THE HUBER MILLS
digital power report
Powering the 21st Century
August 2001/Vol. 2 Issue 8
Published by Gilder Publishing, LLC

A Sense of Power

ADI is an interface company, linking the two all-important digital worlds, digital logic and digital power

The Pentium is all brain, no muscle. The powerchip is all muscle, no brain. Connect them up, and you get intelligent power, highly ordered power–digital power.

But connect them how? The Pentium thinks in bits, the micro-electric code of the digital world. An IGBT, a MOSFET, or an LDMOS powerchip is controlled by analog voltage and current, and a lot more Watts than you can draw straight out the back of a Pentium. And to exercise any useful control over the powerchips, the smartchip needs to know what's going on. But the Pentium also lacks eyes, ears, and fingertips–sensors that must likewise bridge between analog reality and the digital virtuality.

Analog Devices Inc. (ADI) builds bridges across the analog-digital divide. It converts milliamps to bits, and bits to milliamps. It builds smaller, faster, more reliable A/D bridges, which cover more of the "A" side of the waterfront, than anyone else.

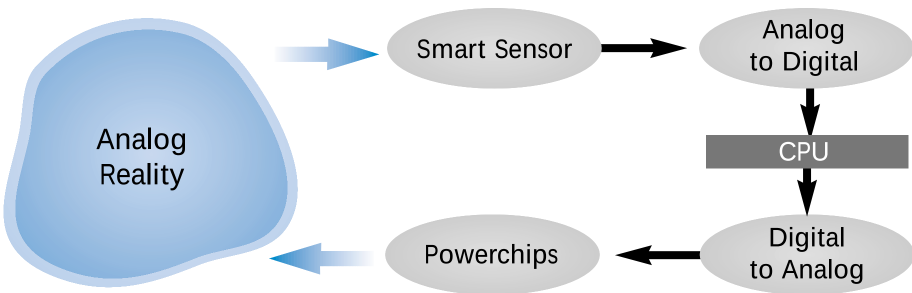
There's a lot to cover. Analog power includes plain old electricity–volts and amps in metal wires–along with magnetic fields and all things electromagnetic, from infrared radiation, to radio, to light, and on up the frequency ladder. It includes position, speed, and acceleration, force, torque, mass, and strain–mechanical power. And fluid-mechanical power: flow rates and pressure in liquids, and sound and ultrasound in gases. And a rapidly-expanding family of chemical and biological sensors, that sense moisture, sniff chemical leaks, and detect contaminants and biological chemicals in foods, drugs, and body fluids.

A/D bridges consist of front-end transducers, analog-to-digital converters, and specialized digital signal processors (DSPs). The front-end devices, which range from the clumsy and mechanical to ultra-sensitive semiconductors, comprise a $20B global market. But the mechanical devices are yesterday's sensor technology, not tomorrow's, and tomorrow's depend very much more on the analog and digital signal processors behind them. With $2.6B in annual revenues, ADI is the largest pure-play manufacturer of A/D devices, and it holds a commanding 40+ percent market share in the most important segment, solid-state A/D converters. It plows a remarkable 15 percent of revenues (some $400 million) back into R&D.

The company was formed in 1965 (three years before Intel) as a self-leveraged buyout of academic talent from MIT. Still headquartered in Norwood, MA, ADI now has manufacturing facilities scattered across the United States, the UK and Ireland, the Philippines, and Taiwan. It started out as a major defense supplier, and as recently as five years ago the defense/industrial market still accounted for two-thirds of its sales. But like other ascendant Powercosm companies, ADI saw the civilian sector overtaking the military in its demand for high-precision power. In the late 1980s, ADI began targeting the "four-Cs" of the civilian sector–computers, communications, cars, and consumer products. It developed specialized chips for audio, video, displays, and test equipment. And then added accelerometers–conventional ones first, and then the sensors that trigger automobile air bags–and a line of controllers for electric motors.

So what do we call a company whose business it is to harvest digital information out of the flow of power? ADI builds micro-converters–power or its component parts on one side, bits on the other. The "linear integrated circuits" ADI manufactures are analog signal processors, comparable to–but not interchangeable with–the more familiar digital ones (DSPs). ADI rose and fell with the NASDAQ last year, probably because telecom analysts recognized that it takes a lot of D-to-A conversion to move bits out of a digital PC or a cell phone into the analog space of airwaves and copper phone lines. But old-school power analysts seem hardly to have noticed ADI at all. How much can minuscule A/D converters really matter, after all, in the world of gigawatt electric power plants, hundred-kilowatt SUV power trains and industrial motor drives, and commercial air conditioners?

Analog-Digital Bridges



Smartchips need to know what's going on in the real world but lack eyes, ears, and fingertips–sensors bridge between analog reality and digital virtuality. Then to exercise control over real systems, powerchips respond not to bits but to analog signals, requiring a second bridge back from Digital to Analog.

