The Dawn of "World Computing"

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Abstract

20th Century systems that deliver basic human needs – communications, power, water, and transportation - to people in Europe and North America will not scale to match the requirements of a world population of 7 billion people. Existing solutions are expensive, ecologically unsustainable and politically destabilizing. The United States, for example, with five percent of the world's population, consumes twenty-four percent of the world's energy resources.[1] In the 21st Century the search for infrastructure solutions that scale will lead to innovative new uses of information technology, with broad implications for the developing world. In the past, computing technology has been associated largely with "high value" commercial markets, particularly enterprise systems and office automation. More recently the focus of information technology has been directed at the dissemination of "Content" through the World Wide Web. However, a relentless decline in computing costs is driving information technology applications into entirely new realms. This decline is exponential, not linear, and its implications on society are profound.[2] Low cost computer-based solutions – cellular phones, e-mail, and instant messaging – are already transforming the communications infrastructure.

This paper proposes a new era of "World Computing", in which information technology is applied to the basic infrastructure systems of society, including power, water, and transportation. The defining character of these new infrastructures will be a mesh of billions of inexpensive sensors and processors connected by wireless networks. Research labs that are exploring the widespread deployment of computing technology have dubbed this vision "Pervasive Computing", "Ubiquitous Computing" or "Ambient Computing."[3] These names focus on the technology itself, rather than its potential use. World Computing defines an exciting application space for this emerging opportunity. The global market for a new generation of computing-enabled products and services will unleash a major wave of innovation in the technology sector, and present huge opportunities for enterprises who deliver scaleable digital solutions. Moreover, creating and implementing World Computing architectures will be crucial to sustainability, as they will deliver core services that are both less costly and more ecologically sound.

Introduction

Basic human needs, wants and desires have scarcely changed over the millennia. People require food, clothing, and shelter. They yearn for comfort, communications, mobility, and security. Since the dawn of civilization, humans have devised technology-based systems (irrigation, wind-power, writing etc.) that satisfy these aspirations. But until the industrial revolution only an elite fraction of most nations could enjoy the benefits that these technologies offer. In the last two centuries the mechanization of labor - powered largely by fossil fuels - has elevated the lifestyles of many individuals. Today more than a billion people enjoy comforts and conveniences once imaginable only by kings and princes. However, the overwhelming majority of the world's 7 billion people are enormously underserved.

At a time when satellite-delivered media disseminated information and entertainment raises hopes and aspirations for the developing world, it is difficult to imagine a stable future that does not address the infrastructure requirements of the world's population. Yet these new expectations are coming at a time when people are questioning the sustainability of the current technology solutions, and the social costs required to maintain them.[4] Simply put, if 20th Century era water, power, transportation and communications networks are not scalable, then what are the alternatives?

The key to addressing the needs and wants of everyone will be to find solutions that dramatically increase the efficiency - and reduce the cost - of the services we depend on. This is a problem that computing technology is uniquely well suited to solve. Modern computers are essentially electronic circuits blazed onto silicon chips and controlled by software instructions. A characteristic feature of these electronic products is that their unit costs, for both hardware and software, are fundamentally volume-based. This quality distinguishes them from the material products whose production consumes natural resources and/or human labor with each additional copy. Such products, even those that are mass-produced in modern factories, do not generally benefit from the dramatic cost reductions delivered by semiconductors and software.

A Vision of World Computing

The basic building blocks of computing are extraordinarily scalable. The incremental cost of creating the next copy of a computing based system will always approach zero once the volume is large enough. Communications between individual computing devices – to deliver actionable information to a controller - is now remarkably inexpensive, and getting cheaper. This is the result of a broad range of technological advances, particularly improvements in radio and power technologies, and from the integration of many core functions into a few integrated circuits.

What can such low cost computing solutions accomplish? With the help of digital control and communications technology - the core of World Computing - it is possible to imagine a sustainable suite of affordable resources (water, power, communications and mobility), which extends to every person on the planet. This breathtaking vision is not only achievable - it is likely. In the developed world, the push for efficient use of resources is already driving computing technologies deep into the fabric of every product and service imaginable. And in the developing world, especially where so many basic services are inadequate or absent, World Computing infrastructure could easily be deployed instead of wasteful and expensive 20^{th} century era legacy solutions.

