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# Analog Dialogue

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# Editors' Notes

# **GROUND, REGULATORS, AND GAMES**

The difficulty of maintaining true ground has been discussed in these pages numerous times, usually in terms of ac and dc behavior. However, circuits such as buck- and boost regulators that rapidly and repeatedly switch large amounts of current, can cause large *transient* ground errors. The origin of this "ground-bounce" phenomenon is explained in easy-to-understand terms, leading logically to a sensible PC-card design approach that minimizes the transients—starting on Page 3.



A *low-dropout regulator* (LDO) is a handy way to immunize a circuit against the battery discharge curve when the upstream voltage becomes so low that the output voltage of a conventional regulator would begin to drop. Some of the fine points of LDO design are discussed in the article starting on Page 8.

At this writing, the Nintendo Wii's successful entry to the games marketplace is legendary. A key internal contributor to its popularity is a 3-dimensional accelerometer that lets the player use natural motions similar to the motions used in a real game to play an electronic game. The role of dynamic *i*MEMS (integrated microelectromechanical systems) in making games more user-friendly is discussed starting on Page 11.

## **NEW FELLOWS NAMED**

Dr. Colin Lyden and Dr. Zoran Zvonar have been elevated to the distinguished position of ADI Fellow during our 2007 General Technical Conference, which attracted approximately 1,900 engineers from the company's design sites worldwide.

The Fellows honor is bestowed on a select group of engineers who have contributed significantly to ADI's business and demonstrated important qualities, such as innovation, leadership, entrepreneurial ability, and consulting skills. In addition, an ADI Fellow must be a company ambassador, bridging across organizations and demonstrating an unparalleled ability to teach and mentor others within the company. With the latest inductions in this, the program's 27<sup>th</sup> year, Analog Devices has a total of 33 Fellows within our community of 3,500 engineers worldwide.

"Engineering excellence and innovation continue to set ADI apart," said Sam Fuller, vice president of Research and Development. "We are fortunate that exceptional engineers like Colin and Zoran, who are recognized both inside and outside the company for their expertise, have chosen to make their careers at Analog Devices. Their work has challenged the conventional wisdom within the company, extended our ambitions for new-product performance, and served as an inspiration for the next generation of engineers to sustain ADI's record of innovation."

**Colin Lyden** received his Ph.D. in 1984 from University College, Cork, Ireland. He joined ADI in 1999 as an engineering director with leadership responsibility for the Limerick CAD group and the Cork Design Centre. His creative ideas and work, blurring the traditional distinctions between sigma-delta, successive-approximation, and pipelined converter architectures, have resulted in performance improvements in a range of ADI products, including the AD7982 and the AD7767 successive-approximation analog-todigital converters.



Colin, who holds 15 U.S. patents, was the lead architect for a new CT medical-imaging analog front end that achieved breakthroughs in both cost and performance—and has been designed into next-generation high-slice CT machines.

**Zoran Zvonar**, having earned his Ph.D. at Boston's Northeastern University in 1993, joined ADI in 1994 as one of the company's first system engineers to specialize in communications algorithms. An expert in wireless system design for varied communications applications, Zoran has extensively published in leading technical journals. He also serves as an editor for the *IEEE Communications Magazine* and is co-author of several books focusing on GSM and thirdgeneration wireless communications systems.



Zoran developed and validated a breakthrough system approach for wireless handsets that resulted in two patents and enabled *direct conversion*—the process of converting analog RF signals directly to digital baseband data—to be applied successfully to the GSM wireless communications standard. He was a member of the core technology design team for ADI's SoftFone<sup>®</sup> and Othello<sup>®</sup> wireless product families.

Dan Sheingold [dan.sheingold@analog.com]

## **GPS NAVIGATION**

In November, I purchased an inexpensive aftermarket GPS navigation system for my car. The system can be helpful, even in well-known locations, where it alerts me to upcoming turns, can plot a scenic route on one of the parkways, and occasionally teaches me a new shortcut. It's also entertaining on long road trips, where it continually counts down the remaining miles and minutes, its highly visible progress display making it seem that the destination is closer than



it actually is. Its main purpose, of course, is plotting a course to an unfamiliar location. The combination of audio and visual clues makes finding addresses easy, and the routing options provide a simple way to choose the shortest route—or the quickest route—to avoid toll roads or local roads, and to navigate around a detour.

The hidden beauty, however, is using the extensive collection of points-ofinterest to show what's available in an unknown area. Recently, a friend from Connecticut met me in Charlestown, Rhode Island, a town that is roughly halfway between our houses. Neither of us was familiar with the area. Upon arrival, we found that the restaurant that we had chosen for lunch was closed. No worries—the GPS showed us several other local restaurants, as well as the town beach, two National Wildlife Refuges, and a seventeenth-century gristmill. It helped us to enjoy a day trip in a beautiful, if unfamiliar town.

I have three complaints about this low-end GPS, however. The first, and most serious, is that the touch screen is becoming less responsive as the summer temperatures in New England continue to rise. A few minutes in front of the air-conditioning outlet usually cures the problem, but I'm a fan of sunshine and open roofs. Too bad the manufacturer didn't use an ADI capacitance-to-digital converter, which includes on-chip calibration logic to compensate for changes in temperature and humidity.

The second problem is that the GPS loses its signal when I travel through Boston's Big Dig tunnels, making it unable to maintain its bearings or to provide instructions for lane splits and exits. Too bad it doesn't include an ADI accelerometer, whose inertial navigation capabilities could provide positional information during these temporary signal losses.

The third minor irritation is that the aftermarket GPS has no connection to the car stereo, and thus cannot mute the music when it needs to provide spoken directions. Fortunately, my system gives several warnings before each turn, allowing me to turn the radio down when necessary.

Readers: What are the best features of your GPS, or your pet peeves with your systems? Designers: What should we be looking for in next-generation systems? Your comments are welcome.

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# Analog Dialogue

www.analog.com/analogdialogue dialogue.editor@analog.com Analog Dialogue is the free technical magazine of Analog Devices, Inc., published continuously for 41 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] or

# Reducing Ground Bounce in DC-to-DC Converters—Some Grounding Essentials

By Jeff Barrow [jeff.barrow@analog.com]

Electrical ground<sup>1</sup> looks simple on a schematic; unfortunately, the actual performance of a circuit is dictated by its printedcircuit-board (PCB) layout. What's more, ground-node analysis is difficult, especially for dc-to-dc converters, such as *buck* and *boost* circuits, which pound the ground node with large, fast-changing currents. When the ground node moves, system performance suffers and the system radiates EMI. But a well-"grounded" understanding of the physics of ground noise can provide an intuitive sense for reducing the problem.

Ground bounce can produce transients with amplitudes of *volts*; most often changing *magnetic flux* is the cause. A loop of wire carrying current is essentially an electromagnet whose field strength is proportional to the current. Magnetic flux is proportional to the magnetic field passing through the loop area,

Magnetic Flux  $\propto$  Magnetic Field  $\times$  Loop Area

or more precisely,

 $\Phi_B = BA \cos\varphi$ 

Where the magnetic flux,  $\Phi_B$ , is the magnetic field, B, passing through a surface loop area, A, at an angle,  $\varphi$ , to the area's unit vector.

