pal* to Niku, while merely a coolly efficient servant to Björklund. In the few seconds Leif had been pondering this, the requested solution had been generated and the screen showed the result.

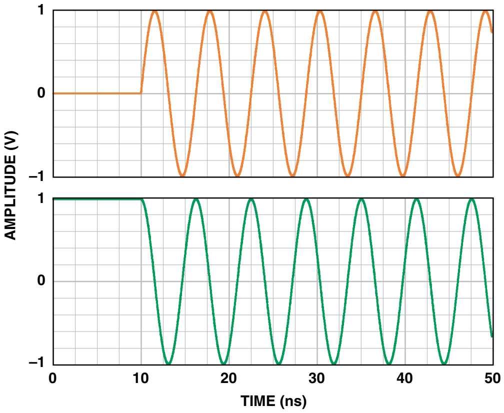


Figure 3. The instant start-up and exactly-sustained amplitude of Dr. Björklund’s “illustrative” oscillator.

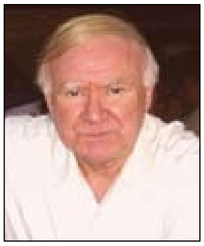
“Thank you very much, Micha. Yes, that’s a useful technique to remember for relatively low-frequency oscillators. Of course, it is not usually as easy to preset the initial conditions in a resonant-tank RF oscillator, but in fact, that is one of the slides I will show in a few moments. So, after that little detour, let’s first get back to the start-up trajectory of the basic Oscar oscillator.”

Standing, Dr. Leif once again found he needed to intervene.

“Niku, I’m quite sure this audience could listen to you all day; I know *I* could,” he quipped. “But you may not have noticed that we’ve exceeded the allocated one hour by a generous margin, and I have yet to pose the traditional teaser. So, may I suggest that you open-access the rest of your work on Michaday, so that interested engineers can check in from time to time at the same address, for the final pages of this interesting story? I suspected you would have too much material to cram into one hour, but even though you didn’t get to the best part I don’t think anybody here today will feel their time was ill-spent. Am I right?”

To Niku’s delight, the audience’s applause was generous. The hand-clapping—at first a random noise—quickly phase-locked into the rhythmic foot-stomping common in Europe, no less in Scandinavia. She thought, “How apt a metaphor for how little Oscar struggles up from the noise floor!” Still standing, Dr. Leif was the last to cease clapping. It was abundantly evident that he was very pleased with how Niku had progressed since he hired her, only a few months ago. Her determination to track down the root causes of observed effects, in a manner that went far beyond the mediocre, shallow, repetitive, and unsatisfying explanations so often found in textbooks, gave him the strong assurance that this young woman was destined to become a major innovator in the coming years.

“Well, that’s it for another D-Day. Now we can all get back to some serious invention-making! And Dr. Björklund, I’d like to see you in my office, please.” With that the audience dispersed, and Leif approached Niku, who listened for a moment, smiled, and then two sets of eyes twinkled conspiratorially. But their brief resonance was lost in the noise floor.



Barrie Gilbert, the first-appointed ADI Fellow, has “spent a lifetime in pursuit of analog excellence.” Barrie was born in Bournemouth, England, in 1937. Before joining ADI, he worked with first-generation transistors at SRDE in 1954. At Mullard, Ltd., in the late ’50s, he pioneered transistorized sampling oscilloscopes, and in 1964 became a leading ’scope designer at Tektronix. He spent two years as a group leader at Plessey Research Labs before joining Analog Devices in 1972, where he is now director of the Northwest Labs in Beaverton, Oregon. Barrie is a Life Fellow of the IEEE and has received numerous service awards. He has about 70 issued patents, has authored some 50 papers, is a reviewer for several professional journals, and is a co-author or co-editor of five books. In 1997, he was awarded an honorary doctorate of engineering from Oregon State University.

PRODUCT INTRODUCTIONS: VOLUME 40, NUMBER 4

Data sheets for all ADI products can be found by entering the model number in the Search box at www.analog.com

October

Accelerometer, 2-axis, ±3-g range	**ADXL323**
Converter, Synchronous Buck, 2-/3-phase, 8-bit VID code	**ADP3193**
Converter, Synchronous Buck, 2-/3-/4-phase, 8-bit VID code	**ADP3198**
Multiplexers, *i*CMOS, 4-/8-channel, low-capacitance, ±15-V operation	**ADG1408/ADG1409**
Temperature Sensor, Digital, 2-channel, over-/under-temperature alarms	**ADT7482**
Temperature Sensor, Digital, 1-wire data interface	**ADT7484A**
Temperature Sensor, Digital, 2-channel, 1-wire data interface	**ADT7486A**
Transceivers, RS-485/RS-422, ESD protected	**ADM307xE**
Transceivers, RS-485/RS-422, ESD protected	**ADM3486E/ADM3490E/ADM3491E**

November–December

ADC, Pipelined, 8-channel, 12-bit, 40-/50-MSPS, LVDS outputs	**AD9222**
ADC, Successive-Approximation, 16-bit, 750-kSPS, ±1.5-LSB max INL	**AD7612**
Controllers, Hot Swap, monitor supply voltage and current	**ADM1175/ADM1176/ADM1177/ADM1178**
Converter, Synchronous Buck, 2-/3-phase, 8-bit VID code	**ADP3199**
Detector, Signal-Power, 50-MHz to 4-GHz	**ADL5501**
Front-End, Mixed-Signal, broadband modems	**AD9857**
Monitors, Digital Power, over-current alert	**ADM1191/ADM1192**
Regulators, Low-Dropout, 500-mA loads	**ADP1715/ADP1716**
Switch, HDMI/DVI, 4:1, equalization and pre-emphasis	**AD8191**
Temperature-Sensor/Voltage-Monitor, Digital, one-wire data interface	**ADT7488A**
Transmitter, HDMI/DVI, high-performance	**AD9889A**
Transceiver, RS-485, high-speed, isolated, ESD protected	**ADM2490E**

Ask The Application Engineer—35

Capacitance Sensors for Human Interfaces to Electronic Equipment

By Susan Pratt [susan.pratt@analog.com]

Q: *What is a capacitance sensor?*

A: Capacitance sensors detect a change in capacitance when something or someone approaches or touches the sensor. The technique has been used in industrial applications for many years to measure liquid levels, humidity, and material composition. A newer application, coming into widespread use, is in human-to-machine interfaces. Mechanical buttons, switches, and jog wheels have long been used as the interface between the user and the machine. Because of their many drawbacks, however, interface designers have been increasingly looking for more reliable solutions. Capacitive sensors can be used in the same manner as buttons, but they also can function with greater versatility, for example, when implementing a 128-position scroll bar.

Integrated circuits specifically designed to implement capacitance sensing in human-machine interface applications are now available from Analog Devices. The AD7142[1] and the AD7143, for example, can stimulate and respond to up to 14 and eight capacitance sensors, respectively. They provide excitation to the capacitance sensor, sense the changes in capacitance caused by the user's proximity, and provide a digital output.

Q: *How does capacitance sensing work?*

A: A basic sensor includes a receiver and a transmitter, each of which consists of metal traces formed on layers of a printed-circuit board (PCB). As shown in Figure 1, the AD714x has an on-chip excitation source, which is connected to the transmitter trace of the sensor. Between the receiver and the transmitter trace, an electric field is formed. Most of the field is concentrated between the two layers of the sensor PCB. However, a fringe electric field extends from the transmitter, out of the PCB, and terminates back at the receiver. The field strength at the receiver is measured by the on-chip sigma-delta capacitance-to-digital converter. The electrical environment changes when a human hand invades the fringe field, with a portion of the electric field being shunted to ground instead of terminating at the receiver. The resultant decrease in capacitance—on the order of femtofarads as compared to picofarads for the bulk of the electric field—is detected by the converter.

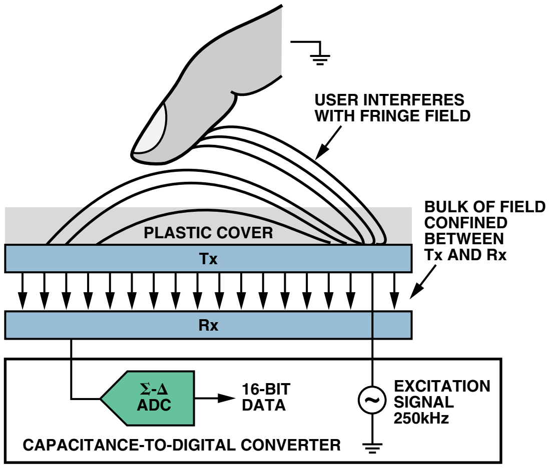


Figure 1. Sensing capacitance.