This vision represents an enormous change in the focus of computing – and of the companies that are organized to bring innovations to the marketplace. Historically, computing-based solutions were deployed to deal with relatively high value tasks. In many cases the first customer was the military, and in countries like the United States, military investment in computing research has been a driving force for innovation. Michael Dertouzos, the head of MIT's Lab for Computer Science, once estimated that between one third and one half of all major innovation in computer science in the United States stemmed from research supported by the U.S. Government's Defense Advanced Research Projects Agency, or DARPA.[5] In the 1950s the military used massive room-sized vacuum tube-based computers to calculate artillery trajectories. In the 1960s governments and large corporations installed mainframe computers to automate payroll and billing systems. In the 1970s minicomputers became popular in smaller businesses and departments. In the 1980s personal computers reached the office desktop and replaced typewriters. In the 1990s, especially following the proliferation of low cost data networking (facilitated by powerful Web servers) personal computers became ubiquitous communication and information appliances. At each stage, entry into dramatically new and large markets became possible because of the continuing decline in the cost of computing.

Throughout this period - but less visible to most consumers – an even broader wave of computing applications, based on semiconductor-based embedded sensors, programmable controllers and digital signal processors has been infiltrating manufactured products at an accelerating rate. Starting with jet fighters and rockets in the 1960s and moving to telecommunications in the 1970s, automobiles in the 1980s, and home appliances to consumer electronics in the 1990s, programmable controllers have made it possible for machines and motors to sense their operating environment and make useful or beneficial adjustments. Today, devices with embedded controllers have transformed many significant "vertical markets" in industries as diverse as telecommunications, industrial controls, manufacturing, and entertainment.

At every step computing solutions were adopted because the value they provided outweighed their cost of installation. Historically this process has been called automation, i.e. the replacement of human work by a machine. But the opportunities afforded to computing based solutions are rapidly extending to "jobs" that no human would ever be assigned to before. As the net cost of computing drops significantly year after year, the applications for inexpensive computing-based solutions will transcend the boundaries of individual devices and are embedded in the world's communication networks, power grids, highways and water systems. In the process such devices will dramatically increase the efficiency of these systems, and make them affordable – and feasible – for billions of people. The new post-industrial era of digitally supported infrastructure will accelerate the proliferation of World Computing.

The Expanding Universe of Sensors and Processors

The innovations that characterize World Computing are well underway in virtually every infrastructure category. Not surprisingly, the adoption process of these new technologies is similar from industry to industry. Computer-based solutions no longer displace people. Instead they provide incremental value for work that was never assigned to humans. In "classic" computing applications data is entered by a human operator, or calculated by software. In applications based on embedded processing, a sensor acquires data when it detects some change in the physical world, and emits an electrical signal in response. Sensors may detect changes in such categories as temperature, electrical energy, flow, gas concentration, humidity, light level, reflectivity, pressure, strain, rainfall, wind speed and direction, fluid levels, radiation, proximity, and magnetism. The electrical signals emitted by a sensor are communicated – increasingly via the Internet - to a processor that is programmed to react to the information it receives.[6]

In the digital environment, systems can be adjusted easily to reflect the actual usage characteristics they experience. Traffic is regulated. Capacity rises and falls with changes in demand. Excess resources are stored, not wasted. Usage may be precisely metered and priced according to volume, time of day, type of content, or many other parameters. The result is a less centralized system, with distributed controls, and consequently smarter, and less vulnerable to catastrophic incidents. Aided by low-cost computing controls these systems will be less expensive to build and more efficient to operate.

A useful way to categorize the major components of large infrastructure systems is to divide them into supporting networks and stand-alone devices. Supporting networks include regional power grids, municipal water systems, national highways and telecommunications backbones. Stand-alone devices include electrical appliances, plumbing fixtures, automobiles and trucks, and telephone sets. The interdependency between these two categories is obvious. Less clear is the differing values that embedded processing offers.

