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Digital Movers

Danaher is a central player in the emerging industrial universe of digital motion

"Electronic motion control brings quantum leaps in flexibility, precision, efficiency, and reliability to applications as diverse as robots, wheelchairs, lift trucks, and packaging machines." Danaher (DHR) says so itself, and it's right. It says so, of course, because is has centered its own business squarely on motion control. Just the right kind of motion control, in which electricity impels the motion, powerchips control the electricity, and smartchips control the powerchips. Motion control, in other words, made possible by the convergence of digital logic and digital power. On the strength of which, Danaher confidently—and correctly—declares, its "motion team is revolutionizing the way things move."

Following an unlikely early history as a real estate and mortgage investment group, the company began transforming itself into what it is today, with its 1996 acquisition of Pacific Scientific, a manufacturer of high performance electric motors and drives. More than three dozen other acquisitions followed in rapid succession. Danaher implemented a consistent, smart corporate strategy: buy an established, gold-standard manufacturer of an essential component of motion-control systems—buy reputation, market share, and established technology. Then migrate customers to the digital-power replacements for yesterday's systems. Thus—and rather ironically, for a company whose core business is "motion"—a core Danaher objective is to "design out moving parts," and, frequently, to supersede its own family of legacy products.

You have to understand the digital power revolution to make sense of Danaher, or recognize its potential. Many people don't. Respected analysts classify the $4 billion (sales) Danaher as "industrial," or even "toolmaker" or "metal products," in part because one-third of the company is still tied up in such things as the hand tools it sells through Sears. The other two-thirds of its operations, however, are generally categorized as "industrial controls."

The blandness of that label obscures the technological revolution unfolding beneath it. Beginning in industrial settings, but now moving rapidly into the transportation sector, the universe of electrically powered motion is now changing in ways that are truly fundamental. We've explored some of them in prior issues, including *The Silicon Car* (*December 2000*) and *Networking the Digital Factory* (*September 2001*). The convergence of digital logic and digital power represents an advance as fundamental as the convergence of steam and steel in James Watt's engine in 1763, or petroleum fuel and internal combustion in Otto Diesel's engine in 1875. Combining fast, intelligent bits with equally fast, equally well-ordered power now makes possible an extraordinary new generation of compact, affordable, product-assembling, platform-moving, and people-moving systems.

We don't even know what to call these new devices yet. "Robot" won't really do. That brings to mind the clunky, oversized, hydraulic-mechanical systems of the 1970s, and in fact captures only a segment of everything that industrial economies move and control, from liquids to hardware. We are looking here at a completely new universe of digital, electro-motive actuators, transducers, or movers— "digital," in that they operate with the speed, precision, and intelligence of a chess-playing supercomputer, "actuators" (or some such) in that they move heavy atoms, rather than ephemeral bits. Call them what you will, the next great productivity boom in the U.S. economy will be propelled by these technologies, and centered on the industries that move stuff, not information—move it out of the mine and the farm, through the factory, along the assembly line, down the highway, over the water, and through the air.

Major players in all of those industries are going to end up buying a lot of motion-control hardware from Danaher.

Through the Keyhole

Most tools, instruments, vehicles, and machines are big because their power trains and control systems are dumb. Make them a lot smarter, and you end up doing the same job in completely different ways—far better, and in far less space.

Consider, as a first example, the tools we use to perform the delicate task of replacing a human heart valve, or excising a brain tumor. At the front end are some relatively simple instruments—scalpels, scissors, and needles—and behind them lights, suction pumps, saws, drills, and so forth. Behind those, a surgeon's hands, to supply all the essential control. The hands are both the best and the worst systems on the scene. Best, because they can sense and move far more intelligently than any autonomous robot. Worst, because they are big, and in some respects, clumsier than properly directed machines. Much of a rib cage or skull has to be sawed open so that hands can move the finer surgical instruments.

Cars are about as bad, and for similar reasons. Most of a car's bulk and weight isn't in the passenger cabin, nor in the chassis, wheels, and other basic parts needed to get the cabin rolling. The bulk is in the engine and power transmission systems, and in the elaborate controls that interface man and machine. Military jets are, in key respects, even worse. The most fundamental aspects of their design are crafted to protect the control system—the human pilot. Without the pilot, the aircraft would be built altogether differently.