In general, there are three parts to the capacitance-sensing solution, all of which can be supplied by Analog Devices.

- The driver IC, which provides the excitation, the capacitance-to-digital converter, and compensation circuitry to ensure accurate results in all environments.
- The sensor—a PCB with a pattern of traces, such as buttons, scroll bars, scroll wheels, or some combination. The traces can be copper, carbon, or silver, while the PCB can be FR4, flex, PET, or ITO.
- Software on the host microcontroller to implement the serial interface and the device setup, as well as the interrupt service routine. For high-resolution sensors such as scroll bars and wheels, the host runs a software algorithm to achieve high resolution output. No software is required for buttons.

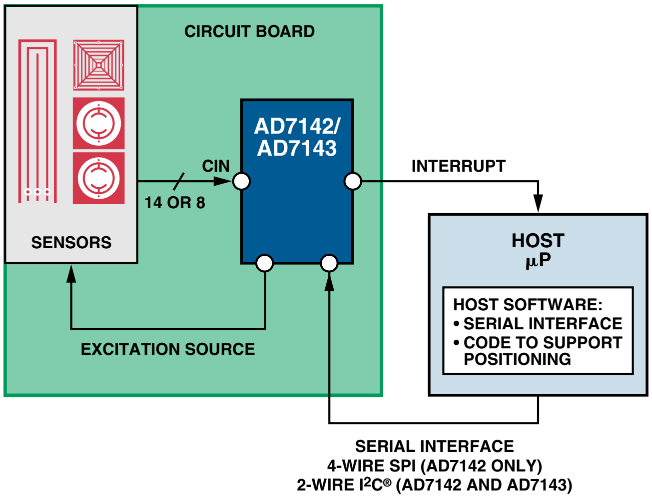


Figure 2. Three-part capacitance-sensing solution.

Q: *What are the advantages of capacitive sensing?*

A: Capacitance sensors are more reliable than mechanical sensors—for a number of reasons. There are no moving parts, so there is no wear and tear on the sensor, which is protected by covering material, for example, the plastic cover of an MP3 player. Humans are never in direct contact with the sensor, so it can be sealed away from dirt or spillages. This makes capacitance sensors especially suitable for devices that need to be cleaned regularly—as the sensor will not be damaged by harsh abrasive cleaning agents—and for hand-held devices, where the likelihood of accidental spillages (e.g., coffee) is not negligible.

Q: *Tell me more about how the AD714x ICs work.*

A: These capacitance-to-digital converters are designed specifically for capacitance sensing in human-interface applications. The core of the devices is a 16-bit sigma-delta capacitance-to-digital converter (CDC), which converts the capacitive input signals (routed by a switch matrix) into digital values. The result of the conversion is stored in on-chip registers. The on-chip excitation source is a 250-kHz square wave.

The host reads the results over the serial interface. The AD7142, available with either SPI®- or I^{2}C-compatible interfaces, has 14 capacitance-input pins. The AD7143, with its I^{2}C interface, has eight capacitance-input pins. The serial interface, along with an interrupt output, allows the devices to connect easily to the host microcontroller in any system.

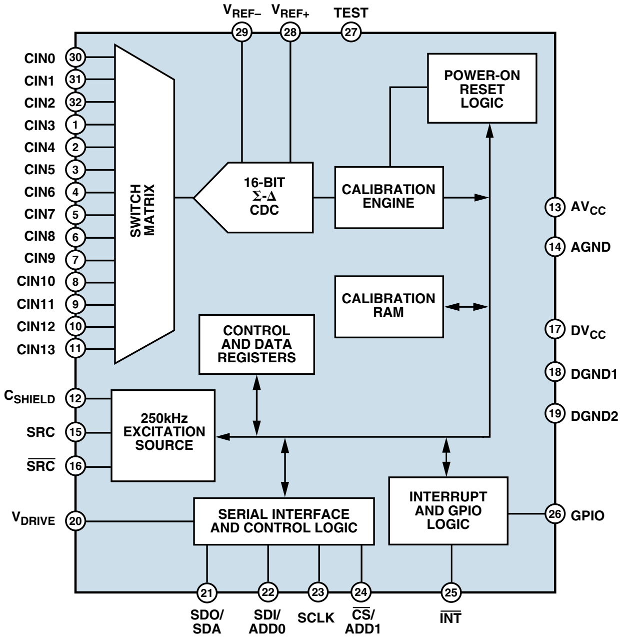


Figure 3. AD7142 block diagram.

These devices interface with up to 14 external capacitance sensors, arranged as buttons, bars, wheels, or a combination of sensor types. The external sensors consist of electrodes on a 2- or 4-layer PCB that interfaces directly with the IC.

The devices can be set up to interface with any set of input sensors by programming the on-chip registers. The registers can also be programmed to control features such as averaging and offset adjustment for each of the external sensors. An on-chip sequencer controls how each of the capacitance inputs is polled.

The AD714x also include on-chip digital logic and 528 words of RAM that are used for environmental compensation. Humidity, temperature, and other environmental factors can affect the operation of capacitance sensors; so, transparently to the user, the devices perform continuous calibration to compensate for these effects, giving error-free results at all times.

One of the key features of the AD714x is sensitivity control, which imparts a different sensitivity setting to each sensor, controlling how soft or hard the user's touch must be to activate the sensor. These independent settings for *activation thresholds*, which determine when a sensor is active, are vital when considering the operation of different-size sensors. Take, for example, an application that has a large, 10-mm-diameter button, and a small, 5-mm-diameter button. The user expects both to activate with same touch pressure, but capacitance is related to sensor area, so a smaller sensor needs a harder touch to activate it. The end user should not have to press one button harder than another for the same effect, so having independent sensitivity settings for each sensor solves this problem.

Q: *How is the environment taken into account?*

A: The AD714x measures the capacitance level from the sensor continuously. When the sensor is not active, the capacitance value measured is stored as the *ambient* value. When a user comes close to or touches the capacitance sensor, the measured capacitance decreases or increases. Threshold capacitance levels are stored in on-chip registers. When the measured capacitance value exceeds either upper or lower threshold limits, the sensor is considered to be active—as shown in Figure 4—and an interrupt output is asserted.

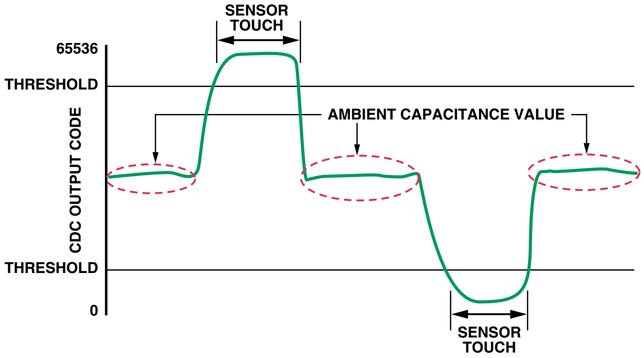


Figure 4. Sensor activation.

Figure 4 shows an ideal situation, where the ambient capacitance value does not change. In reality, the ambient capacitance changes constantly and unpredictably due to changes in temperature and humidity. If the ambient capacitance value changes sufficiently, it can affect the sensor activation. In Figure 5, the ambient capacitance value increases; Sensor 1 activates correctly, but when the user tries to activate Sensor 2, an error occurs. The ambient value has increased, so the change in capacitance measured from Sensor 2 is not large enough to bring the value below the lower threshold. Sensor 2 cannot now be activated, no matter what the user does, as its capacitance cannot decrease below the lower threshold in these circumstances. A worse possibility is that the ambient capacitance level continues to increase until it is above the upper threshold. In this case, Sensor 1 will become active, even though the user has not activated it, and it will remain active—the sensor will be "stuck" on—until the ambient capacitance falls.

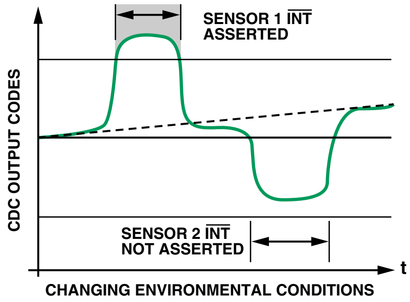


Figure 5. Sensor activation with changing ambient capacitance.