One might assume that innovation would occur first in the supporting networks, where it could have an impact on every connected device. In practice the opposite occurs. Embedded processors, initially too expensive for mass deployment, first appear in stand-alone devices that instantly benefit from the technological advances they provide. The purchaser of an intelligent digital device does not have to wait for the entire network to evolve to begin enjoying its benefits. However, the greatest impact of sensors and embedded processors occurs only when the infrastructure itself is re-tooled or built from scratch as a modern system. (That cycle of improvement will be become possible as the dynamics of the semiconductor business drive the costs of computing ever lower.)

The State of World Computing

The benefits of modern communications and control technologies have been obvious to large sectors of the commercial sector for decades, and many building blocks for a World Computing infrastructure are already in place. The examples below are representative of countless infrastructure improvements throughout the fields of communication, power, transportation and water supply.[7]

Communications: The most dramatic advances to date have occurred in the field of communications, especially with voice telephony. For decades until the 1990s, a mantra of telecommunications professionals was that more than half the world's population had never made a phone call. What's more, the likelihood of extending wired telephone service to the developing world, which is largely rural and poor, seemed remote to non-existent. Today the cellular communications revolution is rapidly putting those fears to rest.

At its core, a cellular phone network is a computer network, and modern cellular handsets are powerful low-cost computers that 'communicate' with digital networks that sense their location and unscramble their radio transmissions. Whereas the capital costs for a fixed line system include material goods like copper cables and wooden poles, the capital costs for computerized cellular network equipment (both handsets and cell sites) will continuously decline, thanks to repeated iterations of semiconductor and software generations. That truth is already recognized globally. Last year the number of cellular phone lines worldwide passed the number of fixed lines.[8] And in the developing countries the rates of cellular subscriber growth are extraordinary. In the Philippines, which as recently as 1993 had scarcely more than one million fixed lines, now has more than 6 million cellular subscribers.[9] In fact, writes Harvard University researcher, Mridul Chowdhury, "More than 50 percent of the installed fixed lines remain unused.[10]

Beyond voice telephony, computing has already redefined the conceptual framework of communications. Today the Internet is the world's overarching end-to-end data network, and its digital backbone serves as the connectivity medium for communications. Network endpoints are small, powerful, inexpensive devices, such as PCs, handheld computers and advanced cellular handsets. Up to now, most data communications has consisted of individuals sending e-mail. In the future that will no longer be true. Increasingly, the Internet will be the essential link for every World Computing solution, especially where sensors relay actionable data to processors. The "content" of these messages may be infinitesimal or huge: sometimes no more than a few bits in length, other time large files of audio or video content. Even voice conversations, the cornerstone of the 20th century telephone network are destined to ride on packet networks in the format of Voice Over Internet Protocols, VOIP.

In truth the continuing evolution of the communications infrastructure will be driven by the embedded processor growth of World Computing. In the current era of the information age most devices connected to the Internet are personal computers. In the future, the population of personal computers will be dwarfed by myriads of devices that need to access, monitor and control countless types of systems, and the communications infrastructure itself. Increasingly, network based applications will rely on embedded processors to mathematically modify and improve information and signals. At the same time the number of communicating devices on the Internet will increase by billions-fold. Just ten years ago, says John Mashey, a Silicon Valley computer scientist and former

Chief Technology Officer of Silicon Graphics Inc, a typical American adult relied on ten microprocessors each day, including those that powered personal computers, automobiles and microwave ovens. Today that number is more than one hundred, with multiple microprocessors in many individual systems. In another ten years, Mashey adds, the number will surpass one thousand processors, and the overwhelming majority of those will be networked.[11] Ultimately the sheer number of processors connected to the Internet will become a tremendous driver for innovation in network services.