A look at Figure 1 gives meaning to the magnetic flux associated with an electric current. A voltage source pushes current through a resistor and around a loop of wire. This current is associated with magnetic flux encircling the wire. To relate the different quantities, think of grabbing the wire with your right hand (applying the *right-hand rule*). If you point your thumb in the direction of current flow, your fingers will wrap around the wire in the direction of the magnetic field lines. As those field lines pass through the loop, their product is *magnetic flux*, directed in this case into the page.



Figure 1. The right-hand rule.

Change either the magnetic field strength or the loop area, and the flux will change. As the flux changes, a voltage is induced in the wire, proportional to the rate of change of the flux,  $d\Phi_B/dt$ . Notice that either a fixed loop and changing current or a constant current and a changing loop area—or both—will change the flux.

Suppose, for example, that the switch in Figure 2 is suddenly opened. When current stops flowing, the magnetic flux collapses, which induces a momentarily large voltage everywhere along the wire. If part of the wire is a ground return lead, voltage that is supposed to be at ground will spike, thus producing false signals in any circuitry using it as a ground reference.



Figure 2. Effect of opening a switch.

Generally, voltage drops in printed-circuit-board sheet resistance are not a major source of ground bounce. 1-oz copper has a resistivity of about 500  $\mu\Omega$ /square, so a 1-A change in current produces a bounce of 500  $\mu$ V/square—a problem only for thin, long, or daisy-chained grounds, or precision electronics.

Charging and discharging of parasitic capacitors provides a path for large transient currents to return to ground. The change in magnetic flux from those changing currents induces ground bounce.

The best way to reduce ground bounce in a switching dc-to-dc converter is to control changes in magnetic flux—by minimizing both current loop *areas* and *changes* in loop area.

In some cases, as in Figure 3, the current remains constant, but the switching produces a change of loop *area*, hence a change of flux. In switch Case 1, an ideal voltage source is connected by ideal wires to an ideal current source. Current flows in a loop that includes a ground return.

In Case 2, when the switch changes position, the same current flows in a different path. The current source is dc and does not change, but loop area does change. The change in loop area means a change in magnetic flux, so voltage is induced. Since a ground return is part of that changing loop, its voltage will bounce.



WHEN THE SWITCH CHANGES CASE, THE LOOP AREA CHANGES. EVERYWHERE ALONG THE WIRE IN THE LOWER LEFT, A VOLTAGE IS INDUCED WHERE THE MAGNETIC FIELD COLLAPSES AS I<sub>1</sub> GOES TO 0 AMPS.

#### Figure 3.

## **Buck Converter Ground Bounce**

For the purpose of discussion, the simple circuit in Figure 3 is similar to—and can be morphed into—the *buck* converter in Figure 4.



Figure 4. To a high frequency switch, an enormous  $C_{\text{VIN}}$  and  $L_{\text{BUCK}}$  look like a voltage and current source.

At high frequencies, a large capacitor—such as the *buck* input capacitor,  $C_{VIN}$ —looks like a dc voltage source. Similarly, the large output buck inductor,  $L_{BUCK}$ , looks like a dc current source. These approximations are made to help foster intuition.

Figure 5 displays how magnetic flux changes as the switch alternates between the positions.



Figure 5. The effect of switching on loop area.

The large  $L_{BUCK}$  inductor holds the output current roughly constant. Similarly,  $C_{VIN}$  maintains a voltage approximately equal to  $V_{IN}$ , so the input current is also more or less constant due to the unchanging voltage across the input lead inductance.

Although the input and output currents are roughly constant, as the switch moves from Position 1 to Position 2, the total loop area rapidly changes in the middle portion of the circuit. That change means a rapid change in magnetic flux, which in turn induces ground bounce along the return wire.

Actual buck converters are made with pairs of semiconductor switches, as shown in Figure 6. Although the complexity has increased with each figure, the analysis of ground bounce induced by changing magnetic flux remains simple and intuitive.



Figure 6. The basic principles are unchanged with semiconductor switching.

The fact that a change in magnetic flux will induce voltage everywhere along a ground return brings up the interesting question: where is true ground? Because ground bounce means a voltage on the ground return trace is bouncing with respect to some ideal point called *ground*, that point needs to be identified.

In the case of power-regulating circuits, true ground needs to be at the low end of the load. After all, a dc-to-dc converter's purpose is to deliver quality voltage and current to the load. All other points along the current return are not ground, just part of the ground return.

Since ground is at the low end of the load, and since changing loop area is the cause for ground bounce, Figure 7 shows how careful placement of  $C_{\rm VIN}$  reduces ground bounce by reducing the portion of loop area that changes.



Figure 7. Careful placement of  $C_{\text{VIN}}$  greatly reduces ground bounce.

Capacitor  $C_{VIN}$  bypasses the top of the high-side switch directly to the bottom of the low side switch, thereby shrinking the changing loop area and isolating it from the ground return. From the bottom of  $V_{IN}$  to the bottom of the load, no loop-area or switch-current changes occur from one case to the next. Consequently, the ground return does not bounce.



Figure 8. A bad layout results in a large change in current loop area from one switch case to the next.

The PCB layout itself actually determines the performance of the circuit. Figure 8 is a PCB layout of the buck schematic in Figure 6. In the switch position shown in Case 1, with the high-side switch on, dc flow follows the outer red loop. In the switch position shown in Case 2, with the low-side switch on, dc flow now follows the blue loop. Notice the changing loop area, and hence, the changing magnetic flux. So, voltage is induced and the ground bounces.

The layout is realized on a single PCB layer for clarity, but using a second layer of solid ground plane would not fix the bounce. Before showing an improved layout, Figure 9 gives a quick example of where a solid ground plane may not be such a good idea.



Figure 9. A solid ground plane is not always a good idea.

Here, a 2-layer PCB is constructed so that a bypass capacitor is attached at right angles to a top-layer supply line. In the example on the left, the ground plane is solid and uncut. Top trace current flows through the capacitor, down the via, and out the ground plane.

Because ac always takes the path of least impedance, ground return current rounds the corner on its way back to the source. So the current's magnetic field and the associated loop area change when either magnitude or frequency of the current changes, hence the changing flux. The tendency of current to flow along the easiest path means that even a solid-sheet ground plane can bounce—irrespective of its conductivity.

In the example on the right, a well-planned cut in the ground plane will constrain the return current to a minimum loop area and greatly reduce the bounce. Any residual bounce voltage that is developed in the cut return line is isolated from the general ground plane.

The PCB layout in Figure 10 uses the principle illustrated in Figure 9 to reduce ground bounce. A 2-layer PCB is designed so that the input capacitor and both switches are built over an island in the ground plane.

This layout is not necessarily the best, but it works well and illustrates a key principle. Notice that the loop area enclosed by the red (Case 1) and blue (Case 2) currents is large. However, the difference between the two loops is small. The small change in loop area means a small change in magnetic flux—and so, a small ground bounce. (In general, however, also keep the loop area small—this figure strives to illustrate the importance of matching ac current paths.)

Additionally, in the ground-return island, where magnetic fields and loop area do change, any ground-return bounce is contained by the cut.