A lot. At least as much as they matter in the world of wireless base stations and broadband telephone lines. ADI is an interface company, a builder linking the two all-important digital worlds, digital logic and digital power. Billions of power A-to-D sensors are going to end up embedded throughout the skin of the Powercosm–which is to say, everywhere that power is generated, applied, converted, or stored, right down at the level of individual valves, windings, airbags, and innumerable other components of power-processing and power-consuming systems. Billions of D-to-A power controllers will end up bridging between brain and muscle in systems that have to project smart power into analog space: cell phones, video displays, DSL lines, ultrasound medical equipment, industrial lasers, cell towers, TV transmitters, and phased array radar.

Networks of A-to-D sensors and D-to-A controllers are now poised to grow even faster than networks of fingers and keyboards, eyes and ears. From refrigerators to electric trains to fly-by-wire jets, from pick-and-place robots in chip fabs to massive automated looms in carpet factories, the machines of the Powercosm will produce, process, and consume more bits than the people lounging out at the edges of the action.

Sense and Control

For a comprehensive technical review of the field, get a copy of Randy Frank's *Understanding Smart Sensors* (Artech House Publishing, 2000). For visionary, non-technical entertainment, read *When Things Start to Think*, written by Neil Gershenfeld of MIT's Media Lab a couple of years ago.

Until recently, the ultra-precise measurement of most power fluxes was impractical, and not useful in any event. Most power depended on the inherently slow click-click bang-bang technologies of Newton and Carnot. These systems couldn't be controlled very fast or precisely in any event, so they just didn't need very fast, high-precision sensing. The first Model T had no gauges in the dashboard (an amp meter was the first arrival, in the mid 1920s); the driver's ears monitored the engine while his eyes tracked the road. With engine speed, fuel tank, alternator, radiator, heater, and air conditioner, it was always power first, then add the gauge later.

Electric utilities didn't do much better. They sold electrons the way others sell pig iron–by the ton, by the kilowatt-hour. They still do. To reckon up the pig-electron bill, the "revenue meter" dispatches about three bytes of data per month to a meter reader. It little notes nor long remembers spikes, dips, sags, or any other subtle aspects of power quality. It ignores the hundred-fold premiums that high-9s electrons command. It overlooks the hundred-fold swings in the spot price of wholesale electric power.

However primitive it may be, every "gauge" or "meter" begins with a transducer. Its job is to convert temperature, pressure, velocity, light, RF intensity, or some other physical quantity, into a flow of electrons, the clearinghouse currency for metrology and data processing. Even the measurement of electric power itself generally requires transducers; to find out what's going on in a 640-kV power line, you don't just connect up a Pentium directly.

Like the systems they monitor, transducers and their ancillary electronics can be big and slow, or small and fast. How good a sensor you need depends on how finely you aim to control, how finely you want to adjust action, to fine tune reaction. Sensors must generally run quite a bit faster than the controllers they serve, for much the same reason that a hawk's eyes must run faster than its wings. The flow of information has to stay well out ahead of the controller.

And until quite recently, the controllers ran relatively slowly. The only really fast power trains were all-electrical ones, and we lacked the technology to control them very precisely, at least at high power levels. We lacked both the smartchips fast enough to oversee the real-time control of electrical transients, and we lacked the powerchips capable of switching and controlling high-power electrical fluxes.

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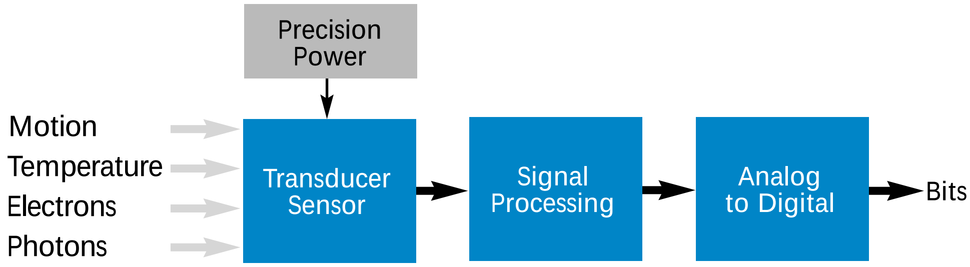
The Digital Power Report is published monthly by Gilder Publishing, LLC. Editorial and Business address: 291A Main Street, Great Barrington, MA 01230. Editorial inquiries can be sent to: peterhuber@gilder.com or markmills@gilder.com. Single-issue price: $50. For subscription information, call 800.261.5309, e-mail us at hmpowerreport@gilder.com, or visit our website at www.digitalpowerreport.com

We don't lack them any more. The fast, high-power powerchips are here, backed by smartchips fast enough to perform the massive number crunching needed for high-precision electrical control. Together, smartchip and powerchip transform junk power from the grid, or a microturbine, or a flywheel, into high-9s power suitable for the servers in a megawatt-level datacom hotel. Together, they control an F-16 or the drive train of a silicon car, or modulate a high-frequency radio transmission with the extreme precision required to punch megabits of data through the airwaves. Together, they control a stepper motor that moves a wafer through a chip fab, or a servomotor that adjusts an aircraft's flap, or steers the wheels of a car.