Even in the factory, the most commodious engineering environment, machines remain far bulkier and heavier than they could be. The robotic welder is doing a job not so very different from the heart surgeon's. The weld itself, the tiny electric-arc-generating gap, the wires delivering power, are all comparatively tiny; much of the robot's bulk lies in the tangle of mechanical/hydraulic control systems that direct the welding to the right place. The same holds for a wide range of devices intended to automate assembly lines—devices that fill boxes, tighten screws, control liquids, and snap together parts. They do indeed automate, but most still depend on a snake's nest of bulky mechanical and hydraulic controls, far larger than the job at hand would seem to require.

Big machines aren't inherently bad, of course, nor are small ones inherently beautiful. Huge excavators mine coal a lot more efficiently; 100-car trains haul it better, and gigawatt power plants transform more of it into useful energy than any alternative. What is objectionable about the big machine is the space, weight, and energy it consumes just taking care of itself. It's bad almost everywhere, but nowhere worse than in transportation. Since humans first began riding horses, and on through modern aircraft, we have continued to use roughly one ton of "vehicle" to move one human passenger, or a couple of hundred pounds of freight. As Jesse Ausubel et al. discuss in a 1998 paper (http://phe.rockefeller.edu/green_mobility/) "the cost of transport has mainly owed to the vehicle itself."

A ten-to-one deadweight-to-payload ratio means that most of everything we sink into transportation, from steel to gasoline to asphalt, is being consumed in unproductive overhead. The story is much the same in most of the machines that power factories. Few yet resemble the truly advanced "pick-and-place" machines used to assemble chips on circuit boards, or the highly automated manufacturing processes that chip fabs like Intel use to distance messy humans from the necessarily ultra-clean semiconductor process.

Now consider the da Vinci Surgical System, manufactured by Intuitive Surgical (ISRG). (Similar systems include Computer Motion's (RBOT) Aesop, and Accuray's (private) CyberKnife.) Like an astronaut operating the space shuttle's robotic arm, the da Vinci surgeon sits at a console and monitor, with her hands on seemingly familiar instruments, that move and push back just as they would if she were reaching directly into a thorax or a skull. And that is indeed where her delicately moving fingers are reaching—but through a keyhole incision in a patient several feet away. That the robotic surgical arm requires only a tiny incision is one huge advantage. Another is that the machine-controlled surgical instruments can now be even more delicate and finely coordinated than the human hands behind them. The computers in the middle can learn to "feel" the boundaries of blood vessels and tumors even better than the surgeon's hands alone ever could. They will soon navigate with the help of high-resolution MRI maps, or even real-time imaging.

Recently seen in action over Afghanistan, remotely piloted vehicles (RPVs) like the General Atomics Predator, work similar magic. A wireless link connects the unmanned aircraft to a distant pilot, who now telecommutes to work. For reconnaissance, and for at least some types of combat too, the aircraft can now be much smaller. It can be built to perform maneuvers that an on-board pilot could not survive. And it can be built much simpler and cheaper. It's far more cost effective to replace one that gets shot down, than to try to build one that is impregnable. Cruise missiles push that notion to

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its logical limit. They are steel-and-silicon kamikazes.

Or consider, as a last example, a neat gadget that's been much in the news lately: the Segway. This is the product of Dean Kamen's DEKA R&D previously secret project, an 80-pound, two-wheel, barbell-with-handle shaped, scooter-like platform, that somehow senses where you want to go, and goes there. The throttle, brake, and steering wheel are all in the machine's own sensors, completely invisible to the rider, and far more responsive than any conventional set of manual controls. Just lean your body to speed up, slow down, or to stop altogether.

What is most remarkable about the da Vinci, the Predator, and the Segway, is how small they are, at least where it matters. The wonder of keyhole surgery is the keyhole itself, the tiny incision that nevertheless gives sufficient access to perform very delicate operations deep inside the body. The Predator moves the cameras and other sensors to equally inaccessible places, on what is already a comparatively tiny airborne platform, and one that will shrink down to bat-sized or even smaller scales within a few years. That the Segway lacks conventional control systems isn't just neat—it's a big part of what makes the scooter so small, maneuverable, functional, and safe.

These three examples all exemplify the same, fundamentally disruptive, technological revolution—and remind us, again, that we don't really know what to call the machines that it is spawning. The Predator and the Segway supply "transportation," though at wildly different ends of that market; the da Vinci brings to mind a factory robot, though surgeons would certainly recoil at the analogy. And though they don't land in the news as often, the technologies in play here are in fact being deployed most aggressively in the industrial setting, because it's heavily electrified already, and because this is where automation, while still evolving very quickly, has already been pushed the furthest. But these technologies are destined to take over much of transportation, too.