Also of interest, the input capacitor,  $C_{\rm VIN}$ , may not at first glance appear to be located between the top of the high-side switch and the bottom of the low-side switch, as discussed in Figure 7, but closer perusal will reveal that it is. Although physical proximity can be good, what really matters is the electrical closeness that is achieved by minimizing the area of the loop.



Figure 10. A good buck layout has a small change in loop area as between Case 1 and Case 2.

# **Boost Converter Ground Bounce**

A *boost converter* is essentially a reflection of a buck converter, so—as seen in Figure 11—it is the *output* capacitor that must be placed between the top of the high-side switch and the bottom of the low-side switch to minimize the change in loop area.



Figure 11. Boost converter means  $C_{VOUT}$  placement is critical in the same way that buck converter's  $C_{VIN}$ placement is critical. a) Bad design. b) Good design.

#### Review

Ground-bounce voltage is induced principally by a change in magnetic flux. In a dc-to-dc switching power supply, the flux changes because high-speed switches direct current between different current-loop areas. But careful placement of the buck/boost input/output capacitor and a surgical cut to a ground plane can isolate bounce. However, it is important to be watchful when cutting a ground plane, to avoid possibly increasing the loop area for some other return current in the circuit.

Also, a good layout locates true ground at the bottom of the load, with no changing loop areas or changing currents. Any other conductively associated point may be called "ground," but it is just a point along the return path.

# **Other Useful Concepts for Ground Analysis**

If you keep the following basic ideas in mind, you'll have a good feeling for what will and will not cause ground bounce. Figure 12 shows that conductors that cross at a right angle do not suffer magnetic interaction.



Figure 12. Conductors that cross at a right angle do not interact magnetically.

Magnetic field lines around parallel wires carrying equal currents flowing in the *same* direction cancel everywhere between the wires, so the total stored energy is less than what would be found for the individual wires. For this reason, wide PCB traces have less inductance than narrow traces.



Figure 13. Parallel wires with currents flowing in the same direction.

Magnetic field lines around parallel conductors carrying equal currents flowing in *opposite* directions cancel everywhere outside of the conductors and add everywhere between them. If the inside loop area can be made small, then the total magnetic flux, and therefore the inductance, will also be small. This behavior explains why ac ground plane return current always flows under the top trace conductor.



Figure 14. Parallel conductors with currents flowing in opposite directions.

Figure 15 shows why corners increase inductance. A straight conductor sees its own magnetic field, but at a corner, it also sees the magnetic field from the right-angled conductor. As a result, corners store more magnetic energy, and so, have more inductance than straight lines.



Figure 15. Why corners increase inductance.

Figure 16 shows that interruptions to the ground plane under conductors carrying current can increase loop area by diverting the return current, thus increasing loop size and facilitating ground bounce.





Component orientation does matter, as shown in Figure 17.



Figure 17. Effects of component orientation.

## Summary

Ground bounce is always a potential problem. For a monitor or TV, it can mean a noisy picture—for an audio device, background noise. In a digital system, it can lead to computation errors—even a system crash.

A careful estimation of parasitic elements followed by detailed simulation is a rigorous way to predict the magnitude of ground bounce. But to guide circuit-design intuition, it is necessary to understand the physics underlying its origin.

First, design the PCB so that the low end of the load is the true ground point.

Then, simplify the circuit dynamics by replacing large inductors and capacitors with current- and voltage sources. Look for the current loops in each switching combination. Make the loops overlap; where that is impossible, carefully cut out a small island of ground return such that only dc flows into and out of the opening.

In most cases, these efforts will give acceptable ground performance. If they don't, consider ground-plane resistance, then the displacement currents flowing in parasitic capacitors across all switches and down into the return path.

No matter what the circuit, the basic grounding principles are the same—changing magnetic flux needs to be minimized and/or isolated.

# ENDNOTE

<sup>1</sup>Many articles on the problems of "ground" have been published in *Analog Dialogue* and are available in our comprehensive online archive. An article co-authored by Paul Brokaw and the present author in 23-3 (1989) pp. 7-9 appears below in miniature. It includes footnote references to earlier related material on grounding and noise. Related material can be found in 11-2 (1977) pp. 10-15; 25-2 (1991) pp. 24-25; 26-2 (1992) p. 27 (includes a good set of references); 30-2 (1996) p. 11 (a bibliography on EMC/EMI/ESD); 39-3 (2005) pp. 3-8. The book of seminar notes, *High Speed System Applications*, ed. Walt Kester and Hank Zumbahlen, Analog Devices (2006), has an extensive section on PC-board layout and design tools (pp. 4.1-4.90). See also a related earlier article, "Reducing Ground Bounce in DC/DC-Converter Applications," by Jeff Barrow—EDN, 7/6/2006.

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# Analog Dialogue Volume 23, Number 3, pp. 7-9



# Ask The Applications Engineer—37 Low-Dropout Regulators

# By Jerome Patoux [jerome.patoux@analog.com]

This article introduces the basic topologies and suggests good practical usage for ensuring stable operation of *low-dropout voltage regulators* (LDOs). We will also discuss design characteristics of Analog Devices families of LDOs, which offer a flexible approach to maintaining dynamic- and dc stability.

- Q: What are LDOs and how are they used?
- *A:* Voltage regulators are used to provide a stable power supply voltage independent of load impedance, input-voltage variations, temperature, and time. Low-dropout regulators are distinguished by their ability to maintain regulation with small differences between supply voltage and load voltage. For example, as a lithium-ion battery drops from 4.2 V (fully charged) to 2.7 V (almost discharged), an LDO can maintain a constant 2.5 V at the load.

The increasing number of portable applications has thus led designers to consider LDOs to maintain the required system voltage independently of the state of battery charge. But portable systems are not the only kind of application that might benefit from LDOs. Any equipment that needs constant and stable voltage, while minimizing the upstream supply (or working with wide fluctuations in upstream supply), is a candidate for LDOs. Typical examples include circuitry with digital and RF loads.

A "linear" series voltage regulator (Figure 1) typically consists of a reference voltage, a means of scaling the output voltage and comparing it to the reference, a feedback amplifier, and a series pass transistor (bipolar or FET), whose voltage drop is controlled by the amplifier to maintain the output at the required value. If, for example, the load current decreases, causing the output to rise incrementally, the error voltage will increase, the amplifier output will rise, the voltage across the pass transistor will increase, and the output will return to its original value.



Figure 1. Basic enhancement-mode PMOS LDO.

In Figure 1, the error amplifier and PMOS transistor form a voltage-controlled current source. The output voltage,  $V_{OUT}$ , is scaled down by the voltage divider  $(R_1, R_2)$  and compared to the reference voltage  $(V_{REF})$ . The error amplifier's output controls an enhancement-mode PMOS transistor.

The *dropout voltage* is the difference between the output voltage and the input voltage at which the circuit quits regulation with further reductions in input voltage. It is usually considered to be reached when the output voltage has dropped to 100 mV below the nominal value. This key factor, which characterizes the regulator, depends on load current and junction temperature of the pass transistor.

- Q: How are regulators distinguished by dropout voltage?
- *A*: We can suggest three classes: standard regulators, quasi-LDOs, and low-dropout regulators (LDOs).