Sensing Power Shadows



Transducers detect the shadows of power. Fast, precise, reliable, tiny (and cheap) sensors are destined to become embedded ubiquitously in the skin of the Powercosm.

If–only if–they're informed by concomitantly fast and accurate sensors. To move the wafer through the chip fab, the stepper motor depends on very accurate, real-time sensing of position, speed, and acceleration at the output end, to control voltage and current at the input. The electric actuator for an airbag depends on the fast and reliable sensing of deceleration. The delivery of high-9s power to a datacom hotel depends on tracking power quality–not with a pig-electron revenue meter that gets read once a month, but with real-time sensors that sample and report at millisecond or microsecond intervals. Every tightly controlled application of force, torque, pressure, or photonic radiation depends on concomitantly precise sensing of how much power is being conveyed in the shaft, fluid, or beam, and what effect it's having on the target or the payload. And across the board, the delivery of highly ordered power depends on temperature sensing, because temperature invariably affects the performance of MOSFETs, IGBTs, laser diodes, Pentiums, chemical batteries, fuel cells, combustion engines, bearings, and flowing fluids.

The sensors, in short, have to stay out ahead of the power, however fast the power gets. The market for smart sensors is now destined to grow in lockstep with the market for smart power–digital power.

Sensors and Shadows

The traditional sensor is just a tiny generator or windmill, or a transistor with its wiring rearranged. The residential electric meter, for example, was (and largely remains) an electrically powered clock, with the turn of the hands determined by how much power has flowed through the power line into the home. Most sensors in practical use today are still comparatively huge electromechanical transducers–the electric-clock utility meter, the propeller in the hose of the gas pump, and so forth. And the market for these sensors remains dominated by a small suite of older, well-established players.

But traditional sensors, mostly electromechanical in their design, cannot keep pace with the new world of digital power. Nothing in the traditional thermo-electromechanical world can keep pace with semiconductor-controlled, all-electrical power trains. So, to begin with, the traditional sensor shrinks down to chip-size scales. TRW's NovaSensor division, BF Goodrich, and Infineon, among others, manufacture nanotechnology-based MicroElectroMechanical Systems (MEMS) sensors to track pressures, acceleration, and proximity in medical, industrial, and automotive systems. Hundreds of young entrepreneurial MEMS companies are now infiltrating traditional sensor markets. (ADI itself was ranked among the leading MEMS innovators (along with EGG IC Sensors and NovaSensor) in a 1997 review of the technology by the National Academy of Sciences.)

Quantum junctions in semiconductors can sense power, too, just as they can switch and convert it. A photovoltaic cell can be a light sensor, and can thus become the front end of a digital camera or a deep-space telescope. Rearrange the wiring, and a transistor becomes a voltage or current sensor. Magnetic fields cause tiny changes in electrical resistance (the magnetoresistive and Hall effects), or can physically strain crystals to squeeze some electrons out of them (the magnetorestrictive and piezoelectric effects). Temperature gradients cause small currents to flow through metal junctions (the Seebeck effect). Electric fields and physical acceleration, among others, can "twist" light beams, or slow them down–effects exploited in optical gyroscopes, pressure gauges, and strain gauges. Magnetic Resonant Imaging (MRI) and Superconducting Quantum Interference Devices (SQUIDs) exploit equally exotic effects.

All of these phenomena are now being harnessed to sense the shadows of power and its components. Picking up the shadow of power isn't inherently difficult. The difficult part is seeing it fast, precisely, reliably, with a tiny sensor that can be built cheaply, that drains off the least amount of power from the target flux, embedded ubiquitously. The difficult part is making the dumb sensor smart.

ADI does *that* extremely well. The company's expertise spans the three key layers of shadow-sensing technology: powering the sensors, the front-end analog processing of the analog signal, and the back-end digital processing thereafter. All three functions rely on integrated, analog circuits, designed to perform specific, low-power functions very fast and precisely.

In the old world of passive sensors, the measuring device was powered by the very thing that it measured–the current in the electric line, for example. Most of the new shadow sensors, by contrast, are active–they require their own independent power supplies. The ultra-sensitive shadow sensor produces a correspondingly weak signal. The solution is to use the sensor's tiny output to modulate a larger but tightly controlled flow of power through the sensor.

The shadow sensor's power supply must be exceptionally linear, however, and very stable. In particular, it must not be susceptible to temperature-induced drift. The standard approach has been to use a Zener diode to establish a reference voltage, but Zener junctions are highly non-linear over real-world temperature ranges. ADI has developed XFET architecture instead, consisting of two matched field-effect transistors (FET) that operate at a slightly different, but stable, predictable, voltage difference. The result is a family of ultra-linear, low-noise reference-voltage circuits that outperform current standards by fivefold or better.