On-chip logic circuits deal with the effects of changing ambient capacitance levels. As Figure 6 shows, the threshold levels are not constant; they track any changes in the ambient capacitance level, maintaining a fixed distance away from the ambient level to ensure that the change in capacitance due to user activation is always sufficient to exceed the threshold levels. The threshold levels are adapted automatically by the on-chip logic and are stored in the on-chip RAM. No input from the user or host processor is required.

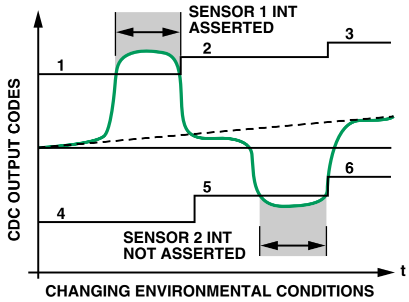


Figure 6. Sensor activation with auto-adapting thresholds.

Q: *How is capacitance sensing applied?*

A: As noted earlier, the sensor traces can be any number of different shapes and sizes. Buttons, wheels, scroll-bars, joypads, and touchpad shapes can be laid out as traces on the sensor PCB. Figure 7 shows a selection of capacitance sensor layouts.

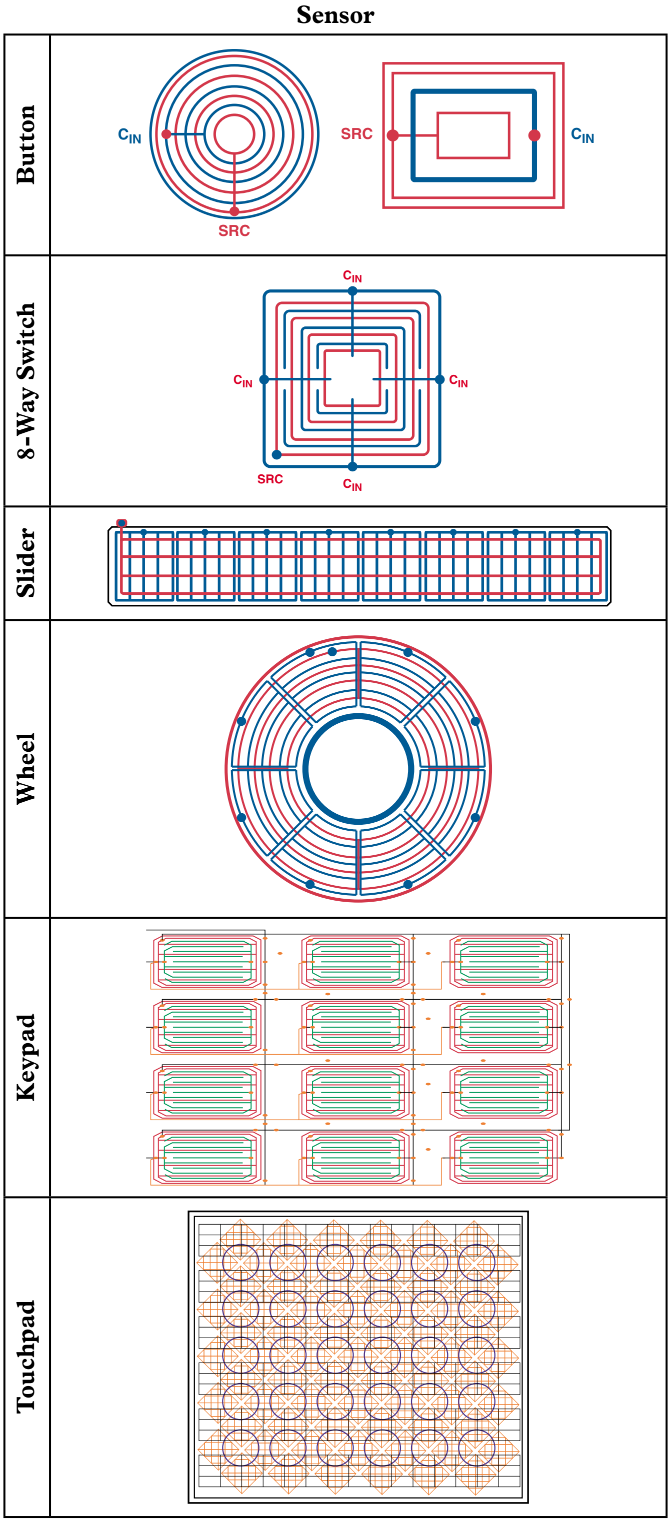


Figure 7. Selection of capacitance sensors.

Many options for implementing the user interface are available to the designer, ranging from simply replacing mechanical buttons with capacitive button sensors to eliminating buttons by using a joypad with eight output positions, or a scroll wheel that gives 128 output positions.

The number of sensors that can be implemented using a single device depends on the type of sensors required. The AD7142 has 14 capacitance input pins and 12 conversion channels. The AD7143 has eight capacitance inputs and eight conversion channels. The table below shows the number of input pins and conversion stages required for each sensor type. Any number of sensors can be combined, up to the limit established by the number of available inputs and channels.

Sensor Type	**Number of C_{IN} inputs required**	**Number of conversion channels required**
Button	1	1 (0.5 for differential operation)
8-Way Switch	4—top, bottom, left, and right	3
Slider	8—1 per segment	8—1 per segment
Wheel	8—1 per segment	8—1 per segment
Keypad Touchpad	1 per row, 1 per column	1 per row, 1 per column

Measurements are taken on all connected sensors sequentially—in a “round-robin” fashion. All sensors can be measured within 36 ms, though, allowing essentially simultaneous detection of each sensor’s status—as it would take a very fast user to activate or deactivate a sensor within 40 ms.

Q: *What design help can you offer first-time users?*

A: Analog Devices has a number of resources available to designers of capacitance sensors. The first step in the design process is to decide what types of sensors are needed in the application. Will the user need to scan quickly through long lists, such as contacts on a handset or songs on an MP3 player? If so, then consider using a scroll bar or scroll wheel to allow the user to scan through those lists quickly and efficiently. Will the user need to control a cursor moving around a screen? An X-Y joypad would be a good fit for this application. Once the type, number, and dimensions of the required sensors have been fixed, the sensor PCB design can begin.

As part of the design resources available for capacitance sensing, a Mentor Graphics PADs layout library is available online. Many different types and sizes of sensors are available in this library as components, which can be dragged and dropped directly into a PCB layout. The library is available as an interactive part of the Touch Controller System Block Diagram.[2] Also available is AN-854,[3] an application note that provides details, tips, and tricks on how to use the sensor library to lay out the desired sensors quickly.

When designing the PCB, place the AD7142 or AD7143 on the same board as the sensors to minimize the chances of system errors due to moving connectors and changing capacitance. Other components, LEDs, connectors, and other ICs, for example, can go on the same PCB as the capacitance sensors, but the sensor PCB must be glued or taped to the covering material to prevent air gaps above the sensors, so the placement of any other components on the PCB must take this into account.

For applications where RF noise is a concern, an RC filter can be used to minimize any interference with the sensors. Using a ground plane around the sensors will also minimize any interference.

The PCB can have either two- or four layers. A 4-layer design must be used when there is no room, outside of the sensor active areas, to route between the IC and the sensors, but a 2-layer design can be used if there is enough routing room.

The maximum distance allowed between the sensor traces and capacitance input pin is 10 cm, but one sensor can be 10 cm from the pins in one direction, while another can be 10 cm from the pins in the opposite direction, allowing 20 cm between sensors.

Q: *My sensor PCB is ready, now what?*

A: Capacitance is notoriously difficult to simulate, so the sensor response in each application must be characterized to ensure that the AD7142/AD7143 is set up optimally for the application. This characterization process need only take place once per application, with the same setup values then being used for each individual product.

The sensors are characterized in the application. This means that any covering material must be in place on top of the sensor, and any other PCBs or components that may have an effect on the sensor's performance must be in place around the sensor.

For each conversion channel, we need to configure:

- Internal connection from the device's C_{IN} input pin to the converter. This ensures that each sensor is connected to the converter using one conversion channel.
- Sensor offset value, to offset for C_{BULK}. This is the capacitance associated with the electric field that is confined within the PCB, between the transmitter and receiver electrodes. This value does not change when the sensor is active, but instead provides a constant offset for the measurement fringe capacitance value.
- Initial values for upper and lower offset registers. These values are used by the on-chip logic to determine the activation threshold for each sensor.