Why didn't Predators and pick-and-place machines happen much earlier? Since the days of Edison, electricity has been by far the fastest, densest form of power that we routinely use—an electric wire conveys far more power, in far less space, than any thermal, mechanical, or hydraulic system can begin to approach. The problem has always been how to control power this concentrated, that moves so quickly. Until recently, the answer has been to dumb things down at the end of the wire, interposing layers of mechanical and hydraulic systems between the electric motor and the final payload, or—in the case of the car—just not bothering with direct electrical drives at all.

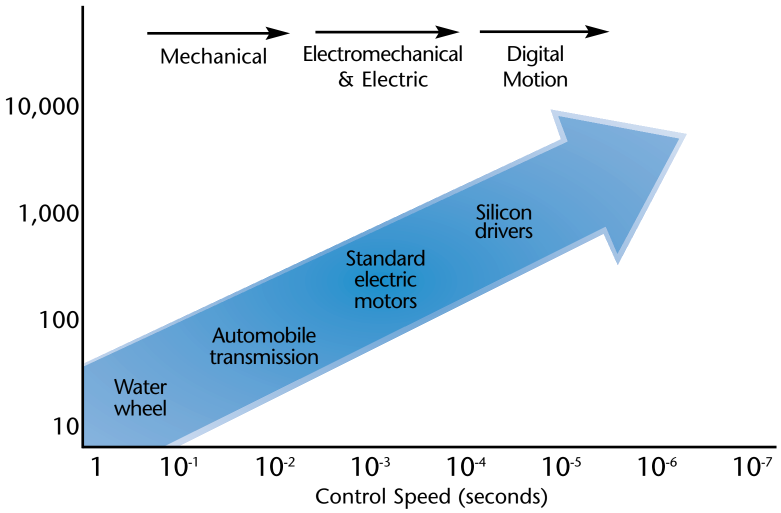
Now, as we discussed in a number of previous issues (including the *Broadband Power* Special Report), digital-power control modules and digital-logic control systems, together with electric motors themselves, have finally advanced to the point where electric motors can be used ubiquitously as "direct drivers" of real payloads. Together, today's powerchips and smartchips let us switch and control electricity precisely enough to move semiconductor wafers, steer a car's wheels, actuate its brakes, or drive countless other payloads directly.

Virtuous Circles

Motors, controllers, and sensors are now co-evolving in tandem, each bootstrapping the others. Every major advance in one of these three segments impels complementary advances in the other two, much as it happened with successive advances in microprocessors, memory chips, disk drives, and display screens. Apple's 1984 Macintosh, for example, contained what was, by today's standards, a huge clunky power supply. But nobody noticed back then, because it didn't matter—the disk drive and video display were huge as well. Year by year, however, all the other components shrank down drastically—even the vacuum-tube display TV gave way to a flat screen. Now there was strong pressure to build much smaller, high-density power supplies. The pressure grew intense when the desktop began collapsing into laptop, palmtop, and cell phone.

The new digital electro-motive technologies define a similar circle of radically new, complementary technologies in which technical advances in one segment propel advances all around the curve. To take surgery from open-chest to keyhole, for example, the mouse and computer had to evolve to the point where they became a complete surgical console—a flight-simulator for surgery, with the surgeon able to handle instruments and view a screen in ways that look and feel just like she's operating directly on the real thing. At the other end of the surgical-robotic arm, sensors had to evolve to the point where they could not only video the real thing, but also sense all the tactile information that the remote surgeon needs at her fingertips. Tiny motors—backed by equally compact power supplies—had to evolve too, to the point where they could do the cutting, aspirating, and stapling through a keyhole.

Identical pressures are building everywhere that digital logic and digital power are coming together. There was plenty of room to spare under the hood of yesterday's car, at least for something as peripheral and comparatively small as the electrical system. The mechanical power train was massive and bulky, and did most of the work; so too were the human-centered control systems. But now, an inexorably rising share of the vehicle's power train is becoming electric. That creates new pressure—and remarkably new opportunity—to begin optimizing all the new electric components—the drives, the control systems, and the sensors. Pound by pound, the new technologies of digital power now promise to repeal, at last, transportation's enduring one-ton-per-passenger law.


