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# Sensors: The Next Wave of Innovation

*the science of future technology*

THE INFOTECH REVOLUTION IS 50 YEARS YOUNG, YET DESPITE ALL THE innovation and surprises to date, it is quite clear that far greater change lies ahead. We marvel at how computers have insinuated themselves into every corner of our lives, knowing all the while that in a very few years, today's marvels will seem quaint compared to what follows. Amid all this change, a half century of history provides us with one important constant—a clear trajectory of innovation and consequence revealing important insights about the nature of surprises to come.

It turns out about once a decade a new technology comes along that completely reshapes the information landscape. Just before 1980, that key enabling technology was the microprocessor, and it's arrival set off a decade-long processing revolution symbolized by the personal computer. In a classic instance of confusing cause and effect, we called it the "PC revolution," but it was really a processing revolution, a decade during which we were utterly preoccupied with processing everything we could stuff into our machines.

Then just as the 1980s were closing, another new enabling technology came along—cheap lasers. Much as the microprocessor slipped into our lives hidden in PCs a decade earlier, lasers slipped into the lives of ordinary citizens hidden in everyday appliances—CD players, CD-ROMs, and long-distance, optical fiber phone lines. Lasers delivered bandwidth—huge volumes of storage on optical disk, and high-quality communications bandwith over optical fiber. The consequence was a shift in emphasis from processing to *access*. The advent of cheap lasers completely reinvented our desktop environment.

Machines on the desk outwardly looked the same, but changed profoundly in function, from being stand-alone processing devices to networked devices defined by what they connected us to. The shift was from 1980s-era "data laundries" to 1990s network windows on a larger information world.

Just as a PC symbolized the processing revolution, the centerpiece of today's laser-enabled access revolution is the Internet in general and the World-Wide Web in particular. Web-surfing would be an outlandish impracticatily but for massive amounts of laser-enabled, fiber-optic bandwidth.

We are approaching the end of the laser decade, and even though a few laser-enabled surprises are still waiting in the wings, we are beginning to see diminishing returns from merely adding more bandwidth to our access-oriented world.[1] It is now clear what will replace lasers as the foundational technology of the next decade. Hints are lurking in many areas. What is the most popular item to steal out of automobiles in Los Angeles today? Air bags—because they contain an expensive and not entirely reliable accelerometer trigger. The consequence has been a booming market for replacement airbags, which thieves are happy to fulfill. But air bags are about to become too cheap to steal, because using MicroElectroMechanical systems (MEMS) technology one can build an accelerometer on a single chip for a couple of dollars that is more reliable cheaper than current sensors.

And that is what the coming decade is going to be shaped by—cheap, ubiquitous, high-performance sensors. We are going to begin adding sensory organs on our devices and our networks. The last two decades have served up more than their share of digital surprises, but even those surprises will pale beside what lies ahead.

## What Are Sensors?

A suite of technologies underly the rise of sensors. Here's a summary of some of the most central.

**Piezo materials** are materials (typically ceramics) that give off an electrical charge when deformed, and conversely deform when in the presence of an electrical field.[2] Put a charge in, the material deforms; deform the material, it sends out a charge. Piezos are particularly useful as surface-mount sensors for measuring physical movement and stress in materials. More importantly, piezos are useful not just for sensing, but *effecting* the analog world. This is an indicator of the real significance of the sensor decade: Our devices won't merely sense and observe. They will also interact with the physical world on our behalf.

Like MEMS, piezo materials have been around for some time, and there is no shortage of interesting work underway. Current research is bringing us to the verge of creating new classes of *smart materials* that actively sense and respond to the surrounding analog environment.

[1]For example, the next big surprise will occur on the Web. Over the next two years, the Web will go from being an information environment to an interpersonal environment in which information plays an important supporting role to human interactions.

[2]The Advanced Research Project Agency (ARPA)—the same agency responsible for the initial research leading to the development of the Internet—has been a key player in catalyzing MEMS research. Just as ARPA's investments in the early 1970s led to huge 1990s commerical payoffs in the form of the Internet revolution, it's 1980s-era investment in MEMS could prove to be of crucial importance in the next decade.

**Micromachines** are semiconductor cousins to MEMS technology. Like MEMS, micromachines are built up from semiconductor manufacturing techniques, but unlike MEMS, they are more complex in design, incorporating in some instances, microscale gears and other moving parts. At the bleeding edge of this field, Japanese researchers have constructed a "microcar" not much larger than a grain of rice.[3]

Micromachines exploit the often overlooked structural qualities of silicon: It has a low coefficient of thermal expansion, high-thermal conductivity, a strength-to-weight ratio more favorable than aluminum, and elasticity comparable to that for steel.