The easiest way to perform the characterization is to connect the sensor PCB to the AD7142/AD7143 evaluation board—available from Analog Devices. The microcontroller and software that are included on the evaluation board can be used to characterize the sensor response and save the setup values.

Q: *What kind of response can I expect?*

A: The practical response from the sensor is defined by the converter's output change when the sensor goes from inactive to active. This change will depend on the area of the sensor—the larger the sensor area, the greater the change when the sensor is active. The sensor response will also depend on the thickness of the covering material—if it is very thick (4 mm or more), the sensor response will be minimal. The reason is that the electric field will not penetrate through very thick covering material, so the user will not be able to shunt enough of the field to ground to generate a large response. Figure 8 is a typical sensor response from a button sensor. It shows a change of about 250 LSBs between the sensor active and sensor inactive in this case.

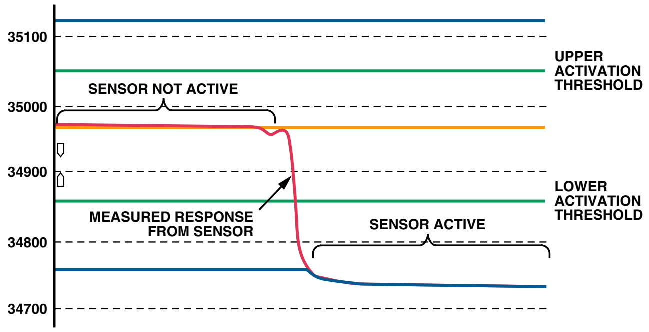


Figure 8. Typical response from a button sensor.

Q: *You mentioned software?*

A: The interaction between the host processor and the AD7142/AD7143 is interrupt-driven. The host implements the serial interface, either SPI or I^2C. The AD7142/AD7143 will interrupt the host when a sensor is touched. The host can then read back data from the on-chip registers. If the sensors are buttons, or other simple on/off type sensors, the host simply reads back from the on-chip status registers; an active button causes a bit to be set in the status register. However, if the sensors have a high-resolution output, a software algorithm must run in the host interrupt routine to process the AD7142/AD7143 data.

The code is provided free of charge or royalties to customers who sign a license agreement with Analog Devices. For a scroll bar, the code typically occupies 500 bytes of data memory and 8k bytes of code memory. For a scroll wheel, the code typically occupies 600 bytes of data memory and 10k bytes of code memory.

Analog Devices provides sample drivers,[4] written in C-code, for basic configuration, button sensors, and 8-way switches using SPI- and I^2C-compatible interfaces. Sample drivers for scroll wheels and scroll bars are available after signing a software license.

Q: *Ideas on assembling my finished product?*

A: No air gap is allowed between the sensor PCB and the covering material or product case because having one would cause less of the electric field to extend above plastic, decreasing the sensor response. Also, the plastic or other covering material might bend on contact, causing the user to interact with a variable electric field, resulting in a nonlinear sensor response. Thus, the sensor PCB should be glued to the covering material to prevent any air gaps from forming.

Also, there can be no floating metal around the sensors. A *"Keep Out"* distance of 5 cm is required. Metal closer to the sensors than 5 cm should be grounded, but there can be no metal closer to the sensors than 0.2 mm.

Finally, the plastic covering the sensor's active areas should be about 2 mm thick. Larger sensor areas should be used with thicker plastic; and plastic thickness of up to 4 mm can be supported.

CONCLUSION

Capacitance sensors are an emerging technology for human-machine interfaces and are rapidly becoming the preferred technology over a range of different products and devices. Capacitance sensors enable innovative yet easy-to-use interfaces for a wide range of portable and consumer products. Easy to design, they use standard PCB manufacturing techniques and are more reliable than mechanical switches. They give the industrial designer freedom to focus on styling, knowing that capacitance sensors can be relied upon to give a high-performance interface that will fit the design. The designer can benefit from the Analog Devices portfolio of IC technology and products, plus the expertise and the hardware and software tools available to make it as easy and as quick as possible to design-in capacitance sensors.

REFERENCES—VALID AS OF JANUARY 2007

[1] ADI website: www.analog.com (Search) AD7142 (Go)
[2] ADI website: www.analog.com (Search) Touch Controller System Block Diagram (Go)
[3] ADI website: www.analog.com (Search) AN-854 (Go)
[4] http://www.analog.com/en/content/0,2886,760_1077_F107310,00.html#software

This article is available in HTML and PDF at *http://www.analog.com/analogdialogue*. Click on *archives*, then select volume, number, and title.

Lens Drivers Focus on Performance in High-Resolution Camera Modules

By Mark Murphy [mark.murphy@analog.com]
Mel Conway [mel.conway@analog.com]
Gary Casey [gary.casey@analog.com]

INTRODUCTION

You are probably aware that your mobile phone has a camera module in it; but if it's more than a few months old, or it wasn't terribly expensive, it's a good bet that, if you photograph someone committing a crime, the resulting blurry images—whether due to insufficient resolution, poor focusing, or movement during exposure—will not be admissible in court. But the camera module's resolution, and performance in general, is improving quickly. In 2000 Samsung released the SCH-V200, a 0.3-megapixel (MP) camera phone, and in 2003 NTT DoCoMo launched the first autofocus handset camera, the 1.3-MP P505iS. Last year Sony Ericsson launched what many consider the first real camera phone, the 2-MP K750i with autofocus. And in March of 2006 Samsung announced the SCH-B600, a 10-MP camera phone!

What is now called the "Evolution of Resolution" is driving camera module development. In order to make the best use of the increased resolution, effective and rapid autofocus (AF) must accompany the increase in pixels. With autofocus becoming a standard feature, ever-increasing resolution will call for more camera features, such as optical zoom, shutter control, and image stabilization (Figure 1).

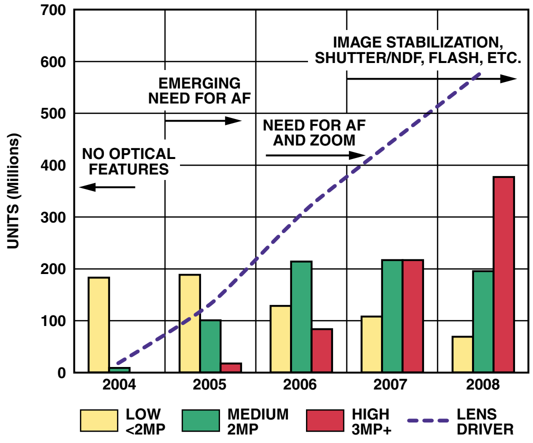


Figure 1. Camera phone and lens driver forecast to 2008.

A key element of many features is the ability to move the lens rapidly so as to achieve optimum focus. The ***lens driver*** provides the power that moves the lens appropriately in response to digital control signals. We will discuss the lens driver's role, describe two useful new products, and consider the future of lens drivers in the marketplace.

Figure 2[1] is a generic block diagram, or *signal chain*, of a digital camera. The image projected by the lens onto a CMOS- or CCD (charge-coupled-device) sensor is scanned and applied to an analog front-end[2] processor (AFE),[3] which amplifies and conditions the raw video signal, and converts it to digital. The AD9822,[4] for example, is a complete 14-bit analog signal processor for CCD imaging applications, featuring a 3-channel architecture designed to sample and condition the outputs of trilinear color-CCD arrays. Once the image is in digital form, it can be edited, downloaded, or stored, and further processed for camera operations, such as gamma-correction, light sensitivity adjustment for flash, and lens drive for focusing. Beyond these basic elements, additional sensors can measure lens position, light, temperature, acceleration, and angular motion (these last for image stabilization)—and motors/actuators can control the shutter, neutral density filter (NDF), iris, and lens cover.

Handset Cameras vs. Digital Still Cameras

Camera phones are the fastest-growing consumer market in the world today and will continue to be for the next several years. Size and cost of these modules are of primary importance, but coupled with this, users are demanding real camera performance. In fact, performance convergence between new camera phones and the digital still cameras (DSCs) of a couple of years ago has already occurred.

High-resolution digital still cameras are readily available at low cost, but their technology is not immediately transferable to handsets. Why not? Their requirements are rather different. DSCs are *cameras*, first and foremost—while the primary function of the handset is to make a call and speak to somebody. The included camera module is one of those useful additional features that may come in handy at times, but it can't add substantially to cost—or make the phone bulkier. In addition, there are severe power-consumption restrictions on camera modules: a camera module that eats significantly into talk time will never be a success.