ADI has also developed AC sensor-excitation circuits that significantly outperform the more common DC power supplies. DC excitation is easier to implement and troubleshoot–but DC signals almost invariably drift with temperature and age. So DC excitation circuits work only to the extent that the sensor's own (tiny) output is significantly higher than the excitation's drift. It takes an AC excitation to reach down into the realm of the ultra-small–and thus ultra-sensitive–sensor. A square wave AC-excitation cancels out the (low-frequency) drift errors in much the same way as multiple wiring paths are used to cancel out other (high-frequency) forms of noise. Using AC excitation techniques, ADI has achieved extraordinary sensor-circuit stabilities, below 5 nanovolts/°C.

Because they are so sensitive, the new-generation sensors tend to pick up all sorts of extraneous noise–microvolt disturbances emanating from solder connections, metal pins on chips, and (one of the biggest problems) the wiring leading to the sensor itself. Capturing the signal while escaping the noise takes ingenious design of the circuits that power the sensor, and that convert the sensor's analog output into digital data. As we've seen with two other companies that build analog circuits, Microsemi (MSCC) (*April 2001 DPR*), and UltraRF/Cree (CREE) (*November 2000, May 2001 DPR*), much of the genius in this line of business lies in the painstaking details of circuit design, wiring, and packaging. One of the most effective techniques that ADI has mastered is "ratiometric" circuit design–cancel out the shadows by using several circuits in parallel and generating the output as a ratio of several independent signals.

Milliamps to Bits

The next step is to convert the analog signal to digital bits. The typical shadow sensor produces a milliwatt- or microwatt-level signal. The signal requires immediate if low-level conditioning. Even before it can be converted to digital form, the signal must be amplified, filtered, and conditioned. And both the signal processor and the analog-to-digital converter (ADC) must run very fast. However small and responsive the transducer itself may be, the effective speed of the device as a whole is determined by how fast this layer performs. The highest-speed sensors require megahertz-speed sampling and signal conditioning.

The market is glutted with good manufacturers of DSPs, the special-purpose microprocessors optimized to process sound or graphics, for example, or encode signals for dispatch over wires or the airwaves. ADI makes DSPs too, but they account for only about a quarter of the company's revenues. ADI's expertise centers instead on the ultra-high-speed integrated analog circuits that process true "signals"–analog currents and voltages, not the "digital signals" that are processed by DSPs. In the end, DSPs are just specialized forms of software burned into silicon–now quite routine, with lots of people competing. Analog signal processors, by contrast, are all hardware, and the best emerge only from the meticulous details of design and packaging, and years of painstaking, incremental advance.

The ADC then samples the conditioned signal at periodic intervals, with shorter intervals, of course, producing a finer output. Each sample becomes a piece of data, which, for high precision, ranges from 12 bit resolution (video displays, ultrasound) to 16 bits (for base stations and industrial process control) to 18 bits in audio systems. The ADC thus produces digital data streams up to millions of samples per second.

Then comes the digital signal processing. Semiconductor sensors tend to be non-linear–the output doesn't change in clean, direct proportion to the input. And semiconductor sensors often drift significantly with temperature and time. Not a big deal in these digital times–databases now routinely translate a ten-digit phone number into a three-digit account balance–there's no clean one-for-one relationship there, either, but with CPUs doing the work, it doesn't matter. Just so long as you have the right processor and database close at hand to do the job.

The translation table for a sensor–the Transducer Electronic Data Sheet (TEDS), or some equivalent–is a sensor-specific database for calibrating the sensor's output on the fly. The TEDS instructs the DSP how to correct for both short- and long-term changes that affect the sensor's output–anything from temperature change to long-term degradation in semiconductor performance. The data itself is stored in flash memory. A DSP does the all-digital number crunching.

Even here, the digital processing of sensor data presents unique challenges. The objective is to build fully-functional sensor modules that are extremely compact and cheap to replicate, so that they can be embedded ubiquitously. There are a number of different ways to do this; ADI's "MicroConverter" is the most impressive we've seen. Small enough to fit in the housing of a sensor, transducer, or cable connector, it's intended as a general purpose product, that will plug-and-play with a wide range of communications networks on one side, and an equally wide range of sensors, both ADI's and other vendors', on the other. It integrates both the analog and the digital signal processing functions into a complete data acquisition system on a single CMOS chip. The device includes the sensor interface, sensor power supply, high-speed high-accuracy data conversion circuits, DSP, and flash memory. It can be reprogrammed for different sensors and applications, and upgraded in the field.