*Standard regulators*, which typically employ NPN pass transistors, usually drop out at about 2 V.

*Quasi-LDO regulators* usually use a Darlington structure (Figure 2) to implement a pass device made up of an NPN transistor and a PNP. The dropout voltage,  $V_{SAT}$  (PNP) +  $V_{BE}$  (NPN), is typically about 1 V—more than an LDO but less than a standard regulator.



Figure 2. Quasi-LDO circuit.

*LDO regulators* are usually the optimal choice based on dropout voltage, typically 100 mV to 200 mV. The disadvantage, however, is that the ground-pin current of an LDO is usually higher than that of a quasi-LDO or a standard regulator.

Standard regulators have a higher dropout voltage and dissipation, and lower efficiency, than the other types. They can be replaced by LDO regulators much of the time, but the maximum input voltage specification—which can be lower than that for standard regulators—should be considered. In addition, some LDOs will need specially chosen external capacitors to maintain stability. The three types differ somewhat in both bandwidth and dynamic stability considerations.

- Q: How can I select the best regulator for my application?
- *A:* To choose the right regulator for a specific application, the type and range of input voltage (e.g., the output voltage of the dc-to-dc converter or switching power supply ahead of the regulator), needs to be considered. Also important are: the required output voltage, maximum load current, minimum dropout voltage, quiescent current, and power dissipation. Often, additional features may be useful, such as a shutdown pin or an error flag to indicate loss of regulation.

The source of the input voltage needs to be considered in order to choose a suitable category of LDO. In battery-powered applications, LDOs must maintain the required system voltage as the battery discharges. If the dc input voltage is provided from a rectified ac source, the dropout voltage may not be critical, so a standard regulator—which may be cheaper and can provide more load current—could be a better choice. But an LDO could be the right choice if lower power dissipation or a more precise output voltage is necessary.

The regulator should, of course, be able to provide enough current to the load with specified accuracy under worst-case conditions.

# **LDO Topologies**

In Figure 1, the pass device is a PMOS transistor. However, a variety of pass devices are available, and LDOs can be classified depending on which type of pass device is used. Their differing structures and characteristics offer various advantages and drawbacks.

Examples of four types of pass devices are shown in Figure 3, including NPN and PNP bipolar transistors, Darlington circuits, and PMOS transistors.



Figure 3. Examples of pass devices.

For a given supply voltage, the bipolar pass devices can deliver the highest output current. A PNP is preferred to an NPN, because the base of the PNP can be pulled to ground, fully saturating the transistor if necessary. The base of the NPN can only be pulled as high as the supply voltage, limiting the minimum voltage drop to one  $V_{BE}$ . Therefore, NPN and Darlington pass devices can't provide dropout voltages below 1 V. They can be valuable, however, where wide bandwidth and immunity to capacitive loading are necessary (thanks to their characteristically low  $Z_{OUT}$ ).

PMOS and PNP transistors can be effectively saturated, minimizing the voltage loss and the power dissipated by the pass device, thus allowing low dropout, high-efficiency voltage regulators. PMOS pass devices can provide the lowest possible dropout voltage drop, approximately  $R_{DS(ON)} \times I_L$ . They also allow the quiescent current flow to be minimized. The main drawback is that the MOS transistor is often an external component—especially for controlling high currents—thus making the IC a *controller*, rather than a complete self-contained regulator.

The power loss in a complete regulator is

$$P_D = (V_{IN} - V_{OUT}) I_L + V_{IN} I_{GND}$$

The first part of this relationship is the dissipation of the pass device; the second part is the power consumption of the controller portion of the circuit. The ground current in some regulators, especially those using saturable bipolar transistors as pass devices, can peak during power-up.

# Q: How can LDO dynamic stability be ensured?

A: Classical LDO circuit designs for general-purpose applications have problems with stability. The difficulties stem from the nature of their feedback circuits, the wide range of possible loads, the variability of elements within the loop, and the difficulty of obtaining precision compensation devices with consistent parameters. These considerations will be discussed below, followed by a description of the anyCAP<sup>®</sup> circuit topology, which has improved stability.

LDOs generally use a feedback loop to provide a constant voltage, independent of load, at the output. As is true for any high-gain feedback loop, the location of the poles and zeros in the loop-gain transfer function will determine the stability.

NPN-based regulators, with their low-impedance emitterloaded output, tend to be relatively insensitive to output capacitive loading. PNP and PMOS regulators, however, have higher output impedance (collector loaded in the case of the PNP). In addition, the loop's gain and phase characteristics strongly depend on the load impedance, thus requiring special consideration for stability.

The transfer function of PNP- and PMOS-based LDOs has several poles that impact stability:

- The dominant pole (P0 in Figure 4) is set by the error amplifier; it is controlled and fixed, in conjunction with the  $g_m$  of the amplifier, through an internal compensation capacitance  $C_{COMP}$ . This pole is common to all of the LDO topologies described above.
- The second pole (*P1*) is set by the output elements (the combination of the output capacitance and the load capacitance and resistance). This makes the application problem more difficult to handle, as these elements affect both the loop gain and bandwidth.
- A third pole (P2) is due to parasitic capacitance around the pass elements. PNP power transistors have a unity-gain frequency ( $f_T$ ) much lower than that of comparable NPN transistors, under the same conditions.



Figure 4. LDO frequency amplitude response.

As Figure 4 shows, each pole contributes 20 dB/decade of rolloff in gain, with up to 90° of phase shift. As the LDOs discussed here have multiple poles, the linear regulator will be unstable if the phase shift at the unity-gain frequency approaches  $-180^{\circ}$ . Figure 4 also shows the effect of loading the regulator with a capacitor, whose *effective series resistance* (ESR) will add a zero ( $Z_{ESR}$ ) into the transfer function. This zero will help to compensate for one of the poles and can help to stabilize the loop if it occurs below the unity-gain frequency and keeps the phase shift well below  $-180^{\circ}$  at that frequency.

ESR can be critical for stability, especially for LDOs with vertical-PNP pass devices. As a parasitic property of a capacitor, however, the ESR is not always well-controlled. A circuit may require the ESR to fall within a certain window to ensure that the LDO operates in the stable region for all output currents (Figure 5).



Figure 5. Stability as a function of output current and load-capacitor ESR.

Even in principle, choosing the right capacitor with the right ESR (high enough to reduce the slope before the frequency response crosses through 0 dB, yet low enough to bring the gain below 0 dB before the associated pole, P2) can be challenging. Yet the practical considerations add further challenges: ESR varies, depending on the brand; and the minimum capacitance value to use in production will require bench tests, including extreme cases with minimum ambient temperature and maximum load. The choice of the type of capacitor is also important. Perhaps the most suitable are tantalum capacitors, despite their large size in the higher-capacitance ranges. Aluminum electrolytics are compact, but their ESR tends to deteriorate at low temperatures, and they don't work well below  $-30^{\circ}$ C. Multilayer ceramic types do not have sufficient capacitance for conventional LDOs (but they are suitable for anyCAP designs, read on).