At the same time, micromachines are in their infancy and it will be some years before elaborate micromachines are anything more than lab curiosities. Simpler micromachine devices will arrive slightly behind MEMS-based devices.

**VLSI video.** Today, a videocam with all the attendant circuitry required to attach it to a computer costs approximately $9 a unit in OEM quantities. This number will drop precipitously as the next generation package everything on a single chip. Even the lens will be glued directly to the chip. Cheap video translates into cheap "eyes."

**MEMS** is by far the most important of the technologies, enabling the rise of sensors in the near term. In concept, MEMS is simplicity itself: It amounts to nothing more than using semiconductor manufacturing techniques to create analog devices. But underlying MEMS technology is an interesting mindshift in chip design. Traditional chips are little more than intricate race tracks for electrons built up through an elaborate process of etching and deposition. One of the worst bugs one can have on a traditional chip is a *released layer,* in effect, a loose piece of circuit material hanging out in microspace above the chip surface. That loose layer interferes with the smooth flow of electrons because it interacts with the surrounding analog environment, and thus is a serious bug. In the MEMS world, however, that bug is a crucial feature because such released layers can serve as the basis for designing analog sensors, sensing everything from acceleration, and temperature, to pressure and fluid flows.

MEMS research has been underway for over a decade,[4] and MEMS-based devices are already finding their way into the marketplace. The automobile indus-

[3]Anyone who has used a disposable lighter has experienced piezo-materials in action—pushing down on the tab flexes a fleck of piezo-ceramics, generating an electrical charge that is converted into a spark.

try, already a major consumer, is likely to be the single largest early market for MEMS devices, adding them to everything from emissions systems and air bags to tire hubs and suspensions.

The fact that MEMS is not a new technology underscores an important point about how each successive decade unfolds. What defines each decade is not the underlying technology's invention, but rather a dramatic favorable shift in price and performance that triggers a sudden burst in diffusion from lab to marketplace.

**Other sensor technologies.** A host of other technologies are being pressed into the service of mediating between the analog and digital worlds. One example is micropower impulse radar (MIR), a recent invention of Lawrence Livermore National Laboratory. Personal radar sounds like an unlikely consumer hit, but consider the following applications, all under commercial development: intelligent oil dipsticks for autos, handheld wall-stud sensors, bulk tank-level sensors, land mine detectors and nondestructive testers for concrete structures.

Global positioning system sensors are also undergoing radical reinvention in terms of lowered cost and increased performance. Systems once costing tens of thousands of dollars are now available in a handheld package for under $500. And cheap laser technology is rapidly changing gyroscopic technology as ring laser gyros (RLGs) displacing traditional spinning-mass systems in aircraft systems, delivering dramatically increased performance in cheaper, more reliable packages. In the long run, it is likely that advanced MEMS accelerometer arrays will in turn displace RLG technology.

## Implications

The impact of sensors will be as surprising in the decade ahead. And the surprises will be additive because of the synergistic interaction among the technology generations. Some of the most interesting applications of sensing technology will be applied to solving some of our existing information technology problems. In addition to the micromachine light valve, MEMS technology could deliver interresting storage packages or a MEMS-augmented optical disk system with capacities over 1,000 times that of a CD-ROM.

But these examples merely touch the most prosaic of possibilities. Casual inspection of prior forecast and subsequent reality of the microprocessor and laser decades makes it clear that the scale of surprise will be enormous even for professional forecasters. But the good news is that hints of what is to come are already occurring.

What's certain is the most expected of futures will arrive late—as always—and in utterly unexpected ways. Even as telecommunications executives continue to try and sell tired old notions of videoconferencing, the interaction of cheap video and laser-based Web bandwidth has already delivered a hint of what the future will really hold. A world of ubiquitous video is not a world of people looking at each other via videoconferencing. Rather it is a world of cameras aimed at everything everywhere, watched over by machines, and only occasionally examined by people.

But the impact of sensors does not stop at mere sensing. What happens when we put eyes, ears, and sensory organs on our devices? Inevitably, we are going to ask those devices to also manipulate the world around them. The sensor decade is really a sensor/effector decade, where our devices will not only observe things, they will also manipulate them.

This has profound implication. Two parallel universes currently exist—an everyday analog universe that we inhabit, and a newer digital universe created by humans, but inhabited by digital machines. We visit this digital world by peering through the portholes of our computer screens, and we manipulate it with keyboard and mouse much as a nuclear technician works with radioactive materials via glovebox and manipulator arms. Our machines manipulate the digital world directly, but they are rarely aware of the analog world that surrounds their cyberspace.