Lens Driver

A lens driver controls the actuator that moves the lens assembly back and forth to adjust focus and/or magnification in camera phones with resolutions typically greater than two megapixels.

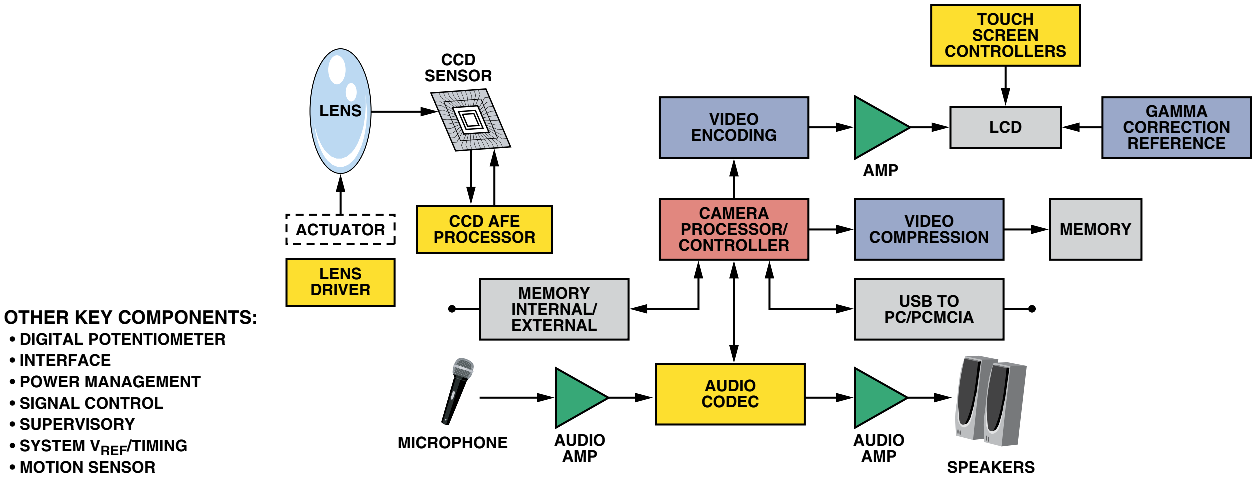


Figure 2. Digital camera signal chain.

Cameras with lower resolutions typically do not require autofocus, so they do not require a lens driver. In addition to focusing, some higher-resolution cameras may use lens drivers to position the lens for image stabilization. Figure 3 shows a lens driver and many of its possible inputs and outputs.

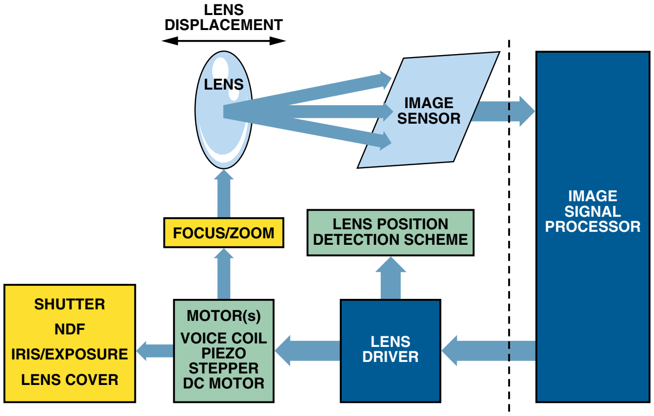


Figure 3. The lens driver has many possible inputs and outputs.

Traditionally, DSCs use digital *stepper motors* as actuators; the stepper has proven to be robust, easy to drive, and it can be used to drive both autofocus (AF) and zoom lens actuators. Another advantage of the stepper is that after a lens movement is complete, and the required focus or magnification is achieved, no holding power is required to keep the lens in place. But steppers currently used in DSCs are physically large, relatively expensive, mechanically complex, noisy, slow, and power-hungry. These factors all tend to make the current crop of steppers unsuitable for camera modules in phones. Furthermore, as features are added to camera phones, it is becoming obvious that space constraints will require a very high degree of integration—a severe disadvantage for the current stepper technology.

An emerging actuator technology is based on piezoelectric materials, of which there are many flavors. The piezoelectric actuator is mechanically simple, can make rapid movements, and is energy efficient. It can be used for both AF and zoom applications, and no hold power is required to maintain lens position after a lens movement is complete. Unfortunately, the drive schemes for piezoelectric elements are complex and still in flux. Also, piezoelectric materials have a high temperature coefficient, demanding temperature compensation of frequency, phase difference, and duty-cycle of the drive signals.

The third option in actuator technology, the *voice-coil motor* (VCM) with spring return, is the smallest, lowest-cost solution for autofocus on the market today; it is also the simplest to implement. These factors are important because camera modules with autofocus are currently the highest-volume products in this market.

Movements using VCMs are repeatable and gearless, with lens position fixed by balancing motor and spring forces. The spring returns the lens to the *infinite*-focus position, and no power is dissipated unless focusing is required. It is mechanically robust, shock-resistant, and has low-cost mechanics. These motors have no hysteresis and therefore have a direct current-vs.-position relationship, so that lens-position feedback may not be normally required.

Figure 4 shows the transfer curve of a typical spring-preloaded linear motor for autofocus—and the dimensions of a typical VCM intended for use in a camera phone. The transfer function shows displacement, or *stroke*, which is the actual distance the lens moves (mm), vs. the current through the motor (mA).

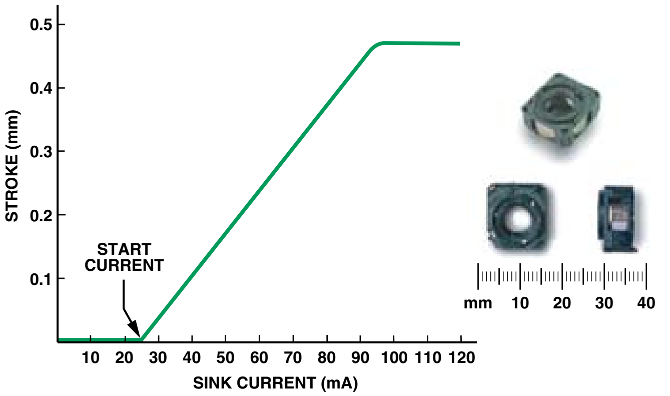


Figure 4. Spring-preloaded voice-coil stroke vs. sink current.

The *start current*, or threshold current that must be exceeded for any displacement of the spring-preloaded linear motor to occur, is usually 20 mA or greater. The rated stroke or displacement is usually 250 µm to 400 µm, and the slope of the transfer curve is on the order of 10 µm/mA. The maximum lens displacement for autofocus is of the order of 300 µm to 400 µm, so the VCM is a good fit for this level of functionality. Unlike the piezoelectric actuator and stepper motor, however, the VCM does consume power while holding the lens in focus.

Table I compares the best-in-class actuator technologies available.

Table I. Actuators Compared

Motor Type	Voice Coil Motor (VCM)	Piezo Motor	Stepper Motor
Size	Small	Small	Largest
Cost	Lowest	Low	Highest
Speed (Autofocus)	10 ms	3 ms	100 ms
Energy (mJ)	2.4	0.7	21
Bidirectional	Yes—with spring	Yes	Yes
Index/Rest Position	Yes	No	No
Repeatability	Good	Poor	Medium
Gears Required	No	No	Yes
Acoustic Noise	—	—	High
Power Transistors to Drive Motor	1	4	8
Application	AF *and* on/off functions	AF and zoom	AF and zoom

Driving the VCM for Autofocus

Analog Devices currently manufactures the only fully integrated product specifically aimed at allowing camera designers to take full advantage of the emerging market for AF. A complete VCM-driver solution, the AD5398[5] comprises a 10-bit digital-to-analog converter (DAC) with 120-mA output-current-sink capability, intended for driving voice-coil actuators in applications such as lens autofocus and image stabilization. The AD5398 is controlled using the industry-standard I^{2}C 2-wire serial protocol. A second VCM driver, the AD5821, is scheduled for release in December 2006. The AD5821 has the same feature set as the AD5398, but includes a 1.8-V-compatible interface—and its hardware shutdown pin, XSHUTDOWN, is active low (on the AD5398, it is active high). Figure 5 shows a block diagram of the AD5821. A 10-bit current-output DAC, loaded by resistor, R, generates a voltage that drives the noninverting input of the operational amplifier. Feedback causes this voltage to appear across R_{SENSE}, generating the sink current required to drive the voice coil.