No company could have built such a device even a few years ago. It takes Pentium-class fabrication techniques to etch the necessary analog circuits on silicon–the submicron-scale, ultra-precise resistors, capacitors, and wires in between. And more of the same to place affordable flash memory and high-power DSP capabilities alongside. But ADI products like this one now support on-board power-management controls in high-end servers. And medical diagnostic equipment that tracks blood pressure, and cardiac electrical function. They provide affordable, reliable management, on a single chip, of all the linearity, temperature drift, and calibration factors needed to keep the LED and photodetector on track in a carbon monoxide detector. They perform much the same juggling of sensor data in a wide variety of industrial applications. Embedded in a personal computer, network server, or other equipment or appliance, these ADI systems monitor power supply voltages, temperature, fan speed, and other vital statistics. (ADCs from ADI were in over 50 percent of all LCD monitors and more than 70 percent of all LCD projectors sold in 2000.) Keeping bit-engines cool is another major application. Working in collaboration with Intel on power and thermal management, ADI introduced a system early this year that monitors the behavior of a single NPN transistor located directly on a Pentium, to track temperatures with a ±1°C sensitivity.

The Visible Electron

The sensing of electricity itself used to be a ho-hum business, split into two almost equally unexciting halves; one cheap and widely deployed but altogether stupid, the other smart enough, but too expensive to matter to anyone but troubleshooting electrical engineers. Coming next: electric sensors that are smart, affordable, tiny, and ubiquitous.

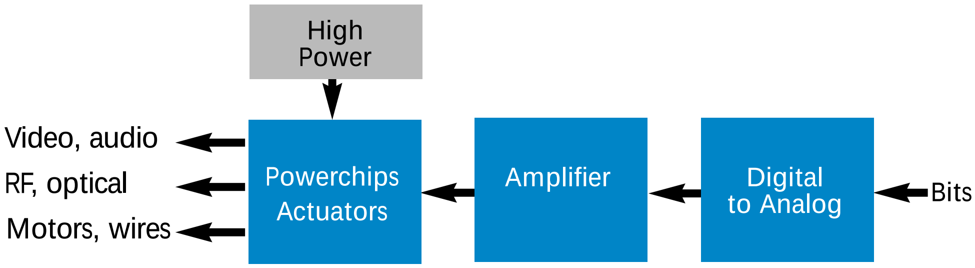
The most familiar electric sensor is the dumb residential utility meter. GE, Siemens, ABB, and Schlumberger are the main suppliers of these low-tech toasters. The meter divisions of these companies will undoubtedly see their sales surge in the next few years, as utilities bumble about upgrading their residential meters to some basic reptilian level of intelligence. Large, new opportunities are also opening up in the emerging markets, like China, which are now rapidly electrifying their economies.

Back on U.S. shores, much of the chatter is about the need for smart meters and real-time pricing. Utilities act at least equally interested in the possibility of automatic meter reading to replace the hapless human meter reader. But these are both telecom opportunities for the most part, and not very challenging ones at that. It only takes a primitive pager to update a retail meter with pricing data every 15 minutes or so; once-a-month meter reading requires even less bandwidth. Smart people keep floating new schemes to transmit the data in question over the power line itself, but why bother? Verizon, AOL/Time Warner, and other wireless and wireline companies are saturating the landscape with much higher-speed networks on which power-related traffic can easily hitch a ride.

With electric power, as elsewhere, high-speed, high-precision sensing is quite different, and far more important. High-9s power is anchored in the control, of current and voltage, and high-precision control, begins, as always, with high-speed sensing. Today, much of the most precise sensing is done with portable high-precision meters, that are carted around and hooked up now and again, to take the occasional snapshot of the electrical scene when new equipment is being installed, or when a post-mortem is under way after something has gone horribly wrong. Leading power quality (PQ) meter vendors range from the smaller private companies–Reliable Power Meters, Dranetz-BMI (part of WPT), Power Meters Limited–to familiar giants like GE, Square D (Schneider Electric), Cutler Hammer (Eaton Corp), and many less familiar. They are joined by manufacturers of specialized scientific instruments, the likes of Fisher Scientific, Tektronix, National Instrument (NATI), Keithley Instruments (DEI), and Honeywell.

So far as ADI is concerned, the key point is that A-to-D conversion begins the process everywhere. The "smart" utility meter now crawling out of the primeval grid needs A-to-D at its front end; so does the truly

Digital Power Control



The main reason to sense power is to control it, which, very roughly, requires a sensor running in reverse. Begin with a very-low-power stream of digital bits. End with high-power, analog action from video screen, to RF signals, to spinning shafts.

smart PQ meter that tracks microsecond transients and teases patterns out of the chaos. By the accounts of the customers we've talked to, the tiny Reliable Power Meters makes some of the best PQ meters. We visited them some weeks ago, and looked under the hood. ADI's chips were on the motherboard. From here on out, the cost of high-precision PQ meters is going to drop; they are going to shift from carry-around boxes to (widely) embedded devices; and beyond the A-to-D layers, their value will reside in the data processing, analysis, and communications systems that convert torrents of digital data into comprehensible, high-value information.