Now we are handing sensory organs and manipulators to the machines and inviting them to enter into analog reality. The scale of possible surprise this may generate over the next several decades as sensors, lasers, and microprocessors co-evolve is breathtakingly uncertain.

## Scaling Change

Such change seems overwhelmingly uncertain because we tend to compress outcomes into a telephoto view of the future—just as a telephoto lens compresses distance, our expectations lead us to compress chronology and overlook the logic of orders of impact as early developments contribute to later innovation.

The history of internal combustion engine provides a good example of orders of impact and their predictability. The first-order impact was the horseless carriage, and that was no surprise to anyone for the simple reason it was precisely what everyone was trying to build. The process of invention and subsequent diffusion was

[4] An affiliate of Toyota Motor Corp., Nippondenso constructed a replica of an early Toyota complete with electromagnetic motor and tiny ring-gear drive in 1996.

chaotic, but the outcome was clear.

The second-order impact—the traffic jam—came as something of a surprise, but only to idealists and others who had not taken the time to anticipate consequences.

But the third-order impact—suburbs—was rather more surprising, even though the first suburbs had already been around for decades on a small scale.[5] But the mobility afforded by the automobile led to the reinvention and dramatic spread of suburban life.

The biggest surprise, however, was the fourth-order impact—the rise of huge, regional conurbations, such as the Atlantic seaboard and the Los Angeles basin. This was unexpected in 1900 because everyone assumed that by conferring mobility, the auto would lead to dispersal of populations, rather than their further concentration.

What assumptions are now blinding us to the impact of cheap and ubiquitous sensors? Look for the same pattern of surprising consequence and interplay between expansion and constraint as sensors assume center-stage in the information revolution in the decade ahead and beyond. And keep in mind that just as microprocessor and the laser innovations continue today, sensor advances will have reverberating consequences well beyond the next decade. While the leading edge of sensing is with us today, the trailing edge is something that will be felt as far out as 50 years from now.

The first-order impact of sensors is quite obvious—cheap I/O for our networks and computing devices, plus modest levels of effecting. The second-order impact is more interesting. As effecting becomes richer, look for sensor/effector arrays to mature into simple classes of *smart stuff,* that is smart materials and intelligent artifacts (smartifacts).[6] In addition, cheap sensors will contribute greatly to making old notions of hyperautomated manufacturing—cybermanufacturing—a practical reality. The block in the past has been one of measurement and control granularity: The available sensors and also effectors has been too coarse to really deliver the requisite levels of materials control. MEMS-scale devices radically reduce the scale of control, and make true automation practical.

This, in turn, leads to important third-order consequences, such as the advent of mass customization. Ever since Stan Davis popularized this concept in the late 1980s, the philosopher's stone of manufacturing has been finding a means of combining the appeal of unique one-purchaser customization with the economies of scale associated with mass manufacturing. The scale change triggered by sensors and effectors could set the stage for this to become a reality across a broad segment of industries.

But there are even more interesting third-order impacts. One of the most important will be an acceleration in the decay and centrality of von Neumann computing architectures. Consider a research initiative already underway to build turbulence-damping *smart-skins* for fighter wings.[7] This work contemplates a leading-edge array of myriad 0.2 millimeter-sized silicon microflaps, interspersed between equally small MEMS turbulence sensors.

This array is comparatively buildable now, but computational control is another matter. Even if one had an infinitely fast supercomputer controller in the fuselage linked by fiberoptic network to the array elements, the limits of light speed alone would make it impossible for the flaps to respond quickly enough to sensor data sent downwire to the computer and then back out as a control instruction. The only option is to create radically new hyperdistributed computational architectures, in effect a community of processors interspersed into the array, where each element is a triad of processor, sensor, and effector. This kind of demand opens the information world to a host way-radical architectural exotica: from theories based on ecology and symbiosis to, in one case, models built around economics.[8]

At the fourth-order level, we will witness a generalized substitution of computation for stuff. We will literally dematerialize objects, substituting as Nick Negroponte likes to observe, "electrons for atoms." Using arrays of sensors and effectors, one can take a structure (say, a bridge truss or aircraft spar) that in inert form lacks the intrinsic structural strength to support a given load, and dynamically sense and align its elements to yield the desired strength at a fraction the weight of a traditional structure.

The essence of this fourth order is that we are connecting two previously parallel universes—a digital universe of our creation and a preexisting analog universe. The two worlds are in collison, and the biggest surprises will come when the boundaries between the two blur beyond recognition. Warriors fighting virtual war

[5]The first suburbs arguably appeared in the greater Boston area in the 1820s, and later experienced a dramatic period of growth in the late 1800s, thanks to the advent of street car systems.