Power conversion and control

The two overarching trends in motion and control: (1) Higher power density in motors and converters; (2) Faster controllers, that provide more precise control.

The evolution of Segway-like control interfaces adds significant additional momentum to push the redesign further still. Such controls are far more compact than the steering columns, rack and pinion gears, pedals, hydraulic brakes, and other mechanical human-to-machine interfaces they replace. They consist entirely of micro-sensors, computers, and software. In the Segway, for example, the conventional bike or scooter's steering column gives way to five discrete, solid-state gyroscopic sensors—which track any angular movement of the scooter in any direction, whether caused by the motors, the rider, or the terrain. Other sensors, equally compact, track the movement of each wheel. A number of different processors draw on these data, with the network as a whole continually monitored by the Texas Instruments TMS320 digital signal processor. Once you begin building transportation systems around such technologies, you enter a whole new realm of engineering, in which radically different designs become not only possible but inevitable, because they offer such large improvements in performance.

The imperative to optimize and shrink the motors and motion-control systems reaches its pinnacle when the human controller surrenders hands-on control entirely, in favor of either remote fly-by-wire (as in the da Vinci surgical system) or completely autonomous operation (as in the case of many factory robots). The Pentagon buys RPVs to keep the human operator at a safe distance from harm; so do oil companies to search for offshore oil, and so do many others in the civilian sector, to keep employees at a safe distance from toxic chemicals, fire, nuclear radiation, explosives, or underwater hazards. RPVs fly, roll, crawl, and swim, carrying cameras, sensors, telecom links, and—for the military—weapons of various kinds, to where they're needed, without any human pilot on the scooter at all.

And without the pilot to worry about, much of the rest shrinks drastically. The Predator is about the size of a pterodactyl. General Atomics also builds the Prowler, roughly half the size, and a comparable-sized high-altitude (65,000 ft) Altus—all pilot-free. Military RPV programs are now focused on platforms under six inches across. Fully functional bat-sized, then butterfly-sized, RPVs have already been built. AeroVironment's electric-powered Black Widow typifies a new family of tiny flyers, with two-mile range and a live color video downlink. The company is now developing a wing-flapping, dragonfly-like Microbat that weighs half an ounce, including its camera and telecom downlink.

Many of these devices, and others like them, are already well past lab-bench theory. They are close to the point where they can be churned out at low cost and in large quantities, much like artillery shells. All have been made possible by complementary advances in solid-state power electronics and digital controllers. For future progress, all now await complementary advances in the power train itself—in the systems that store, convert, control, and condition the electric power on which all the other components ultimately depend.

Devices that move and process things will never shrink as dramatically as devices that move and process bits. You can't shrink the final payload, after all—the human passenger in the car, or the ton of coal extracted from the mine, or the product moving down the industrial assembly line. But you <u>can</u> drastically shrink much of the platform, which still typically accounts for most of the bulk and weight. When a swarm of disposable RPV dragonflies replaces a piloted high-altitude spy plane, the whole calculus of weight, power, and cost changes not incrementally, but by orders of magnitude. Fly-by-wire keyhole surgery doesn't change the size of the chest or abdominal incision "a little bit"—it changes it enough to turn weeks of intensive care into outpatient surgery.

The new technologies, in short, completely change the balance of what has to fly through the air, or probe into the human body, or twist and gyrate alongside the assembly line—and who may sit back comfortably at some remote terminal. They fundamentally alter what kind of hardware, and how much of it, must go into bulky human-actuated control systems, and how much can be loaded into sensors, software, and microprocessors.

Motors, Sensors, and Controllers

The extension of digital intelligence into digital motion is made possible by the coming together of advanced electric motors, high-precision controllers, and sensors. Microprocessors still do all the thinking. Motors do the moving. Sensors and controllers provide the essential bridge between the two. Danaher has systematically focused its business on these three, strongly complementary segments of the electro-motive revolution. Danaher motors are in the Segway, too—but for now, its products are much more likely to be found in a food-processing plant, steel mill, water-purification system, and other factories of every description, than scooting down a sidewalk. Hence the "industrial controls" label most frequently attached to Danaher's principal pursuits.