At the other end of the market, ADI's chips are headed into a lot of utility meters, too. ADI already manufactures the SALEM–a "solid-state all electronic meter" - that can perform the utility "wish list" of revenue functions from real-time pricing and diagnostics to remote meter reading. Or an ADI AD7756 "Active Energy Metering IC" can piggyback existing meters, to provide higher accuracy along with automatic-meter-reading interfaces to existing communications networks. ADI is selling the SALEM in Tunisia, Mexico, and China, where new grids are being built out more or less from scratch. The U.S. market presents a bigger challenge, because it's already built out and dominated by established owners of brain-dead boxes. Those vendors aren't in any hurry to denounce their own ubiquitously deployed products, nor to engage the contentious debates about restructuring residential rates. But the fact remains: the residential utility meter as we know it is a ridiculous anachronism. It is going to be replaced, sooner or later. Its replacement will be built around analog-to-digital microconverters–like ADI's.

Digital-to-Analog Control

Billing is necessary, of course, but as we've said, the main reason to sense power is to control it. To do that requires, very roughly, a sensor running in reverse. Begin with a very-low-power stream of digital bits. End with high-power, analog action. The sensor bridges from A to D. The digital-to-analog controller (DAC) bridges from D to A.

The basic operation of all DACs is the same; run bits into a buffer, a set of precision resistors, and a powered analog amplifier, to output an analog current that mirrors the amplitude directive contained in the original bit stream. The ultimate targets of the analog output fall into three main categories: human ears and eyes–which detect analog sound and light. Metal wires and the airwaves, which transmit electromagnetic waves in analog form. Motors and machines, which are controlled by powerchips, which are controlled in turn by analog voltage and current.

ADI products power digital-to-analog-human interfaces in everything from toys to scientific instruments. They show up on computer graphics cards, in LCD monitors and projectors, TFT-LCD panels, oscilloscopes, ultrasound systems, digital cameras, videophones, GPS, video editors, and CAD/CAM systems. They're in hands-free cell phones, DVDs, and CD players. The Bose Corporation's Lifestyle home theater systems contain two ADI 32-bit audio signal processors, and Bose uses ADI DACs across its entire line. Sony's Playstation2 contains an ADI audio DAC. High-fidelity, high-speed sound and graphics controllers demand astonishing amounts of signal processing. ADI makes the highest speed (205 MHz) high-resolution analog interface chip for LCD monitors and projectors. It's used today in high-end applications–engineering workstations, film editing, and medical imaging. And today's high-end is tomorrow's mass market.

Our eyes and ears will continue to require analog interfaces to the digital world. So will metal wires and the airwaves. We often call those media digital, we think of them as digital, and they fake digital performance convincingly–but deep down they remain relentlessly analog. Light in fiber-optic glass does a lot better, but sharp, pulsed electromagnetic waveforms just don't remain sharp and pulsed for very long in copper or in the air. ADI's DACs thus land in almost every segment of the wired and wireless infrastructure, too. They're in multicarrier and multimode transmitters, DSL and SONET systems, phased array transmitters, fax modems, and wireless local loop transceivers. ADI is a market leader in the production of DSL chipsets, and related products optimized for "voice over data" applications. It supplies power management and DAC systems to Ericsson, Kyocera International, Motorola, Phillips, Qualcomm, Robert Bosch, and Samsung. And ADI DACs show up in fiber-optic transmitters too–they continuously sense laser diode optical output and adjust the power input accordingly, to stabilize performance that would otherwise drift when temperatures change and diodes age.

Motors, machines, and high-9s electric power systems represent the third and least noticed market for DACs. Most of ADI's industrial customers are in automation and process control–and they comprise one of the fastest growing segments of ADI's business. Air conditioners waste a lot of power in the very sharp transients that on-off cycling entails. By adding ADI DAC control to the motor, Toshiba-Carrier raised the efficiency of a line of commercial air conditioners by a whopping 30 percent, (for which ADI won two prestigious Japanese energy conservation awards). ADI's DACs land in washing machines and refrigerators, too. ADI DACs are in industrial robots, actuator controls, weight scales, and a wide range of process and quality control systems. Rockwell Automation (ROK) recently awarded ADI a multi-year contract as a preferred supplier of analog semiconductor products for Rockwell's industrial automation, avionics, communications, and electronic-control systems.

The Wired Powercosm

The next "big thing" is not B2B or B2C, it's T2T–Thing-to-Thing, with Powered Things leading the way. Wing flaps networking with thrusters; industrial ovens with lasers; flowing fluids with pumps; tires with brakes; exhaust pipes with engine valves; air conditioners with power plants; Pentiums with motherboard bricks. The Powercosm is getting networked. Its clients will be sensors and controllers, not PCs or PDAs. Sense-and-control technology is now converging with high-speed, bi-directional, digital communication.