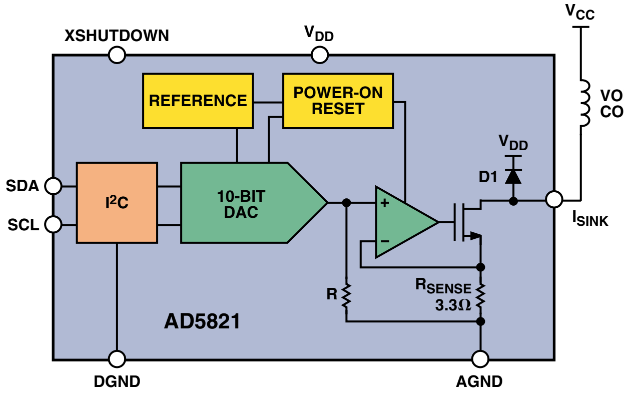


Figure 5. AD5821 block diagram shows connection to voice coil.

Resistors R and R_{SENSE} are interleaved and matched on-chip. Their temperature coefficients and any nonlinearities over temperature are therefore matched, minimizing the output drift over temperature. Diode D1 provides output protection, and dissipates the energy stored in the voice coil when the device is powered down.

The Future

Stepper motor manufacturers will be forced to reduce size and cost. This will require drivers having a higher degree of integration, more efficient drive schemes, lens position feedback, smaller size, and lower cost. Many camera module manufacturers are experimenting with piezoelectric actuators, which in themselves present a great many challenges to lens-driver manufacturers. Also not far off are electrically focused liquid lenses.

Figure 6 shows a conceptual block diagram of a piezoelectric solution for lens driving. This could also apply to stepper drivers, except that the number of drivers required would be doubled.

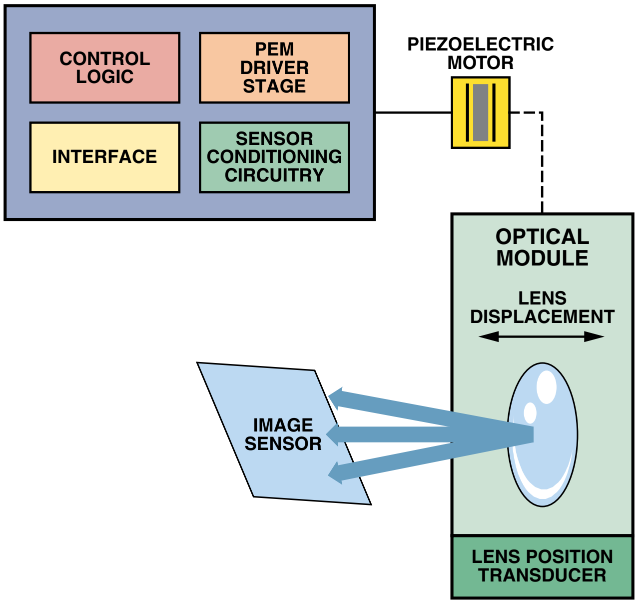


Figure 6. Block diagram showing possible piezoelectric solution.

Piezoelectric actuators require a drive with a mixture of analog drivers, digital flexibility, signal conditioning and conversion, and, in some cases, power management. Analog Devices has expertise in all of these areas. The camera module for the handset market is complex and multilayered; there is an interdependency between companies making the image sensors, those who produce the mechanics for the optical module, the lens manufacturers, and the lens driver manufacturers. Digital still cameras are evidence of what can be achieved by dedicated design, but one of the primary challenges in reducing size, cost, and power is to further integrate additional functionality within the lens driver. As camera modules continue to evolve, ADI will continue to lead in the development of new lens drivers and other components.

REFERENCES—VALID AS OF JANUARY 2007

[1] ADI website: www.analog.com (Search) digital camera (Go)
[2] http://www.analog.com/library/analogdialogue/archives/34-06/imaging/index.html
[3] ADI website: www.analog.com (Search) camera/camcorder analog front ends (Go)
[4] ADI website: www.analog.com (Search) AD9822 (Go)
[5] ADI website: www.analog.com (Search) AD5398 (Go)

This article is available in HTML and PDF at *http://www.analog.com/analogdialogue*. Click on *archives*, then select volume, number, and title.

Digital Isolation Offers Compact, Low-Cost Solutions to Challenging Design Problems

By David Krakauer [david.krakauer@analog.com]

INTRODUCTION

For designers of isolated systems, rapid advances in digital isolation technology are yielding new capabilities that greatly simplify their job. Examples include integrated, isolated power and truly bidirectional isolation channels that can reduce system costs and save circuit-board real estate. These advances are fueled by a shift away from LED-based optocouplers toward newer isolator technologies that are compatible with standard foundry CMOS processes. They enable integrated circuitry to be packaged with chip-scale microtransformers, thus fitting more functionality into a single package.

This article discusses two kinds of devices that embody these advances. In the first example, *isolated power*, chip-scale microtransformers are complemented by switches, rectifiers, and regulators to produce an isolated, regulated dc-to-dc converter; when integrated with isolated data channels it provides a complete isolation solution. In the second example, *bidirectional isolation*, integrating the requisite buffers and drivers creates an isolator that has truly bidirectional isolation channels without the need for external signal conditioning.

Isolated Power: *iso*Power

Galvanic isolation is employed to transmit data and/or power across a safety barrier, while also blocking charge or current flow across that barrier. The Analog Devices *i*Coupler® family[1] of digital isolators uses chip-scale microtransformers to provide cost-effective, space-efficient isolation. *i*Coupler technology was introduced in "*i*Coupler Digital Isolators Protect RS-232, RS-485, and CAN Buses in Industrial, Instrumentation, and Computer Applications" (*Analog Dialogue* 39-10, October 2005).[2]

Figure 1 shows a 4-channel digital isolator, which houses three dice in a single package. Two CMOS interface circuits (left and right) integrate *drive* and *receive* electronics. The middle die contains four chip-scale microtransformers, each comprising metal (AlCu and Au) coils on either side of a 20-µm polyimide insulation layer. The polyimide is capable of withstanding more than 5 kV rms for one minute.

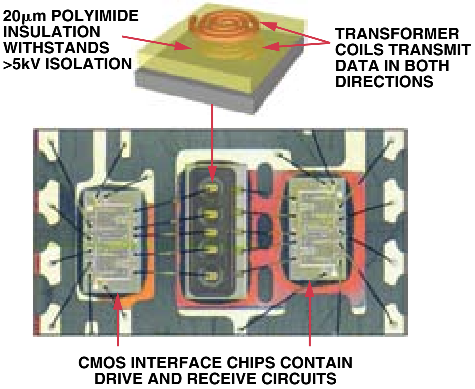


Figure 1. Construction of *i*Coupler digital isolator.

Unfortunately, in most applications that require isolated data transmission, isolated power must be available on both sides of the isolation barrier, or it must be provided separately. System designers typically introduce isolated power by designing an isolated power supply using discrete components—including a transformer with the appropriate isolation rating—or by purchasing a commercial off-the-shelf isolated dc-to-dc converter.

Each approach has its advantages and disadvantages. In the first instance, isolated power supplies may be custom tailored to an application, allowing system designers to optimize their cost, isolation rating, power output, or other important specifications depending on the application requirements. The downside, however, is that custom solutions tend to be bulky, require safety certification, and can lengthen development times.

Commercially available isolated power supplies, on the other hand, can reduce time to market, but they carry a price penalty and may not be optimized to fit a particular application. While smaller in size than their custom counterparts, they are still fairly bulky, with only limited availability of surface-mount package options.

A third way is *iso*Power, which combines the benefits of both options. *i*Coupler digital isolators condition and drive data across the transformers as described in the article, "High Speed Digital Isolators Using Microscale On-Chip Transformers."[3] *iso*Power uses the same chip-scale microtransformer technology, but instead of transmitting only data, *iso*Power employs switches, rectifiers, and regulators to generate power that is isolated to the same degree as the data channels.

Figure 2 shows the isolated power section of the ADuM5240,[4] ADuM5241,[5] and ADuM5242,[6] the first *i*Coupler products with *iso*Power. Four cross-coupled CMOS switches generate an ac waveform that drives the transformer. On the isolated side, Schottky diodes rectify the ac signal. The rectified signal is passed to a linear regulator, which maintains the output voltage at a nominal 5-V setpoint. Efficiency can be significantly improved by giving up one of the isolation channels to provide feedback across the isolation barrier to the transformer switches.