The requirement to design networks for billions of sensors is already driving exciting new research at universities and industrial laboratories around the world. These next generation highly distributed networks will almost certainly rely on wireless technology for communications. Individual sensors will not function in a network sense until they need to, if only to prolong battery life. According to David Culler, a computer scientist and leader of sensor prototyping at the University of California, "The devices have to organize themselves in a network by listening to one another and figuring out who can they hear." Only then do their radios turn on. Signals may pass from one sensor to another, each of which is only awake long enough to relay the message before going back to sleep.[12]

Electrical Power: Modern communications and control technologies are already revolutionizing the consumption, distribution and generation of electricity. Not surprisingly, until now much of the progress has been on devices at the edge of this system. Digital technology is already deeply embedded in industrial motors, and heating, ventilation and cooling systems, as well as home appliances like refrigerators, microwaves and stereos. And modern battery-powered electronic equipment use embedded intelligence to increase battery life by optimizing power management.[13]

One step higher, at the level of individual buildings, sensor-based innovation promises to significantly reduce energy consumption. Many buildings, for example, now incorporate timers and motion detectors for systems that can be powered down when they are not being used. At the University of California Berkeley's Center for Information Technology Research in the Interest of Society (CITRIS), researchers have demonstrated how outfitting a building with a network of wireless sensors called "smart dust motes" can lead to substantial energy conservation. The sensor network keeps tabs on light, temperature, and energy use at locations throughout a building, calculating and transmitting the cost of energy use in specific areas and by specific appliances. In 2001, the CITRIS team successfully installed a prototype network of 50 sensors at a cost of $100/sensor. They predict, however, that the cost could soon fall to $1/sensor.[14]

Yet until now, the power distribution grid itself remains a hugely expensive relic of our pre-digital past. In the North America, explains author Peter Fairly, "The existing networks of high-powered transmission lines, the inter-connected web of electricity that keeps the continent charged was built in the middle of the last century and was never meant to handle the complexity and congestion of today's ever growing energy demands and changing markets."[15]

The North American power grid has been called the largest machine ever built by man. In many respects it is a marvel of engineering, distributing power over vast distances. In others respects it is terribly obsolete, and it is rarely operated at peak capacity. The U.S. grid operates under massive inefficiencies, due in large part to its reliance on ‘dumb’ electro-mechanical switches and a highly centralized distribution network. One of the main problems in distributing energy is telling it where to go; currently, the only intelligence in the system is the unregulated interplay between supply- and demand-side parties. A power plant produces electricity and dumps it onto the grid, where it sluices around, directionless, in electricity "canals." When consumers in a certain area need energy, their local substation draws the amount needed off the grid.[16]

The obvious problems with this system are: 1) in times of low energy usage, energy is wasted as it runs unused through the grid and gradually dissipates as heat; and 2) in times of high usage, energy becomes expensive and inaccessible as local grids become congested and/or run out of energy. These problems have become even more pronounced as more transmission networks have been linked together into huge service areas. As energy meanders around the massive network, it leaves and reenters local areas of the grid. This causes "loop flows," or energy bottlenecks, which drive up prices, set the stage for outages, and waste tremendous amounts of energy to heat dissipation.

There is little likelihood that this infrastructure is optimal for any society, let alone the nations of the developing world. But computing technology will soon infiltrate the world’s power grids with dramatic results. Just as silicon chips in a cell phone handset process electromagnetic signals to transmit information, electrical power processors embedded in power grids will improve the operation of the system. “Call it Moore’s Law for power electronics,” says Fairly.[17]

Researchers at the University of Puerto Rico-Mayaguez have begun work on a three-year project that will explore the feasibility of decentralized power distribution networks. The researchers believe that a design based around nodes called “Intelligent Power Routers" arranged in a mesh hierarchy will be more reliable, cost-effective, and scalable than the current model, which relies on centralized control stations and constant human oversight. Under the new system, intelligent routers stationed throughout the grid would measure energy levels and direct current flow along "transactional pathways," rather than simply down the path of least resistance. The intelligent power routes will act like data routers in a computer network, and they will be able to maintain power service "even when the designated principal control center of the system has collapsed due to a natural or man-made disaster."[18]

Scientists at power generation equipment manufacturer Siemens in Germany foresee the deployment of computer controlled decentralized energy management systems that supply – and meter - power in parallel with fluctuations in demand, and are supplemented by fuel cell or off-peak storage systems.[19] Low-cost sensors already in production can be used to measure voltage, current, and power factor on overhead or underground power lines. The sensors will enable companies to better avoid and respond to power outages based on power distribution problems.[20]

Exciting World Computing-style advances are also appearing in the field of power generation. In an intelligent, decentralized power grid it will be easier to add power from new sources, including solar and wind powered systems and highly efficient micro turbines. Digital power controllers convert raw electrical power from any power source into high-quality power required by electronic and electrical equipment. Micropower generators can supply power directly, provide back-up power, or return excess power to the grid. In a decentralized system both individual locations and the grid as a whole will be more resilient to natural and man-made disasters, as there would be no single nexus to fail. In the developing world distributed micropowered grids will make it possible to add and store capacity without massive capital expenditures.