Motors—The electric motor market is huge—over $30 billion per year in sales, with comparatively simple, dumb motors still heavily dominant. Leading heavy motor manufacturers include GE, Emerson, and Rockwell Automation's Reliance subsidiary. All three of those companies are already on our Power Panel, albeit for other reasons. There are many other motor manufacturers, such as Baldor (BEZ), A.O. Smith (AOS), and on the small precision end, Micromotor.

The motor side of Danaher's digital motion accounts for roughly a third of the company's revenues. The Segway's DC brushless, electric servo motors were supplied by a Danaher subsidiary, Pacific Scientific. Using precision sensor-based interaction between the motor and the drive electronics, and a unique approach to the wire windings, Danaher's Segway motor supplies some 40 percent more torque per unit volume than alternative commercial designs; redundant windings in a single housing also provide an exceptionally high degree of reliability; and the motor is also designed to simplify mass manufacture through a proprietary injection-molding process. Of far more immediate, practical importance, Danaher motors drive countless electric "lift trucks" that already populate warehouses, refineries, and industry by the millions, and do so with high efficiency that greatly increases the battery life and overall performance.

Following its acquisition of the 45-year-old Pacific Scientific in 1996, Danaher made a series of complementary acquisitions of other manufacturers of advanced electric motors: A Swedish manufacturer (since renamed Inmotion) of complete servo motor, drive and control solutions used in plastic and metal processing, material handling, packaging, textile production, robotics, and lift trucks; another servo-motor manufacturer, American Precision Industries; and Warner Electric, a leader in linear and conventional motors. Anchoring this group is Danaher's Kollmorgen, a world leader in servo and stepper motor systems used in industrial, medical, and aerospace markets—motors that operate flight surfaces on smart munitions, that drive the enormous radio telescope pedestals, that power implantable heart pumps, that sort mail, and that polish wafers.

Sensors—Sensors are the second key component in the rise of digital motion—and Danaher has built up an equally impressive portfolio of industrial sensor companies.

As we discussed in the *Sense of Power* issue (*August 2001*), the smartchip can control the powerchip precisely only insofar as it can keep precise track of the key metrics of power and its effects—position, speed, acceleration, force, torque, pressure, voltage, current, and so forth. Tight control requires tight feedback; you can't fly blind.

Push the sensor technology far enough, and you can engineer something far beyond fly-by-wire—call it fly-by-intuition, perhaps, or maybe fly-by-empathy. That's roughly what Kamen's Segway begins to deliver. It has been compared to "skiing without the snow." From under the transporter's hood, an array of gyroscopes, tilt sensors, and an accelerometer report where a rider is leaning about 100 times a second. (The gyros and tilt sensors are from Silicon Sensing Systems, a JV between BAE Systems and Sumitomo Precision Products.) Ten microprocessors, running custom-designed software, then instruct the power supplies to dispatch current to the motors to move the wheels accordingly—to keep both scooter and rider upright. Tellingly, more than half the power drawn from the scooter's rechargeable batteries is used to run the microprocessors and control electronics; less than half turns the wheels.

Some 20 percent of Danaher's total revenues are in industrial sensors—about half targeting food and chemical processing, the remainder in drinking and waste water, a vast business still largely locked in mid-20th-century technologies. Danaher began building out its sensor capabilities with the acquisition of Fluke in 1998. Fluke is a leading manufacturer of electronic test tools and software for manufacturing and service industries—chemicals, petroleum, pulp/paper, food/beverage manufacturing, and waste/water management, among many others. Other Danaher acquisitions manufacture scientific and industrial temperature measurement and calibration equipment, sensors for the power, automotive, metals and materials handling industries, for utility transmission and distribution, for food processing and biopharmaceuticals, and so forth. Together, these subsidiaries supply industrial and factory sensors that span every critical industrial aspect of mechanical, hydraulic, and electrical power, and related metrics such as position, speed, and temperature.

Controls—Control itself is the third principal dimension of Danaher's motion-control business. Here again, Danaher has executed a series of neatly complementary acquisitions that span the industrial landscape. Overlapping in part with the "motor" market, related powerchip and motor drive markets generate over $12 billion in sales, but involve a larger and more diverse set of players—Rockwell and Emerson again, but also ABB, Siemens, Hitachi, Mitsubishi, Toshiba, and Danaher. Danaher sells roughly the same dollar-volume of electronic motor drives as an Emerson or Hitachi.