# Analog Devices anyCAP family of LDOs

LDO implementation is considerably easier now, thanks to improvements in both dc and ac performance associated with regulators employing the Analog Devices anyCAP LDO architecture. As the term implies, regulators embodying it are relatively insensitive to both the size of the capacitor and its ESR, thus allowing for a wider possible range of output capacitance. The approach has spread and is now more widely available in the marketplace, but it may be helpful to understand how this architecture (Figure 6) simplifies the stability issue.



Figure 6. Simplified schematic of anyCAP LDO.

The anyCAP family of LDOs, including the 100-mA ADP3307<sup>1</sup> and the 200-mA low-quiescent-current ADP3331,<sup>2</sup> can remain stable with output capacitance as low as 0.47  $\mu$ F, using good-quality capacitors of any type, including compact multilayer ceramic. ESR is essentially a nonissue.

The simplified schematic of Figure 6 shows how a single loop provides both regulation and reference functions. The output is sensed by the external R1-R2 voltage divider, and fed back to the input of a high-gain amplifier through diode D1 and the R3-R4 divider. At equilibrium, the amplifier produces a large, repeatable, well-controlled offset voltage that is *proportional to absolute temperature* (PTAT). This voltage combines with the complementary temperature-sensitive diode voltage drop to form the implicit reference, a temperature-independent virtual band-gap voltage.

The amplifier output connects to an unusual noninverting driver that controls the pass transistor, allowing the frequency compensation to include the load capacitor in a pole-splitting arrangement based on Miller compensation. This provides reduced sensitivity to value, type, and ESR of the load capacitor. Additional advantages of the pole-splitting scheme include superior line-noise rejection and very high regulator gain, thereby providing exceptional accuracy and excellent line and load regulation.

#### Q: Would you discuss the Analog Devices families of LDOs?

*A:* The choice of LDO depends, of course, on the supply voltage range, load voltage, and required maximum dropout voltage. The main differences between devices focus on power

consumption, efficiency, price, ease of use, and the various specifications and packages available.

The popular ADP33xx anyCAP family of ADI LDOs has been on the market for several years. Based on a BiCMOS process and a PNP pass transistor, it allows good regulation and many of the advantages mentioned above, but tends to be somewhat more expensive than CMOS parts.

Some recent designs, such as the ADP17xx family, are entirely CMOS-based, with a PMOS pass transistor, which allows the fabrication of LDOs at lower cost, but with a trade-off on line-regulation performance. Devices in this family can handle a large range of output capacitance, but they still require at least 1  $\mu$ F and  $\leq$ 500-m $\Omega$  ESR. For example, the 150-mA ADP1710<sup>3</sup> and ADP1711<sup>4</sup> are optimized for stable operation with small 1- $\mu$ F ceramic output capacitors, allowing for good transient performance while occupying minimal board space, and the 300-mA ADP1712,<sup>5</sup> ADP1713,<sup>6</sup> and ADP1714<sup>7</sup> can use  $\geq$ 2.2- $\mu$ F capacitors.

Both of these families have 16 fixed-output-voltage options, from 0.75 V to 3.3 V, as well as an adjustable-output option in the 0.8-V to 5-V range. Accuracy is to within  $\pm 2\%$  over line, load, and temperature. The ADP1711 and ADP1713 fixedvoltage versions allow for a reference-bypass capacitor to be connected; this reduces output voltage noise and improves power-supply rejection. The ADP1714 includes a tracking feature, which allows the output to follow an external voltage rail or reference. Dropout voltages at rated load are 150 mV for the ADP1710 and ADP1711; and 170 mV for the ADP1712, ADP1713, and ADP1714. Power-supply rejection (PSR) is high (69 dB and 72 dB at 1 kHz), and power consumption is low, with ground current of 40  $\mu$ A and 75  $\mu$ A with 100- $\mu$ A load.

Typical transient responses of the ADP1710 and ADP1711 are compared in Figure 7 for a nearly full-load step, with  $1-\mu F$  and  $22-\mu F$  input- and output capacitors.



Figure 7. Transient response of ADP1710/ADP1711.

The operating junction temperature range is  $-40^{\circ}$ C to  $+125^{\circ}$ C. Both families are available in tiny 5-lead TSOT packages, a small-footprint solution to the variety of power needs.

# **REFERENCES–VALID AS OF JULY 2007**

<sup>1</sup>ADI website: www.analog.com (Search) ADP3307 (Go) <sup>2</sup>ADI website: www.analog.com (Search) ADP3331 (Go) <sup>3</sup>ADI website: www.analog.com (Search) ADP1710 (Go) <sup>4</sup>ADI website: www.analog.com (Search) ADP1711 (Go) <sup>5</sup>ADI website: www.analog.com (Search) ADP1712 (Go) <sup>6</sup>ADI website: www.analog.com (Search) ADP1713 (Go) <sup>7</sup>ADI website: www.analog.com (Search) ADP1714 (Go)

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# **Elements of Motion: 3D Sensors in Intuitive Game Design**

By Adam S. Champy [adam.champy@analog.com]

# INTRODUCTION

A video game system comprises a platform, a display, one or more I/O interfaces known as *controllers*, and software. The platform can be a computer or a dedicated console; the display, which may be housed with the platform, is often audiovisual; and controllers used to play the game, can range from mice and keyboards, to panel-bound buttons, scroll wheels, and joysticks to two-handed "gamepads" and freely moving wireless devices that simulate the physical motions involved in the game.

In recent months, new generations of sophisticated gaming hardware containing high-end computer systems using dual-core processors have been introduced. Furthermore, the three new console systems currently competing for the market's attention have more computing- and graphics horsepower than do many computers. For serious gamers, multi-GPU (graphical processing unit) video cards are viewed as a worthwhile investment. Of all the advances in processing, graphics, sound, and even the games themselves, the most momentous change is the introduction of intuitive, motionbased game control. This change is being driven by a new generation of very low power motion sensors built using microelectromechanical systems (MEMS), the same accelerometer technology first used in the automobile industry for airbag crash sensing. MEMS-based 3D motion-sensing game controllers are influencing not only how games will be played, but more importantly, they are strongly influencing how games will be designed.

This article reviews the current capabilities of gaming systems, describes how game elements can enable—or prevent—intuitive game design, and how existing control hardware limits game design. Also discussed are: the operating principles of the 3D motion sensors used in the next generation of gaming systems, how motion sensing decreases the learning curve for beginning and expert gamers, and the important specifications and development principles with which game developers need to be familiar.

# **Design Elements That Limit Intuitive Gaming**

"Of course, when playing a game, the nearest thing to the player is the controller. The controller should therefore be regarded as an extension of the player rather than as part of the console. I always bear in mind the importance of the fact that the player will have far more contact with the controller and UI [user interface] than the console itself."

—Akio Ikeda, responsible for accelerometer hardware in the *Nintendo Wii*<sup>™</sup>, in an interview with Satoru Iwata, Wiilaunch website, Summer 2006.

Each game's plot assumes that the player has some previous knowledge of the effects—and perhaps strategy and tactics—of picking up a card, rolling a die, or hitting a button. Often, this is suggested to the purchaser in the game's "recommended age" on the package. For example, the game *blackjack* (or "21") makes the assumptions that a beginning player has, or can easily acquire, the following knowledge:

how to add

the concept of comparison, such as "less than," "equal to," and "greater than"

familiarity with cards, and their numerical values; in particular, the *ace* card, which has no number label on it—and has a choice of two values in the game.