Water Supply: The availability and distribution of water has been a critical element of organized society since the invention of gravity-fed irrigation and plumbing – two of the earliest technologies of civilization. In ancient cities, however, only the royal and the rich enjoyed indoor plumbing and privies. Ordinary folk used the banks of the river to collect water for drinking, bathing, washing, and to relieve themselves. Later societies, notably the Romans, became expert at moving water long distances via aqueducts. But it was industrialization and the population growth of cities that spurred the development of "modern" water systems to deal with both the storage and distribution of fresh water as well as the disposal of waste and run-off. Perhaps the greatest infrastructure innovation of the 20th Century was the building of massive dams for water storage and power generation. These huge dams were erected over many years at enormous cost with massive steam- and diesel-powered earth moving machinery, literally the groundbreaking technologies of the last two centuries. The irrigation techniques however have changed hardly at all from the time of the Mesopotamians.

World Computing offers the first glimpse of what some observers are already calling the "Waternet." Although it is unlikely to be worldwide, like its ubiquitous electronic cousin, the Waternet will consist of efficient, intelligent water-using devices, attached to a highly instrumented backbone network. The key elements of this network will include a decentralized distribution system, with multiple pathways for water to travel, as well as network storage of water, and perhaps even local generation, regulated by quality monitoring processors. "Like with our computers, we didn't start connected," explains Canadian technology writer Bill Buxton. "We had our own wells or cisterns, and we used things like septic tanks for our waste. Just as people have connected their PCs to the Internet via their local Internet Service Provider (ISP), so have most of us moved away from wells cisterns and septic tanks and taken our plumbing online by hooking up with our local WSP (Waternet Service Provider)."[21]

As with other large systems discussed here, innovation in the Waternet will first appear on the devices that are attached to its edge, such as faucets, toilets, showers and fire hydrants. Today, nearly all of these devices are mechanically – and manually – controlled. Outside of a few airport washrooms, electronic sensors have barely entered the realm of the Waternet. But the inevitable collision of the increasing scarcity of water and the increasing abundance of cheap computing is bound to produce a new generation of efficient plumbing appliances that will work better than their mechanical predecessors.

The real Waternet revolution – and the one that will extend the reach and utility of fresh water will come when embedded processors systems are deployed to help manage larger water networks. As with electrical power systems, innovative solutions will migrate one step higher from edge devices to building and municipal systems. For example, building intelligent leak-location systems are already commercially available. One manufacturer's system offers a network of up to 3,000 meters of sensor cable, with multiple probes and alarm activation mechanisms. This system can also activate "relay nodes" adjacent to the alarm to provide "selective software-driven valve or power system shutdown facilities."[22] At the municipal level many manufacturers provide flow sensors and meters to monitor the intake of fresh water and discharge of wastewater, which will enable cities to better allocate the expenses they incur in operating water treatment facilities.

The other major application of the Waternet is irrigation – in most regions of the world the single largest use of water. Intelligent irrigation systems are World Computing applications that use soil moisture sensors and computer software to provide optimum levels of water to plants. These self-tuning systems use electronic probes to monitor moisture. When the system senses that an area is overly dry it automatically delivers water via existing irrigation techniques (flood, sprinklers, drip, subsurface), thereby saving money, producing better crops and reducing environmental harm. Information from the system can also be used to control other devices anywhere on the property including pumps, external lighting, wind generators, and heaters.[23]

Finally, while water purification will remain an expensive low volume endeavor for the foreseeable future, there are aspects of the process, particularly energy consumption that will benefit from the decentralization of infrastructure inherent in the World Computing vision. At the very least, sensors will be deployed to monitor the purity of wastewater, as a prerequisite for re-using it for irrigation purposes.