For thirty years, power control sensors communicated via a low-speed analog transmission standard set by the Instrument Society of America (ISA). In 1993, the National Institute of Standards and Technology (NIST) and the Institute of Electrical and Electronics Engineers (IEEE) set about establishing a universal communications standard for smart sensors; more recently, the Ethernet-Industrial Automation Open Networking Alliance (IONA) and players like GE-CISCO Industrial networks have been pushing power-datacom toward Ethernet standards. Other power-datacom protocols include Echelon's LonTalk industrial systems, two major automotive standards (SAE J1850 and CAN 2.0), and the Supervisory Control & Data Acquisition (SCADA) System designed for the grid but also used in the gas, oil, and water industries. In some key respects (such as packet prioritization), these communications protocols are more advanced than those we know of as WWW. Most of them are designed for bandwidths at or above DSL and cable modem speeds (1 Mbs and up). Judging from the bandwidth metric alone, power datacom is destined to generate more traffic than human clients currently do.

As noted, ADI's products serve the more familiar Web too. Telecom applications generate 45 percent of ADI's revenues; another 20 percent are tied to computers and consumer products, and how they interface with our analog eyes and ears. But industrial and military markets make up the rest, and it is those markets that now present the little-noticed prospect for exceptionally rapid growth. The silicon car and the silicon factory contain more clients than the silicon desktop and palmtop; there are far more things that move, than people that talk or type.

The T2T market is much too big, and spans far too many industries, for any one company to end up dominating it as (say) Intel has dominated microprocessors. The opportunity is large enough for many players to share handsomely in the spoils. Infineon (IFX), (*December 2000 DPR*) and STMicro (STM) are formidable competitors in the automotive sector, but ADI has a solid foothold there too. ADI is already a dominant provider (500,000 units/month) of the sensors that trigger air bag deployment; other ADI sensors go into GPS navigation, anti-lock brakes "smart" suspension, and roll-over monitors.

In other markets, ADI's competitors include Linear Technology (LLTC), Maxim Integrated (MXIM), Texas Instruments (TXN) (both directly and through Burr-Brown which TXN acquired in August 2000), and a number of credible mid-sized competitors such as Xicor (XICO). Motorola (MOT), National Semiconductor (NSM), Fairchild (FCS), Agilent Technologies (A), and Cirrus Logic (CRUS) make impressive analog chips too, though they clearly lack ADI's single-minded focus and depth of experience in the space. Microchip Technology (MCHP) joined the front ranks when it acquired A/D specialist, TelCom Semiconductor last October. One can never ignore the Pacific Rim players, but as always, they're dominated by the conglomerates: Mitsubishi Semiconductors, Fujitsu Microelectronics, NEC Electron Devices, Sony Semiconductor, and Toko Group.

Several of ADI's larger competitors, along with a considerable number of niche A/D players, are mainly targeting telecom/datacom applications–important markets, but also well understood in the investment community. Much less widely recognized is that T2T networks and their A/D clients are going to grow as fast in the coming decade as the Web grew in the '90s. As Gershenfeld's book (though not its title) recognizes, the revolution is not so much when things begin to think, as when thinking things begin to talk. Power technologies are going to feed much more data into many more high-speed networks than do keyboards and mice. The new terabytes of digital data moving through power-data networks will begin with A/D converters that sense the energetic forces, fluxes, waves, pulses, and packets of energy in the mechanical, hydraulic, pneumatic, and electrical universe that surrounds us. And the world's leading manufacturer and developer of analog A/D technologies is ADI.