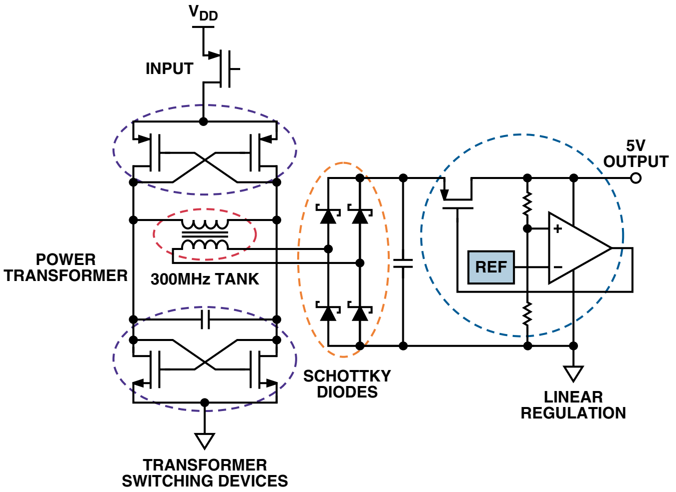
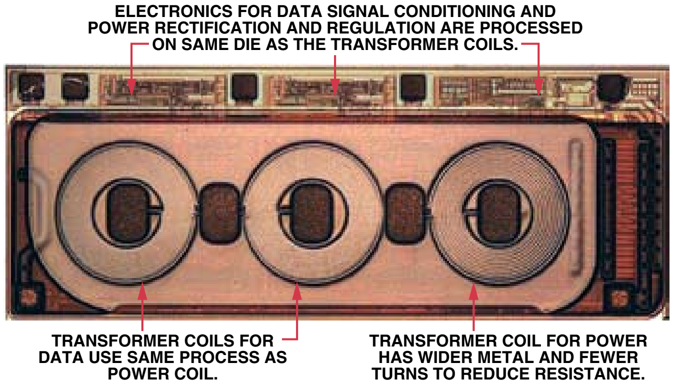


Figure 2. *iso*Power digital isolator implements isolated power.

Figure 3 depicts the transformers used in the ADuM524x family. The chip-scale microtransformers are made from 6-µm thick gold, separated by a 20-µm polyimide insulation layer, which is capable of providing greater than 5-kV rms isolation. Because the transformer coils, only 600 µm in diameter, have a low L/R ratio compared with conventional transformers, high-efficiency power generation requires high-frequency switching—on the order of 300 MHz.


ELECTRONICS FOR DATA SIGNAL CONDITIONING AND POWER RECTIFICATION AND REGULATION ARE PROCESSED ON SAME DIE AS THE TRANSFORMER COILS.

TRANSFORMER COILS FOR DATA USE SAME PROCESS AS POWER COIL.

TRANSFORMER COIL FOR POWER HAS WIDER METAL AND FEWER TURNS TO REDUCE RESISTANCE.

Figure 3. Chip-scale microtransformers.

As noted earlier, the transformers used to generate power employ the same process as those used to isolate data. The only significant difference between data and power channels is the conditioning circuitry on either side of the isolation barrier.

*iso*Power Example

Combining data and power in a single, small, surface-mountable package, the ADuM524x family provides significant size and cost savings. Figure 4 shows typical physical configurations for isolated SPI interfaces. The *i*Coupler-and-*iso*Power solution (Figure 4a) uses an ADuM5240 and an ADuM1201[7] to provide four channels of isolated data and up to 50 mW of isolated power, enough to power an ADC and a remote sensor. It is more compact and less expensive than the traditional approach using three optocouplers and an isolated dc-to-dc converter (Figure 4b). A third solution, using discrete transformers and other components, would consume even more area. Other combinations of ADuM524x *iso*Power and ADuM120x *i*Coupler products are possible, as are combinations of ADuM524x and most other *i*Coupler products.

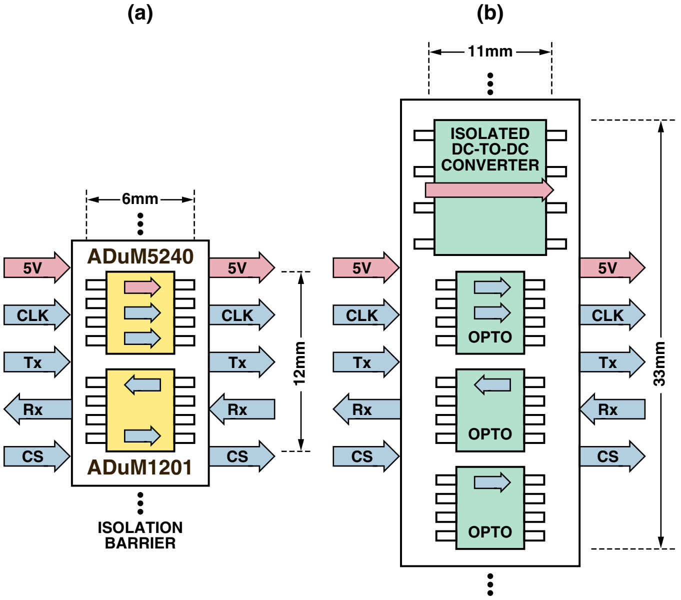


Figure 4. Isolated SPI interface using *i*Coupler technology (a) and optocouplers (b).

The small size and low cost of an *iso*Power solution opens up new possibilities for the placement and distribution of isolated sensors and reduces the cost of existing solutions, thereby enabling wider adoption of isolated sensors.

A case in point is turbidity sensors: they measure the amount of particulates in a liquid solution and can be used to determine the cleanliness of a volume of water. They are increasingly being used in home appliances, such as dishwashers and washing machines, both to conserve water and to improve cleaning performance. Conventional appliances wash or rinse for a set time, overestimating the required level of cleaning to ensure that the load is fully clean at the end of the cycle. A turbidity sensor, however, can let the system know when to stop cleaning. The machine will use the optimal amount of water for the optimal time, thus minimizing waste while maximizing useful cleaning performance.

Because turbidity sensors must be immersed in the water, they present two challenges to an appliance designer. First, the sensor must be small enough to fit unobtrusively anywhere within the space where clothes or dishes are to be placed. The size of the sensor is, therefore, critical. Second, the powered circuit is immersed in water, so the sensor must be safely isolated from the rest of the system. If the physical insulation should fail, the user and the system electronics must not be harmed, and there must be no possibility of fire. Both the power and the data must therefore be isolated.

The block diagram shown in Figure 5 demonstrates a cost-effective solution. The AD7823[8] low-power ADC uses a 3-wire interface to convert the analog output of a turbidity sensor. The digitized turbidity data is transmitted across the galvanic isolation barrier of the ADuM1200[9] and ADuM5242. The 50 mW of isolated power from the ADuM5242 is sufficient to supply the ADuM1200, the AD7823, and the turbidity sensor. The combined area of the isolators and converter is less than 100 mm^2, excluding external components.

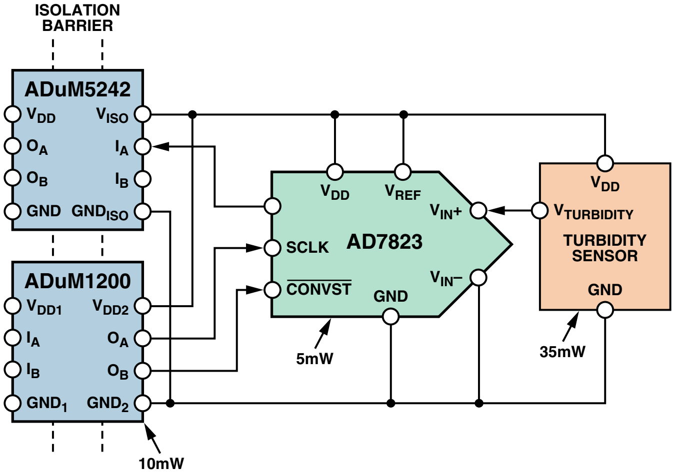


Figure 5. Isolated turbidity sensor.