Once players start to consider blackjack as a gambling game, learning risk and reward, comparing to a dealer's "hand"—whether 21 or some other value, and tactics such as doubling-down, they grow from beginner to expert. In blackjack, different user interaction formats don't change the game itself, whether using a physical deck of cards or the position of a mouse on a computer. The effect of the action "Hit me!" is always the same, and the target is always 21.

Virtual gaming environments can radically change how a player interacts with a game, especially where speed and dimensional motion are involved. The nature of the interaction between the controller and the user interface (UI) historically has levied unnatural constraints on the user experience. Consider, for example, *passing* in the basic U.S. Football video game, in which a player chooses to throw a ball to one of three virtual players, using a keyboard or game controller (Figure 1).



Figure 1. Pressing a button substitutes for the natural physical action of throwing a ball.

Standard controllers and interfaces weakly replace intuitive natural spatial relationships. Figure 1 shows a progression of throwing a ball (green area in (a)) to one of three players, associated with buttons X, Y, and Z. In (b), the thrower elects to pass to the player at the right, using button Z. In Figure (c), the thrower's square no longer has the ball, and player Z (now green) has received the throw. This is of course very different from playing a game on a real field—when passing to a teammate, you don't consider moving a finger hovering over a Z button, you would just physically pass the ball to the right. So someone who plays many sports, but has not played in a virtual environment, would have to learn to associate throwing with pressing the Z button (in this version of the game).

Thus, instead of transferring one's own real-life experience to the virtual world, the game player must learn platform-specific skills in order to play. This impedes the novice player and limits the marketable audience for a game to those who want to spend the time to learn a new skill that is not necessarily useful in the real world. Almost anyone who meets the stated criteria for blackjack can sit down at a blackjack table anywhere and play for the first time, but very few inexperienced electronic game players could pick up a game controller as a beginner and immediately play electronic football against another player—without feeling nervous or overmatched. The difference is that the physical skills that blackjack requires in any medium are simple, intuitive, easily learned, and fun.

# **Design for Intuitive Gaming: Historical Use of Motion**

"The motion sensor provided an intuitive, easy-to-understand way to operate the machine, which goes really well with our portable game consoles. We believe a wide range of age groups will also enjoy playing 'Yosshie-no Banyu-Inryoku."

-Satoru Okada, General Manager, Research & Engineering Department of Nintendo, quoted in Analog Devices press release introducing *i*MEMS ADXL202<sup>1</sup> Yosshie-no Banyu-Inryoku application, 2004. Today's biggest news in gaming is the incorporation of motion sensing in mainstream console and game design. Both the *Nintendo*  $Wii^{TM}$  and *Sony PlayStation*  $3^{TM}$  games feature MEMS motion sensors. The bigger *impact*, though, is that motion sensing is now driving the actual game *design* as well as reporting a set of motions in an existing game format. Nintendo is using an Analog Devices ADXL330<sup>2</sup> three-axis *i*MEMS sensor to give the revolutionary "Wii<sup>TM</sup>-Mote" controller 3D motion-sensing capability.

This is not the first time MEMS motion sensors have been used in controller design, however. Microsoft and Logitech pioneered the idea in 1998 with the *SideWinder® Freestyle Pro* and *WingMan Gamepad Extreme* game controllers, both featuring an Analog Devices ADXL202 two-axis *iMEMS* sensor. The Freestyle Pro won "The Most Promising New Peripheral' award at the Electronic Entertainment Expo in 1998.

At this stage of game development, few designers used motion sensing as an intrinsic element of game design. Two-axis tilt-sensing simply replaced the D-pad (direction pad) if the user wanted to control the game with tilt instead of button presses. And tilt could do some breakthrough things to add to the game-playing experience: As you lean the controller back, you could pop a wheelie on a motorcycle in a riding game. In a flight-simulator, tilting your controller left and right could cause a Star Wars X-wing fighter to swoop left or right with your motion. In driving and flying games, experiences that had relied heavily on the D-pad for control benefited the most from this type of tilt motion control. But the concept, not an integral part of the game design, did not find major consumer traction. The increased cost of the motion-enabled controller and the lack of true motion-based experiences limited the appeal for those Microsoft and Logitech products.

Nintendo was the first to codesign hardware and a game concept with motion sensing, in their Yosshie-no Banyu-Inryoku and Koro-Koro Kirby (Kirby Tilt 'n' Tumble) GAMEBOY titles. These innovative games proved that a market existed for intuitive motion-based gaming. Both incorporated ADXL202 accelerometers in the game cartridge itself, using tilt to move the character in a way many ages and skill levels could understand. Koro-Koro Kirby uses the principle of a marble on a tilting table, a toy many children and adults have played with in real life. When transferring this game experience to the virtual world, Nintendo required no new skills to be learned, as the player controls Kirby, the marble, with physical tilt. The MEMS accelerometer uses so little power that it could be used as the primary control for the entire course of game-play in a portable application, without excessive drain on the battery. The cost of adding motion using IC accelerometers had also reached a point where they would not impact consumer prices. These titles appealed to a wide audience, were intuitive, easily learned, and fun. Hundreds of thousands of copies were sold worldwide.

# **Design for Intuitive Gaming: Developing Motion-Based Applications**

"Since I'd worked on products using acceleration sensors before, I had a general idea of the characteristics and limitations I could expect from this technology. From that experience, I already knew that we would need an absolute reference point near the TV in order to improve reliability of control".

—Akio Ikeda, in an interview with Satoru Iwata, Wii Launch Website, 2006.

The first step in designing any game is to generate the core plot and user concept. This includes the virtual world that a UI designer will create, the goals for each player, and the interaction the player has with the user interface. The most basic element of intuitive design is to capture an activity someone already does in the real world and bring it into the virtual world, where creativity, different challenges, and fantasy can exist—but the player does not need to learn any new skills to play. The translation of physical activity to control starts with a motion sensor. There are a few major categories of ways to use sensor data in game design, but they all start with the fundamentals of how motion sensors work accelerometers in particular. [See Principle of Operation.]

The most important thing to remember is that accelerometers measure acceleration. Anything that includes motion, including vibration and shock, can be measured by the accelerometer, so each application has different accelerometer requirements and limitations.

# MOTION GAMING APPLICATION CATEGORIES Simple Tilt Threshold

Kirby Tilt 'n' Tumble is a prime example of using tilt thresholds. Using tilt is the equivalent of using Earth's gravity field as a 1-g reference acceleration along the vertical (Z) axis (depending on location, g is approximately 9.8 m/s<sup>2</sup>, or 32 ft/s<sup>2</sup>). The X and Y axes will each experience 0 g when the device is perfectly level (Figure 2).



Figure 2. Output response of stationary ADXL330 three-axis accelerometer with orientation to gravity. (a) Device's Z axis horizontal, various X and Y orientations. (b) Device's Z axis vertical, arbitrary X and Y orientation.

When the player tilts the controller, the game designer wants to know if the amount of tilt has crossed a particular threshold. The method used to measure tilt is an inherent trigonometric relationship. The X and Y outputs of an accelerometer as a function of the tilt angles,  $\theta_x$  and  $\theta_y$  (the angles the X and Y axes make with the horizontal), are proportional to  $g \sin \theta_x$ and  $g \sin \theta_y$ .