A German subsidiary that Danaher acquired in 1995 specializes in electronic controls to drive electro-mechanical, mechanical, pneumatic, and electric systems. Another Danaher subsidiary provides solid-state control systems for diesel and electric fire pumps. Yet another focuses on temperature and process controllers. All Danaher control subsidiaries make aggressive use of data networks to provide integrated control across factory floors and wide-area networks.

In the control of electricity itself, Danaher now owns a world leader in powerchip-based power transfer switches and controls (Cyberex); a manufacturer of high-voltage switches, advanced electronic controls, and related gear for utilities and every level of the grid, from high-voltage backbones down to surge suppressors at the end of the line, and spanning factory-floor power conditioning and uninterruptible power supplies for offices. Danaher took a run at buying Cooper Industries last year—large pieces of which look like a perfect fit. (While Cooper initially fended off the $5.5 billion offer, negotiations apparently continue under a December 2001 confidentiality agreement between the firms.)

Digital Logic, Digital Power, Digital Motion

Even in its motion-control businesses, Danaher still derives significant shares of its revenues from sensor and control systems that haven't yet crossed the threshold into the world of truly digital power. This just reflects industrial history and present, practical reality. The factory floor isn't all da Vincis and Segways and Predators yet—and given the gigantic sprawl of infrastructure that defines industries, it will take decades to get there. What Danaher does have are the two things that it needs to ride that great—and inevitable—wave of change. The company has a robust (and often dominant) presence in many key product sectors of motors, sensors, and controls. And it has a clear and definite corporate strategy of migrating a huge market into the new world of digital power controlled by digital logic.

Danaher isn't the biggest in any of its principal business sectors—and it faces daunting competition in the likes of Siemens, GE, or Mitsubishi. Danaher is a pure play, however, and it has exactly the right vision. It is buying (first), and now developing, its way into best-of-the-breed technologies in three key market segments. It is fast emerging as the leading, horizontally integrated vendor of the hardware components of automation and motion control. It is targeting the industrial opportunity one layer below Rockwell Automation (*Networking the Digital Factory, September 2001*). As noted, though Rockwell has a venerable and impressive motor group too, its core focus is in the networking of the digital industrial infrastructure. Danaher's focus is on the hardware itself. It will sell a single motor drive for one application, a stand-alone box of controls for another, and sensors for a third—and in doing so, secure the opportunity to continue adding digital-power hardware step by step across the customer's premises, for years to come.

Danaher does not aim to mass manufacture identical motors in hundred-thousand-unit lots. Each of its groups builds flexible, highly customizable devices. Danaher's industrial customers increasingly build their operations around autonomous manufacturing "cells," each one integrated into its own supply chain, so that the factory can meet highly variable customer needs. This is the logical progression from just-in-time-manufacturing—inventory control upstream of the factory—to just-what-you-need manufacturing—product customization on the demand side. Danaher's customers thus require an expanding array of semi-unique solutions for each new cell.

Danaher's Kollmorgen thus builds drive motors with integrated powerchips that can be adapted and reprogrammed to serve dozens of requirements. More generally, Danaher has selected acquisitions with an eye to fitting them into this industrial trend. Danaher then systematically restructures, organizes, and trains each of its businesses and subsidiaries around this core, flexible manufacturing philosophy.

Danaher has a particularly strong presence in the movement of fluids, for example. That huge market spans water, chemicals, and food processing, and large (if often unnoticed) segments of many "solid" enterprises like chip fabs. Danaher's Veeder-Root has 60 percent of the market for petroleum tank-level sensing. And here, as elsewhere, Danaher has aggressively migrated this seemingly pedestrian business into digital technology. Over 40,000 sites with fuel tanks are now networked into Danaher's central monitoring station in Connecticut, where the company tracks fuel levels.

An unexciting thing to track, one might suppose. Until one grasps that given the right sensors and software, this is also how you monitor for leaks, right down to those the size of a pinhole, which are too small for all ordinary sensing systems to track, but quite big enough to create huge environmental liabilities.

In the past, you tested for leaks by shutting down use of the tank and then performing various on-site static tests. Danaher's systems, however, can remotely integrate snapshots taken in the short quiescent intervals during normal use, and take it all from there. Danaher's monitoring system (incorporating advanced magnetostrictive level sensing and hydrocarbon vapor detectors) combines logic around the controls and sensors for the pumps and tank. Danaher bought the leading submersible electric pump manufacturer last year—and will shortly own the company that is the primary supplier of the above-ground pumps consumers use to dispense gasoline. So Danaher can now extend sensor, pump, and network integration to a new level. By precisely correlating what leaves the tank through the pump, as it's supposed to, and what remains safely in the tank, and detecting what's not supposed to be in the tank (excess water vapor), and connecting lines, Danaher can sense, calculate, and distinguish between natural emptying, sloshing, and signal noise, on the one hand, and a leak on the other.