Transportation*:* The movement of people, goods and services on roads and highways is perhaps the hallmark achievement of the industrial revolution. Other modes of transportation, notably steamships, railroads, and airplanes have a huge impact on our lives and our economies. Moreover, each of these transportation categories has already witnessed tremendous technological innovation. In many cases – perhaps because of their enormous construction expenses – railroads and large vessels like planes and ships have served as prototyping platforms for many of the digital technologies discussed in this paper. For example the *USS Yorktown* is one of the most automated ships ever built. According to the ship's Website, the naval cruiser serves as a "Floating guinea pig for cutting-edge technology and policies to reduce crew and save money. The old helm, or steering wheel, no longer exists. It was removed and presented to the skipper as a memento. Sailors who used to rove the ship around the clock to check spaces for fire, flooding and security have been replaced with a series of remote sensors, alarms and cameras"[24]

But perhaps the most iconic symbol of the developed world is the network of highways that cross North America and Europe, and the vehicles that travel on them. Ships, planes and trains are amazing technologies, but in a sense they extend the possibilities of long distance travel from explorers, soldiers and kings to the middle class. More amazing still has been the development of the automobile. The ability to drive by oneself from home to work, to school, a store, or to take a driving vacation, is an unprecedented luxury for human beings, and one that once tasted most people are loathe to give up. Nor is it surprising that so many people in the developing world crave personal mobility. Yet the mere suggestion that individuals throughout the world would seek to duplicate our mobile car culture raises the issue of the sustainability of a lifestyle that we have taken for granted.

In 1999, for example the average American driver used about 690 gallons of gasoline and drove over 13,000 miles. The number of licensed U.S. drivers topped 185 million in 1999, and Americans consumed 130 billion gallons of gasoline a year, at an average price $1.53 per gallon, or roughly $200 billion per year. That adds up to 43 percent of total U.S. oil consumption and 17 percent of the nation's total energy consumption.[25] Imagine statistics like this applied to the populations of China, India and Indonesia.

If the bad news is that personal transportation is one of the most extravagant inventions of mankind, the good news is that automobiles, trucks, and the network of highways they operate on can offer one of the most ideal scenarios imaginable energy saving technologies made possible by embedded sensors and the process control technologies of World Computing.

Once again the starting point is the edge devices themselves. Due to healthy competition and regular turnover cars and trucks are already some of the most technologically advanced products in the world. But in a world of cheap oil, manufacturers were not always quick to completely embrace the potential of sensor technology. Nor was the technology inexpensive enough to accomplish all that was possible. Now that is about to change. Today's vehicles typically have upwards of fifty microprocessors on board, including electronic controls for the engine timing, fuel/air mixture, brakes, transmission, airbag, lights, door locks, windows, seats, cruise control, instruments, climate, and diagnostics.[26] Some luxury automobiles have triple this number, including a smart tire pressure monitoring system that provides regular status reports.[27] But that is just the beginning.

Automotive manufacturers are eager to discuss the future of the motor vehicle and there are many possibilities about non-polluting technologies in the future. One solution that is available today is the Hybrid Electric Vehicle, or HEV, which features both a gasoline engine and an electric motor. These automobiles use dozens of embedded sensors and programmed controllers to dramatically reduce gasoline consumption, potentially by as much as 85 percent. HEVs in action are marvels of electronically guided decision making. For example:

- When one typical HEV is using very little energy - going downhill, traveling under about 20 kilometers per hour, or idling – its sensors shut the engine off. During these times, the car is powered only by energy supplied by the battery. When the car is idling, the battery power operates the air conditioning and other on-board systems. When the driver depresses the accelerator, a motor/generator powers the car at low speeds. At a certain point the electric system starts the gas engine, which takes over.

- When the car is using a lot of energy - for example, accelerating quickly or driving uphill - the gas engine and electric motor/generator are used simultaneously for added horsepower.

- When the car is cruising, the gas engine is used exclusively to power the wheels while the motor/generator restores charge to the battery. Once charge has been restored, the motor/generator once again adds power to the wheels.