Bidirectional Isolation

In isolation, the term *bidirectional* has traditionally referred to an isolator with separate *transmit* and *receive* channels in one package—the isolator as a whole is capable of bidirectional data transfer, but the individual channels are unidirectional. This approach is compatible with communications protocols such as RS-232, RS-485, and SPI, but it is not compatible with true bidirectional communication protocols, such as I^{2}C, SMBus, and PMBus, which support bidirectional data transfer through a single channel. Bidirectional and unidirectional isolation are compared in Figure 6.

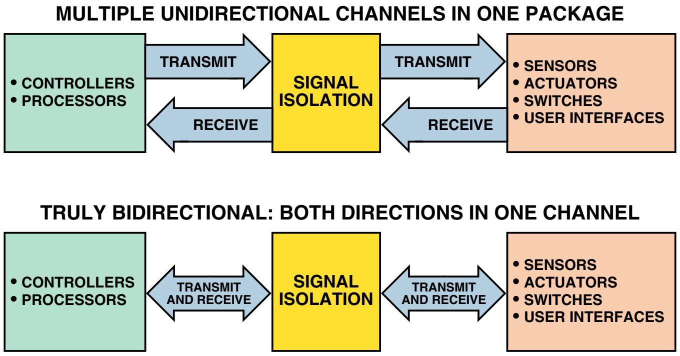


Figure 6. Bidirectional isolation vs. unidirectional isolation.

The inter-integrated-circuit (I^{2}C) bus is a popular 2-wire, bidirectional communication protocol that was developed to provide simple, low-cost, short-distance communication between an on-board controller and its peripherals. I^{2}C buses limit the cost of applications in which multiple devices share a single bus with a host controller, as shown in Figure 7. Two bidirectional wires—one for the data and one for the clock—are used to achieve low cost at the expense of data rate, so I^{2}C is typically used in systems with many peripherals running at data rates less than 1 Mbps. Systems that use a limited number of peripherals running at higher data rates will often employ protocols such as SPI.

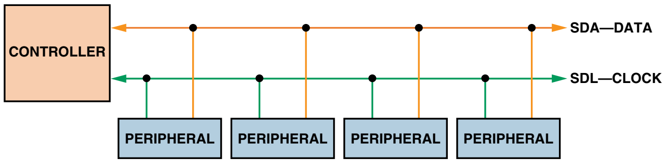


Figure 7. The I^{2}C bus provides communications between host and peripherals.

The I^{2}C isolation challenge has been that optocouplers are based on diodes that can transmit in only one direction, and are therefore inherently unidirectional. A bidirectional I^{2}C bus could be isolated using optocouplers, but the implementation isn't pretty (Figure 8a). A special buffer is used to separate each bidirectional channel into two distinct channels: *transmit* and *receive*. Once separated, the four unidirectional channels can be individually isolated and then recombined. This solution requires four isolators and expands the bus from two wires to four wires. Additional circuitry is also required, making this solution costly and large, and defeating the original purpose of the 2-wire bus implementation: to save money and space.

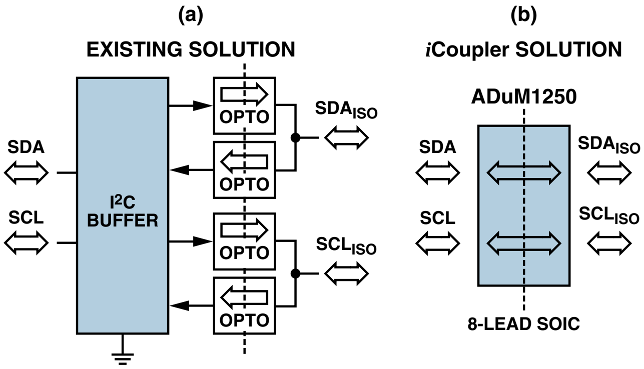


Figure 8. *i*Coupler simplifies bidirectional isolation.

The good news is that by adopting the new digital isolation techniques the circuitry that is used to separate, isolate, and recombine the data channels can be integrated into a single package. This approach can be implemented with the new ADuM1250[10] and ADuM1251[11] hot-swappable dual I^{2}C isolators. Figure 8b illustrates how much more compact the *i*Coupler solution is.

Figure 9 shows how bidirectional isolation is achieved within the package. Just as the discrete solution employs a buffer to separate the two bidirectional channels into four unidirectional channels and four isolators, so, too, does the ADuM125x. The difference is that all the electronics are integrated onto a single IC. A designer sees only the 2-wire interface, and the entire device is less than 40 mm^2, a 90% reduction compared with the optocoupler/buffer solution, which takes up about 350 mm^2.

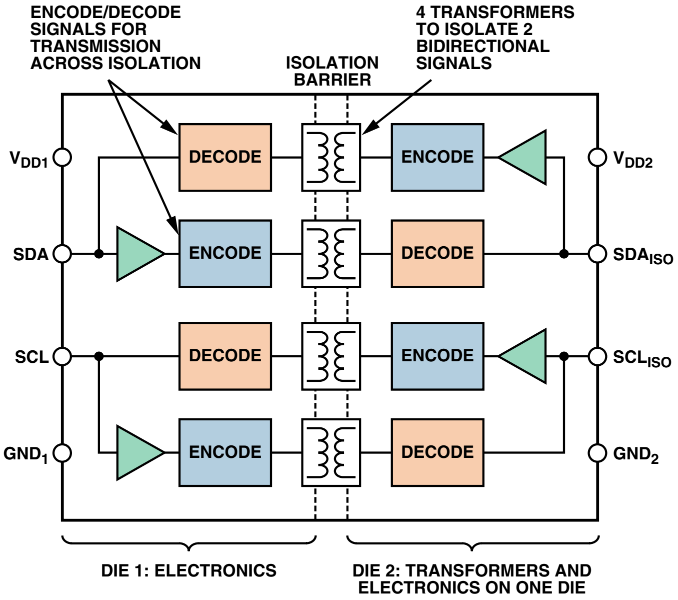


Figure 9. Bidirectional isolation using the ADuM1250.

Future Isolation Solutions

As these examples illustrate, digital isolation continues to offer simplified and novel solutions to challenging design problems. This is achieved at low cost through the use of standard foundry processes that enable integration of features not typically found in classical isolation solutions. In the near future, we can expect to see further advances, with *iso*Power being integrated into an increasing number of isolation applications; and we can also expect to see other novel solutions for isolating buses that are more complex than I^{2}C.

REFERENCES—VALID AS OF JANUARY 2007

[1] http://www.analog.com/en/content/0,2886,767%5F827%5F95767,00.html
[2] http://www.analog.com/library/analogdialogue/archives/39-10/iCoupler.html
[3] ADI website: www.analog.com (Search) High Speed Digital Isolators Using Microscale On-Chip Transformers (GO)
[4] ADI website: www.analog.com (Search) ADuM5240 (GO)
[5] ADI website: www.analog.com (Search) ADuM5241 (GO)
[6] ADI website: www.analog.com (Search) ADuM5242 (GO)
[7] ADI website: www.analog.com (Search) ADuM1201 (GO)
[8] ADI website: www.analog.com (Search) AD7823 (GO)
[9] ADI website: www.analog.com (Search) ADuM1200 (GO)
[10] ADI website: www.analog.com (Search) ADuM1250 (GO)
[11] ADI website: www.analog.com (Search) ADuM1251 (GO)

This article is available in HTML and PDF at *http://www.analog.com/analogdialogue*. Click on *archives*, then select volume, number, and title.

Analog Dialogue

Analog Devices, Inc.
Worldwide Headquarters
Analog Devices, Inc.
One Technology Way
P.O. Box 9106
Norwood, MA
02062-9106 U.S.A.
Tel: 781.329.4700
(800.262.5643,
U.S.A. only)
Fax: 781.461.3113

Analog Devices, Inc.
Europe Headquarters
Analog Devices, Inc.
Wilhelm-Wagenfeld-Str. 6
80807 Munich
Germany
Tel: 49.89.76903.0
Fax: 49.89.76903.157

Analog Devices, Inc.
Japan Headquarters
Analog Devices, KK
New Pier Takeshiba
South Tower Building
1-16-1 Kaigan, Minato-ku,
Tokyo, 105-6891
Japan
Tel: 813.5402.8200
Fax: 813.5402.1064

Analog Devices, Inc.
Southeast Asia
Headquarters
Analog Devices
22/F One Corporate Avenue
222 Hu Bin Road
Shanghai, 200021
China
Tel: 86.21.5150.3000
Fax: 86.21.5150.3222

Printed in the U.S.A. M02000404-xx-2/07

www.analog.com/analogdialogue

ANALOG
DEVICES