In a game like *Tilt 'n' Tumble*, where the player is trying to imitate the effects of real gravity, it's not necessary to know the actual angles (calculated by inverse trigonometric functions); the device's outputs physically model the forces affecting virtual marble movement.

For this game, which depends on just the X- and Y-axis angles to the horizontal, a three-axis accelerometer is not necessary. In fact, with the X and Y axes horizontal and the Z axis vertical, the device's Z output is proportional to the *cosine* of the angular deviation,  $\theta_z$ , from vertical—not very useful in this application without further processing.

Historically, Kirby used an XY accelerometer. Microsoft's *Sidewinder Freestyle Pro* used an XY sensor to measure tilt to control the rate of left-right up-down action on the D-Pad. If the application *only* needs tilt, a 2-axis accelerometer is the low-cost alternative.

## **Gesture Recognition: User-Generated Acceleration**

Interested in more than gravity measurements? Games such as *Wii Sports Tennis*, as demonstrated at the 2006 E3 Media and Business Summit, use player-generated motion that far exceeds the acceleration of gravity. For applications of this sort, the ADXL330 has a measurement range of  $\pm 3 g$  minimum in each axis. Unfortunately, a game concept that involves high-speed motion, such as a golf swing, could exceed the measurement range of many low-g accelerometers. To get a sense of acceleration for an activity, if the arm is considered to swing in a circle around the body, angular acceleration is:

$$\mathbf{A} = v^2 / r$$

with components in the x, y, and z directions. If the maximum acceleration temporarily exceeds the device's measurement range, design choices include using an accelerometer that has higher maximum range, but sacrifices resolution, or simulating the overload condition—which requires a measurement of when the overload starts and when it ends. This requires very linear performance over the entire range, right up to saturation.

User-generated motion is difficult to model, because human players have anatomical differences and intuitively move in different ways with the same intent. Game developers require a great deal of testing and tweaking to model this interaction successfully. Recording a large variety of motions and generating motion-matching algorithms and thresholds in a testable model has proven to be the most productive approach.

#### **Position Measurement: Integration of Acceleration**

A challenging question facing designers is whether accelerometers can be successfully employed to measure position changes, since position is the double integral of acceleration with respect to time. The obvious approach is to doubly integrate acceleration over appropriate periods of time. Along the X axis,

$$X = \iint_{T} \left(\frac{d^2 X}{dt^2}\right) dt dt$$

For constant acceleration, a,

$$X = X_0 + \frac{dX}{dt} \Big|_0 t + \frac{1}{2}at^2$$

Thus the X position at any time depends on the initial position, the position gained over time at the initial velocity, and the square of time.

Integration is reasonable over relatively short times. For long periods, the risk is in the  $t^2$  term. Errors increase with the square of time; the error after 1000 seconds is 1,000,000 times greater than at 1 second. Any small offset errors in the acceleration measurement, especially with consumer-grade devices, will soon produce an intolerable error level, and eventually (hours, or even minutes) drive the computed position to its limits. Even a noise-free accelerometer with no error will have other problems integrating over long periods of time. For example, the human holding the controller may hit the controller against an object or drop it to the ground, causing thousands of *gees* of shock, driving the accelerometer output to its limits.

Nintendo has solved this problem in the Wii by using a positional reference in conjunction with the accelerometer. By correlating

the position to the reference, Nintendo can limit the length of integration with periodic resets, thus appropriately reducing error growth.

## **Engineering an Intuitive Motion-Based Game: Selecting Sensors**

"I sympathize when people complain about how un-user-friendly the old controllers can be; I can remember trying to master the mouse-and-keyboard interface when I first played Marathon, and then the two-joystick setup for Halo, and it was a serious challenge ... By contrast, the Wii controller is a snap. Nintendo really has removed a major barrier for nongamers. There's almost no learning curve at all."

—Lev Grossman, responding to reader feedback to his article, "A Game for All Ages," Time magazine, May 15th, 2006.

The first sections of this article described some of the ways acceleration data is measured and used in game control. The problem with real-world accelerometers, however, is that they do not perform perfectly, they occupy space, they require electrical power, they are subject to changing temperature, and they can be subjected to abuse. This final section provides some insight into the performance characteristics gaming requires, what to expect from a sensor vendor, and how to test these parameters.

## Linearity

The Newtonian world is linear and motions are linear, so accelerometers should be linear. Linear behavior, across the full-scale range, is essential because humans expect predictable response for intuitive gaming. If you move your arm twice as fast, the on-screen action should be twice as fast. If the actual speed is faster or slower, you have to learn nonlinear motion as a special skill, making the game nonintuitive. Tilt games that unexpectedly jump from one angle to another without the corresponding user motion can be jarring.

Testing linearity across the  $\pm 1$ -g range is relatively simple. Using a rotating socket, each axis can be tested in line with gravity, in opposition to gravity, and at in-between positions, noting the angle and output acceleration at each measurement point. Beyond 1 g, shakers and rate tables become necessary. Accelerometer vendors can furnish statistical data on linearity to validate data sheet values. More complex, but possibly faster, approaches use ac motion tests and total harmonic distortion measurements to correlate directly to linearity.

## **Power Consumption**

Most consumer MEMS motion sensors are used in low-voltage wireless devices. Reduced power consumption in an accelerometer can free up the power budget for more robust communications, cheaper components in other parts of the design, and longer battery life. Low-power devices such as the ADXL330, which typically draws 200  $\mu$ A from 2-V supplies—even without power-cycling—help in developing wireless controllers that, in addition to having long play times, are also free to move in the natural and intuitive ways gamers want to use motion. Accelerometers with fast turn-on times allow power to be cycled, thus saving even more power. The game designer can turn them on and off, sampling at the rate the human player is expected to move. A 100-Hz sampling rate is suggested as a floor for smooth motion gaming, enabling 50 Hz of bandwidth.

## **Temperature Performance**

Temperature performance is critical, considering that the motion-sensitive device is most often held in a person's hand, thus getting much warmer during the playing time. Excellent temperature behavior is also important because performance must be predictable in any play environment, whether outside or indoors. Consoles may even be used at low-temperatures in automobiles equipped with audiovisual systems.



Figure 3. ADXL330 X-axis zero-g bias, 8 random devices.

The most critical impacts temperature performance can have on game play are linearity of the *zero-g bias* over temperature, and the temperature coefficient of sensitivity. The zero-*g* output voltage is essentially the dc offset of the device. Many accelerometer vendors publish "box-specifications" on zero-*g* bias, declaring an arbitrary range of error through which the output can travel. Some accelerometers use a temperature sensor to provide digital temperature compensation. While these techniques can keep the offset within a range, step discontinuities often occur when the output is swept over temperature—sometimes up to 25 mg, corresponding to an error of over 1 degree in tilt applications. Testing this performance is as simple as sweeping the accelerometer through a range of temperatures and monitoring the output. This test is highly recommended; some sensors can produce surprising results.