Tomorrow's markets for digital motion technology—like the Segway—make it onto the cover of *Time*. Today's, however, often lie hidden below Wall Street's radar screen. Some are literally buried, too, underneath Exxon filling stations. The Segway buzz has the feel of unserious entertainment about it. But the technology is in filling stations and factories today, and will rapidly infiltrate countless Segway-like movers over the course of the next decade.

From Desktop to Exoskeleton

When the desktop computer first arrived on the scene around 1980, many sage observers viewed it as a neat but not so very important curiosity. E-mail and the Internet were still evoking similar reactions a decade later. Such reactions are understandable—and rational—most of the time. Change-the-world technologies are constantly bursting on to the scene, but the real world resists being changed, and most "revolutionary" technologies are soon forgotten.

We don't imagine that the da Vinci, Segway, or Predator, still less a Danaher gas tank monitor, will change everything either—not those particular designs or products. Apple's original Mac didn't—it's in museums. Like the Mac, however, the new electro-motive platforms are important for the forward-looking possibilities they now clearly reveal. They represent the best that can be done today—an already remarkable best—with technology that is now improving at a very rapid pace indeed.

Sensors, motors, and their integrated controller/drives are all now improving at remarkable rates, with the improvements compounding year by year, and with prices falling all the while. These systems are built around semiconductors, digital logic, and digital power. And all of those core technologies are now advancing at the rates things routinely do in semiconductor- and information-centered devices. Which makes it certain that new digital-power/digital-motion applications will emerge quickly over the course of the next few years, and at an accelerating pace thereafter—much as they did around the digital desktop in the '80s, and in the wired world in the '90s.

Before the $100 million project that culminated in the Segway, Kamen used similar engineering and components to build the iBot under contract with medical products giant Johnson & Johnson. Now awaiting FDA approval, the iBot is a six-wheeled, stair-climbing wheel "chair," that stands, too, with the user maintaining his balance much as a Segway rider does. (In a shoving match with a live human, the iBot is the last one standing.) Like the Segway, the iBot can climb stairs and maneuver over sand or gravel. Meanwhile, a Honda research program based in Torrance, California, is developing a human-like, five-foot-tall, 16-joint robot that walks on two legs and lifts heavy loads, pushes carts, and so forth, in that company's "Humanoid Robot Research and Development Program."

The Pentagon's high-tech research arm is funding similar research into "exoskeletons" for soldiers—wearable Segways or iBots, really, that walk and run rather than roll. The R&D focus is on energy sources, power supplies, haptic interfaces, control algorithms, actuators, and the integration of all of these systems "into a machine with an anthropomorphic architecture." The exoskeleton-wrapped soldier must be able to "wear," not "drive" it—other things, like combat, should occupy his mind, after all. As in the Segway, the exoskeleton's control systems must "enable direct and seamless interaction between human and machine." The technology is now at hand to deliver precisely that. And before long for construction workers and surgeons, too.

At this state in the technology's evolution, the tendency is still to wonder what specific implementation of such products might come next. But the right question is: What segment of the world of powered motion <u>won't</u> be transformed by the technology now at hand? Until now, machines added dumb power or simple-minded precision to our lives—but never nimble, thoughtful, responsive, intuitive dexterity. Man-machine interfaces have inched forward for a long time—but now they are leaping forward. The ratio of brute force, on the one hand, to digital logic and digital power on the other, has been very low, until now—and the ratio of platform deadweight to useful payload has been preposterously high. Now, both of those ratios can be reversed. So they inevitably will be. Payload is better than deadweight. Logic and highly ordered power are cheaper, and perform far better, than brute force.