Peter Huber and Mark Mills
July 27, 2001

The Power Panel

Ascendant Technology	Company (Symbol)	Reference Date	Reference Price	7/27/01 Price	52wk Range	Market Cap	Customers
Sense & Control	Analog Devices (ADI)	7/27/01	47.00	47.00	30.50 - 103.00	16.9b	Toshiba-Carrier, Electrolux-Frigidaire, Bose, Intel, Nortel, Ericcson
Electron Storage & Ride-Through	C&D Technologies (CHP)	6/29/01	31.00	29.05	23.40 - 61.88	760m	Lucent, Nortel, Verizon, Tyco, BellSouth, MCI WorldCom
	Maxwell Technologies (MXWL)	2/23/01	16.72	18.77	13.31 - 22.56	188m	GM, Delphi, Visteon, Valeo, Onemocall, EPCOS, Boeing, Lockheed Martin, Rockwell
	Active Power (ACPW)	8/8/00	17.00*	9.40	7.69 - 79.75	372m	Enron, Broadwing, Micron Technologies, PSI Net, Comcast Cable, ABC
	Beacon Power (BCON)	11/16/00	6.00*	4.60	3.65 - 10.75	195m	Century Communications, Verizon, SDG&E, TLER Associates, Cox Cable
	Proton Energy Systems (PRTN)	9/29/00	17.00*	8.40	5.25 - 36.00	278m	Matheson Gas, NASA
Photon Power	Coherent (COHR)	5/31/01	35.50	37.00	25.00 - 82.00	1.0b	Hitachi, Ford, Visteon, United Technologies, JDS Uniphase, Boeing, Applied Materials, Heidelberg Printing, Seagate
Powerchips	Cree Inc. (CREE)	4/30/01	21.53	23.89	12.21 - 73.75	1.7b	Siemens, Sumitomo, Microsemi, Infineon, OSRAM, Kansai Electric Power
	Microsemi (MSCC)	3/30/01	28.00	62.90	18.94 - 73.24	881m	Lockheed Martin, Mitsubishi, Medtronic, Boeing, Motorola, Palm, Compaq
	Fairchild Semiconductor (FCS)	1/22/01	17.69	23.37	11.19 - 42.75	2.3b	GE, Emerson Electric, Rockwell, Siemens, Bosch, PowerOne, Artesyn, Invensys, IBM, Delta, Marconi
	IXYS (SYXI)	3/31/00	6.78	12.20	10.20 - 44.50	326m	Rockwell, ABB, Emerson, Still GmbH Eurotherm Ltd. (UK), Alpha Technology
	International Rectifier (IRF)	3/31/00	38.13	36.40	27.38 - 69.50	2.3b	Nokia, Lucent, Ericcson, APC, Emerson, Intel, AMD, Ford, Siemens, DaimlerChrysler, Bosch, Bose, Delphi, Ford, TRW
	Advanced Power (APTI)	8/7/00	15.00	13.30	8.44 - 49.63	114m	Alcatel, Ericsson, ITI, Power-One, Advanced Energy Industries, Emerson
	Infineon (IFX)	11/27/00	43.75	25.16	20.36 - 70.00	15.8b	Siemens, Visteon, Bosch, Mansmann-Sachs, Hella, Delphi
Network Transmission and UPS: High-temperature superconductor	ABB (ABB)	9/29/00	24.24**	10.70	10.22 - 18.95**	N/A	National Grid (UK), Microsoft, Commonwealth Edison, American Electric Power
		*** Effective April 6, 2001, ABB was listed on the NYSE. The reference price has been adjusted to reflect this change. The 52-week range covers the period from April 6, 2001 only.*					
	American Superconductor (AMSC)	9/30/99	15.38	17.69	10.75 - 61.50	359m	ABB, Edison (Italy), ST Microelectronics, Pirelli Cables, Detroit Edison, Electricite de France
Power: Heavy-Iron-Lite	General Electric (GE)	9/29/00	57.81	44.65	36.42 - 60.50	444b	Reliant Energy, Enron, Calpine, Trans Alta, Abener Energia, S.A.
	Catalytica Energy Systems (CESI)	9/29/00	12.38	16.15	9.13 - 24.00	208m	GE, Kawasaki Turbines, Enron, Rolls Royce, Solar Turbines
Distributed Power Generation Microturbines	Capstone Turbine Corp. (CPST)	6/29/00	16.00*	12.05	10.87 - 98.50	920m	Chevron, Williams ECU, Tokyo Gas, Reliant Energy
Fuel Cells	FuelCell Energy (FCEL)	8/25/00	24.94	16.99	15.50 - 54.38	639m	Santa Clara, RWE and Ruhrgas (Germany), General Dynamics, LADWP
Silicon Power Plants In-the-room DC and AC Power Plants	Emerson (EMR)	5/31/00	59.00	55.79	51.00 - 79.75	23.9b	Citicorp, Verizon, Nokia, Motorola, Cisco, Exodus, Qwest, Level 3, Lucent
	Power-One (PWER)	*(see below)*					
Motherboard Power Bricks, High-end DC/DC converters	Power-One (PWER)	4/28/00	22.75	15.37	11.00 - 89.81	1.2b	Cisco, Nortel, Teradyne, Lucent, Ericsson

Note: This table lists technologies in the Powercosm Paradigm, and representative companies that possess the ascendant technologies. But by no means are the technologies exclusive to these companies. In keeping with our objective of providing a technology strategy report, companies appear on this list only for the core competencies, without any judgment of market price or timing. Reference Price is a company's closing stock price on the Reference Date, the date on which the Power Panel was generated for the Digital Power Report in which the company was added to the Table. All "current" stock prices and new Reference Prices/Dates are based on the closing price for the last trading day prior to publication. IPO reference dates, however, are the day of the IPO. Though the Reference Price/Date is of necessity prior to final editorial, printing and distribution of the Digital Power Report, no notice of company changes is given prior to publication. Huber and Mills may hold positions in companies discussed in this newsletter or listed on the panel, and may provide technology assessment services for firms that have interests in the companies.

** Offering price at the time of IPO.*