[6]"Smartifact" is a term first coined by researcher Harry Vertelney at Apple Computer in the 1980s to refer to new forms of software-based agents. "Smartifact" is used here to connote something different: physical objects possessing rudimentary intelligence sufficient to be aware and affect the environment around them.

[7]This research is being led by John Kim at the University of California at Los Angeles, under a grant from ARPA.

[8]Bernardo Huberman at Xerox's Palo Alto Research Center is doing especially interesting work on this front.

games over networks may discover after the fact they were killing real opponents.[9] Autonomous smartifacts, successors to current military unmanned aerial vehicles (UAVs), will become annoyingly commonplace. And just as the first biplanes were quickly turned from reconnaisance duty to war-fighting, these new automonous smartifacts will be inevitably applied as *warbots* of unprecedented lethality. ARPA recently commissioned research on micro UAVs—autonomous flyers smaller than a dollar bill using micromachine engines to sustain a one-hour flight time, and a 16-kilometer range. Just the thing for a 21st century James Bond, or a terrorist bent on assassinating a well-guarded head of state.

As the foregoing example implies, things get especially interesting as device size shrinks. One of the most interesting implications is that if one shrinks the device sufficiently, it becomes possible to dispense with batteries entirely, allowing the gizmo to run off ambient energy—sunlight vibration or perhaps airflow over tiny MEMS cilia. And cost shrinks with size, opening the door to what researchers refer to as MEMS dust—tiny, disposable devices used in a toss-out-and-forget manner for any number of applications from environmental sensing to surveillance.

The impact of ubiquitous sensors on the digital computing order could be especially surprising. In the short term, the challenge is interfacing analog sensor devices with digital computers and networks. However, it is inevitable there will come a point when it will seem obvious that the logical next step is to create analog computers and networks in order to more effectively interface with and exploit the growing sensor arrays. And it may prove likely that there are instances where it is simply impossible to accomplish a desired goal with digital technology at all.

A modest indicator of this trend is visible today in the audiophile world. CDs may have replaced phonograph records, but the most sophisticated audiophile stereo systems available rely upon old-fashion vacuum tube technology to perform their magic. Audiophile ears can tell the difference between sound that has been deconstructed into bits and reconstituted as an analog waveform, and the sound that has remained in analog form all along.

Thus, the long-term consequence of the coming sensor revolution may be the emergence of a newer analog computing industry in which digital technology plays a mere supporting role, or possibly plays no role at all. At first, these new analog devices will probably occupy a place similar to that once occupied by supercomputers and parallel processing systems—specialized devices tailored to work on especially challenging tasks. But in the longer term, say 40 to 70 years from now, the digital order we take for granted may prove to be merely a transitional phase in a longer process of connecting symbolic universes of our creation with the preexisting physical world. Outlandish as this may sound, imagine telling information professionals in 1948 that one day they would all but abandon vacuum tubes for computing tasks, and do their work on digital electronic computers based on microprocessor descendants of the transistor invented in that year.

## Digital is Dull?

But there is still one additional implication that will shock today's digital establishment. Ever since the invention of the transistor, digital has been cool, and analog has been the forgotten, old-fashioned stepchild. That is going to reverse itself in the next decade. Analog is going to be the great new unexplored frontier, and digital will seem, well, just a bit dull.

Three decades ago, a generation of graduate students quietly made fun of their professors who were trained in a world of analog electromechanical devices. They thought, "Oh, those old fuddy-duddies, vacuum tubes, how quaint. Digital is hip." Well, those professors will have their revenge, for their once-arrogant students will become the old fuddy-duddies. The next generation will think their digitally steeped teachers had it so easy. "Digital representations? It's so straightforward, it's so discrete, it's so easy to contain," they'll probably say. "Analog is messy and subtle and unpredictable, and that's where the big wins are, so get out of the damn way and let us get on with the job of innovation."

Of course, reality will be subtly different. Analog will be the frontier, but it, in turn, will lead to new digital challenges. That said, research librarians would do well to dust off some old Ph.D. dissertations on once interesting, now seemingly irrelevant analog problems because we may suddenly discover a host of insights from the analog era of the 1950s are going to be very relevant to the sensor-driven years after the turn of the century.

[9]This is often referred to as the "Ender's Game scenario," a reference to a science fiction novel in which a group of kids are training in a computer simulation to eventually save Earth from invaders, only to learn that their graduation simulation was, unbeknownst to them, an actual war commanded by them. Ender's Game Orson Scott Card Aug. 1977 Analog, 1985 TOR.

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