The first electrical revolution began to pick up speed about a century ago, at the dawn of the 20th century. It took a while, but it changed everything. The rise of the grid and the light bulb didn't obsolete just candles and gas lamps, it transformed the factory, office, and home. Lamplighters were replaced by simple switches, many of which were then automated. Steam engines disappeared from most factories entirely. The second great volume of that history is being written today, at the dawn of the 21st century. The rise of the direct-drive electric power train doesn't obsolete just drive shafts and hydraulic lines, it transforms the way we control power all the way down to the final payload. Many conventional control systems simply disappear. Many other aspects of control can now be distanced from the payload, permitting the human controllers, if they remain on the scene at all, to work from a distance, in tight integration with control-enhancing computers.

Peter Huber and Mark Mills
January 29, 2002

The Power Panel

Ascendant Technology	Company (Symbol)	Reference Date	Reference Price	1/29/02 Price	52wk Range	Market Cap
Project, Sense, and Control	Danaher Corp. (DHR)	1/29/02	61.56	61.56	43.90 - 66.48	8.8b
	FLIR Systems (FLIR)	1/9/02	41.64	42.00	4.81 - 49.55	695.2m
	Analogic (ALOG)	11/30/01	36.88	41.87	33.40 - 50.00	553.0m
	TRW Inc. (TRW)	10/24/01	33.21	39.91	27.43 - 45.45	5.0b
	Raytheon Co. (RTN)	9/16/01***	24.85	35.38	23.95 - 37.44	12.8b
	Rockwell Automation (ROK)	8/29/01	16.22	18.90	11.78 - 49.45	3.5b
	Analog Devices (ADI)	7/27/01	47.00	41.66	29.00 - 64.00	15.1b
	Coherent (COHR)	5/31/01	35.50	30.40	25.05 - 53.75	867.4m
Electron Storage & Ride-Through	C&D Technologies (CHP)	6/29/01	31.00	20.65	16.35 - 55.65	538.9m
	Maxwell Technologies (MXWL)	2/23/01	16.72	10.31	5.81 - 22.50	104.8m
	Beacon Power (BCON)	11/16/00	6.00*	0.99	0.75 - 10.25	42.3m
	Proton Energy Systems (PRTN)	9/29/00	17.00*	6.58	4.00 - 16.50	218.6m
	Active Power (ACPW)	8/8/00	17.00*	5.12	3.56 - 30.20	207.5m
Powerchips	Cree Inc. (CREE)	4/30/01	21.53	19.40	12.21 - 37.75	1.4b
	Microsemi (MSCC)	3/30/01	14.00	17.45	9.47 - 40.10	495.4m
	Fairchild Semiconductor (FCS)	1/22/01	17.69	25.63	11.86 - 30.33	2.6b
	Infineon (IFX)	11/27/00	43.75	19.83	10.71 - 45.30	13.7b
	Advanced Power (APTI)	8/7/00	15.00	11.00	6.50 - 21.00	95.9m
	IXYS (SYXI)	3/31/00	6.78	9.39	4.27 - 23.88	251.4m
	International Rectifier (IRF)	3/31/00	38.13	39.47	24.05 - 69.50	2.5b
Network Transmission	ABB (ABB)	9/29/00	24.24**	9.75	6.10 - 18.95	11.5b
	American Superconductor (AMSC)	9/30/99	15.38	8.50	8.35 - 27.90	173.9m
Distributed Power ****	General Electric (GE)	9/29/00	57.81	36.46	28.50 - 53.55	362.1b
	Catalytica Energy Systems (CESI)	9/29/00	12.38	3.82	3.80 - 24.00	66.3m
	FuelCell Energy (FCEL)	8/25/00	24.94	15.98	10.48 - 46.72	623.0m
	Capstone Turbine Corp. (CPST)	6/29/00	16.00*	4.42	3.20 - 47.38	340.5m
Silicon Power Plants	Emerson (EMR)	5/31/00	59.00	55.99	44.04 - 77.40	23.6b
	Power-One (PWER)	(see below)				
Motherboard Power	Power-One (PWER)	4/28/00	22.75	9.80	5.32 - 49.13	772.7m

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.*

** *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.*

*** *The October 2001 issue closed on September 16, 2001 and was posted at 8 a.m. on September 17, 2001. Due to the markets' close in the week after September 11, our reference price reflects Raytheon's closing price on September 10, 2001.*

**** *The former category, "Power: Heavy-Iron–Lite" has been rolled into "Distributed Generation." All the companies previously listed remain, but are now included in this one category, a rationale consistent with the general metrics outlined for these companies in the relevant issues of the DPR.*

More information about the Powercosm and its technologies
is available on www.digitalpowerreport.com