#### **Robustness and Self-Test**

Because shock, vibration, and dropped controllers can cause thousands of *gees* of input to the accelerometer, a robust mechanical sensor design is necessary. The ADXL330 is designed with the same mechanical features as are used in harsh automotive environments for functions such as vehicle stability control. If something does go wrong, a good MEMS sensor should have full mechanical and electrical self-test features to help diagnose a problem before the player even picks up the controller.

# **Going Forward**

Historically, standard gaming controllers limited intuitive gaming, requiring a player to learn specific control skills. As games progressed, developers started to translate real-world experiences into virtual-world gaming. Now, the latest approaches in intuitive gaming use motion to enable a new generation of designs, making games more intuitive and fun. This article has presented a foundation for using accelerometers in game controllers, including operating mechanisms, measurement techniques, and specific parameters that directly affect gaming performance, price, reliability, verification, and test.

#### **REFERENCES-VALID AS OF JULY 2007**

<sup>1</sup>ADI website: www.analog.com (Search) ADXL202 (Go) <sup>2</sup>ADI website: www.analog.com (Search) ADXL330 (Go)

#### **ACCELEROMETER-PRINCIPLE OF OPERATION**

The motion sensors typically employed in the newest games are 3-axis accelerometers—three-dimensional motion sensors with electrical outputs corresponding to acceleration components in the x, y, and z directions. Figure A shows an electrical block diagram of a complete 3-axis acceleration measuring system, the  $\pm 3$ -g ADXL330, a tiny (4-mm-square by 1.45-mm-high) integrated circuit. It operates on voltages from 1.8 V to 3.6 V, drawing as little as 180  $\mu$ A. It can sense both dynamic (motion, shock, and vibration) and static (gravity-force) acceleration.



Figure A. ADXL330 block diagram.

The sensor is a polysilicon surface-micromachined structure built on top of a silicon wafer. Polysilicon springs suspend the structure over the surface of the wafer and tend to resist accelerating forces. The structure's deflection is measured using a differential capacitor that consists of plates—attached to the moving mass—moving between paired independent fixed plates, at voltages driven by out-of-phase square waves. Acceleration deflects the moving mass and unbalances the differential capacitor, resulting in a square-wave output with amplitude proportional to acceleration. Phase-sensitive demodulation techniques are used to read the magnitude and polarity of acceleration.

Each demodulated output is amplified and brought off-chip through a 32-k $\Omega$  resistor. External capacitors, chosen by the user, provide filtering and set the bandwidth. The device also has a self-test facility to detect malfunctions. Figure B is a photograph of an accelerometer chip.



Figure B. Accelerometer chip photo.

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# **PRODUCT INTRODUCTIONS: VOLUME 41, NUMBER 2**

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

# April

ADC, Successive-Approximation, 18-bit, 1-MSPS,
7-mW power consumption AD7982
Comparator, Voltage, dual-polarity outputs,
reference ADCMP361
Comparator, Voltage, dual, reference ADCMP670
Comparators, Voltage, dual,
programmable-hysteresis, reference ADCMP34x
DAC, Current Output, 10-bit, 120-mA output current AD5821
DACs, Voltage Output, quad, 12-/14-/16-bit, 5-ppm/°C reference AD56x5R
<b>DACs, Voltage Output</b> , quad, 12-/16-bit, $I^2C^{\text{®}}$ interface AD5625/AD5665
Isolators, Digital, 2-channel,
50-mW dc-to-dc converter ADuM524x
Processors, Audio, for advanced TV ADAV4101/ADAV4201
Processors, Audio, for advanced TV ADAV43x2/ADAV44x2
Switch, CMOS, multimedia ADG790
Synthesizer, Frequency, integer-N PLL, high-voltage charge pump ADF4113HV

## May

Driver, Half-Bridge, isolated,	
100-mA output current	ADuM1233
Gyroscope, low-power, programmable	ADIS16255
Gyroscope, yaw-rate	ADXRS612
Regulator, Linear, micropower, 50-mA output	ADP1720
Transceiver, high-performance, narrow-band,	
ISM band	ADF7021
Transmitter, HDMI/DVI, high-performance	AD9889B
Voltage Monitor/Sequencer, quad	ADM1185

# June

ADC, Pipelined, 10-bit, 200-/250-/300-MSPS,	
1.8-V supply	AD9211
ADC, Sigma-Delta, 20-bit, 3-channel,	
in-amp, reference	AD7785
Amplifier, Audio, Class-D, 2-W, filterless, stereo	SSM2306
Amplifier, Instrumentation, programmable-gain,	
high-precision	AD8231
Amplifier, Instrumentation, programmable-gain,	
10-MHz bandwidth	AD8251
Amplifier, Operational, dual, low-noise,	
low-power, precision	AD8667
Amplifier, Operational, dual, low-power,	
high-precision, auto-zero	AD8539
Amplifiers, Operational, low-cost,	
JFE I-input, precision	ADA4000-x
Codec, Audio, 24-bit, 192-kHz, PLL, four ADCs,	1074
	AD19/4
<b>Codec, Audio</b> , 24-bit, 192-KHZ, PLL, two ADCs,	A D1020
Code And behavior and be	AD1928
Codec, Audio, high-definition audio	AD198/
comparator, voltage, last, low-power,	
Convertor Surphysical Duck 2 /2 phase	
8-bit VID code Intel	ADP3193A
<b>DAC Valtage-Output</b> guad 12 bit unipolar	
or bipolar outputs	AD5726
Driver ADC differential extremely low	1123720
harmonic distortion	ADA4937-1
<b>Drivers</b> , <b>Differential</b> , triple, high-resolution	
component video	AD814x
-	

Front-End, mixed-signal, broadband modem AD9868	\$
Generator, Clock, 14-output, on-chip VCO AD9516-x	c
Gyroscope, low-power, programmable ADIS16251	L
Gyroscopes, yaw-rate ADXRS61x	c
Isolators, Digital, 2-channel, hot-swappable, I <sup>2</sup> C, 5-kV ADuM2250/ADuM2251	L
Microcontrollers, Analog, PWM generator, H-bridge motor control ADuC7128/ADuC7129	)
<b>Modulators, Quadrature</b> , 869-MHz to 960-MHz/ 1805-MHz to 1990-MHz	L
Monitor, Current-Shunt, high-voltage AD8212	2
Monitor, Current-Shunt, high-voltage, dual AD8213	;
Multiplexer/Demultiplexer, 1:2/2:1, 3.2-Gbps AD8153	\$
Output Stage, Power, 2-channel, Class-D audio-amplifier ADAU1513	;
Reference, Voltage, 1.25-V, precision, micropower,	
shunt-mode ADR1581	
Signal Splitter, Active, RF, 1:2, single-ended ADA4304-2	2
Switch, Crosspoint, $4 \times 4$ , 6.25-Gbps,	
input equalization AD8156	)
Switch, Crosspoint, $32 \times 32$ , buffered,	,
Video, 000 MITZ	)
switch, Grosspoint, triple 10 $\times$ 9, bullered, video 500 MHz AD\$174	ť
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# **AUTHORS**

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after a hiatus of a few years, during which—while he was Director of Engineering at Primarion—his team designed (for Intersil) the product that won EDN's Innovation-of-the-Year Award in the Power Sources category. Jeff holds 10 U.S. patents and has authored more than a dozen articles and professional papers.

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