- When the car is decelerating, the motor/generator works in reverse, drawing on kinetic energy from the wheels to add charge back to the battery. This process is called regenerative braking.[28]

HEVs are literally studded with sensors and embedded digital controllers. For example, one HEV manufacturer's braking system alone requires fifteen discrete sensors to maintain the correct charge level to prolong the life of the battery. Four of these sensors are for temperature, ten are for voltage, and one is for current. These sensors work in tandem to supply information to the "Motor Control Module", which in turn constantly determines the function of the motor/generator in every operating mode.[29]

Finally, the highway network itself is also bound to get smarter. Roads with embedded low cost sensors are increasingly common throughout the world, and their promise is to make driving safer, more energy-efficient and more environmentally responsible. By improving traffic flow, sensor-equipped "Intelligent Transportation Systems" will reduce fuel consumption, air pollution and highway accidents. The newest systems will include data gathered from video cameras, microwave radar, infrared, laser radar, ultrasonic, acoustic, magnetic and inductive loop sensors.[30]

Conclusion

Few information technology developments are more exciting than the movement to use computing to re-invent basic infrastructure throughout the world. Perhaps the most promising aspect of this trend is its momentum, even without explicit government policy initiatives. Like many other technology innovations, World Computing advances will begin on the edges of networks, where the technologies deliver value directly to their customers. Perhaps too, following the growth of the Internet in the 1990s, these solutions will self organize and spread from one region to another before they ultimately interconnect. However, it is also clear that proactive nations could decide to adopt World Computing programs as a matter of social policy. In the developing world the opportunity is to leapfrog older, capital intensive, and less efficient solutions and deliver basic infrastructure at a fraction of the cost of that was required in the 20th Century. In the developed world the opportunity is to reduce the enormous waste that the operation of our present Industrial Age infrastructure generates.

Of course, a citizen in North America or Europe might ask why this is so important, especially if our current infrastructure appears to be functioning well. One ringing answer to this question has been delivered many times in many industries by the advance of computer technology. Obsolete systems, no matter how superbly constructed, ultimately fall behind and pass their reigns over to digital solutions that are faster, better, cheaper, or a combination of all three.

More exciting, surely, is the intellectual and commercial promise that World Computing offers. At the scientific level the challenge of creating vast mesh networks with billions of low cost processors has already captured the imagination of many researchers in universities and large companies. Projects to create "Ad Hoc", or self-organizing mobile networks, where an embedded sensor – no matter how isolated - would be recognized and accepted on a network when it had useful information to deliver are under active investigation, and have already spawned dozens of papers and conferences at leading universities worldwide.[31] Other research efforts are focused on "Smart Sensor" networks, which consist of a number of sensors spread across a geographical area, with wireless communications capabilities and sufficient intelligence for signal processing and networking of the data. As in decades past, DARPA, along with the U.S. National Institute of Standards and Technology, has been a leader in supporting major research efforts in both of these areas.[32]

Repeatedly since the 1970s, the semiconductor and software industries have mobilized to act – and innovate - in response to new market opportunities. "Writes information scientist Ilkka Tuomi, "The semiconductor industry has several times hit the speed limit. First it was bailed out by the digital clock and calculator industry, then by mini and mainframe computers. In the mid-1980s, just when no one seemed to be able to make a profit, the IBM PC and Microsoft saved the day. In the mid-1990s, the Internet and World Wide Web exploded the hard disk and memory market and created the need for new processor architectures that were able to handle images sound and video."[33] Today, World Computing solutions have the potential to drive the next great wave of technology advances to sweep the global information society. This technology wave is destined to dominate the marketplace just as steadily as the waves of proceeding decades. The interesting question is whether any government or commercial policy could stimulate this process and make it happen faster.

Clearly an opportunity exists for government- and private-sponsored World Computing initiatives. As with other major undertakings a focused effort with a specific goal could galvanize the research and commercial computing communities. In the 1960s the United States achieved tremendous technical progress by aligning itself behind the goal of putting a man on the moon. In the 1970s similar progress occurred in the field of biomedical research as a result of President Nixon's War on Cancer. In the 1980s and

1990s the unplanned successes of the personal computer, the World Wide Web, and cellular telephony stimulated tremendous spurts of innovation, investment and commerce. If our communications infrastructure is the first great world system to be transformed by computing technology, progress in electric power, water and transportation cannot be far behind.

Footnotes:

[1] See http://www.mindfully.org/Sustainability/Americans-Consume-24percent.htm
[2] Gordon Moore, "Cramming More Components Onto Integrated Circuits," Electronics Magazine, April 19, 1965; See http://www.intel.com/research/silicon/moorespaper.pdf
[3] See http://www.computer.org/pervasive; http://www.ubiq.com/hypertext/weiser/UbiHome.html
[4] According to one source, a single American consumes as much energy as: 2 Japanese, 6 Mexicans, 13 Chinese, 31 Indians, 128 Bangladeshis, 307 Tanzanians, or 370 Ethiopians. See "Consumption by the United States;" http://www.mindfully.org/Sustainability/Americans-Consume-24percent.htm
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[6] See http://www.measure.com/how2measure.html
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[9] See "Philippines: The Number's Up for Fixed Lines" http://www.atimes.com/reports/CG18Ai01.html
[10] See Mridul Chowdhury, ".ph" www.cid.harvard.edu/cr/profiles/Philippines.pdf
[11] John Mashey, Personal Interview; January 10, 2003.
[12] See Wade Roush, "Wireless Sensor Networks" Technology Review, p. 37, February 2003
[13] See Perry S. Marshall, "Brains and Brawn – The Power of Smart Batteries" http://www.sensorsmag.com/articles/0402/14/,
[14] See http://www.berkeley.edu/news/media/releases/2001/05/25_dust.html
[15] See Peter Fairly "A Smarter Power Grid," http://www.technologyreview.com/articles/fairley0701.asp
[16] See "Girding up for the Power Grid" Wired News; http://www.wired.com/news/business/0,1367,44516,00.html
[17] Ibid, Fairly, http://www.technologyreview.com/articles/fairley0701.asp
[18] See http://www.ece.uprm.edu/~bvelez/projects/softpower/softpower.htm
[19] See "The Virtual Power Plant," http://w4.siemens.de/FuI/en/archiv/pof/heft1_02/artikel21/bild1
[20] See http://www.epri.com/OrderableitemDesc.asp?product_id=000000000001006870&targetnid=249807&value=02T029.0&marketnid=249635&oitype=1&searchdate=3/13/2002

[21] William Buxton "Less is More" (More or Less)", in P. Denning (Ed.), *The Invisible Future: The seamless integration of technology in everyday life*. McGraw Hill, New York, 2001; p. 145 – 179. See also http://www.billbuxton.com/LessIsMore.html

[22] See "Intelligent Linear Water Leak Detection: The Leaklokator http://www.wayscale.com/intelligent-water-detection.shtml
[23] See "Modular System" in Intelligent Irrigation Systems; http://www.iisystems.com.au/index.html
[24] See http://www.ussyorktown.com/yorktown/helm.htm
[25] In 1999, the average price in the United States was $1.53 per gallon-compared to $4.69 in Britain and $3.87 in France. The reason for the difference is almost entirely one thing - tax. While the tax take by governments in America is 34 percent of the retail price, it is 82 percent in Britain and 80 percent in France. Cambridge Energy Research Associates, "Gasoline and the American People" http://www20.cera.com/gasoline/summary/
[26] See "How Car Computers Work;" http://www.howstuffworks.com/car-computer.htm
[27] See http://www.sensorsmag.com/articles/1101/40/index.htm
[28] See http://www.insightcentral.net/
[29] Ibid, http://www.insightcentral.net/
[30] Laurence A. Klein, "Sensor Technologies and Data Requirements for ITS Applications, Artech House, 2001
[31] For examples, see "Papers on Ad-hoc Multihop Wireless Networks," http://www.ics.uci.edu/~atm/adhoc/paper-collection/papers.html or "Publications on Mobile Ad-hoc Networks," http://www.ics.uci.edu/~atm/adhoc/paper-collection/papers.html
[32] See "Project: Wireless Ad Hoc Networks" http://w3.antd.nist.gov/wctg/manet/#smarts
[33] Ibid, Tuomi, "The Lives and Death of Moore's Law"; First Monday, http://firstmonday.org/issues/issue7_11/tuomi/index.html