Designing a positioning system for finding things and people indoors

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Despite extraordinary advances in global positioning system (GPS) technology, millions of square meters of indoor space are out of reach of Navstar satellites. Their signals, originating high above the earth, are not designed to penetrate most construction materials, and no amount of technical wizardry is likely to help. So the greater part of the world's commerce, being conducted indoors, cannot be followed by GPS satellites. Continuous indoor tracking of people and assets remains in the realm of science fiction—a multibillion-dollar industry waiting to be born [see "A more frustration-free future," p. 78].

Consider some everyday business challenges. Perpetual physical inventory is needed for manufacturing control, as well as to keep assets from being lost or pilfered. Mobile assets, such as hospital crash carts, need to be on hand in an emergency. Costly and baroque procedures presently track and find manufacturing work-in-process. Nor is the office immune: loss of valuable equipment such as laptop computers has become a serious problem, and locating people in a large office takes time and disrupts other activities.

What these systems share is a need to find and track physical assets and people that are inside buildings. Mounting satellite emulators under the roof is not the answer. The design differences between an efficient asset-tracking system and GPS are more basic. First and foremost, control of the situation shifts from users of GPS receivers, querying the system for a fix on their position, to overhead scanners, checking up on the positions of many specially tagged objects and people. In GPS, each receiver must determine its own position in reference to a fixed infrastructure, whereas inside a building, the tracking infrastructure must keep tabs on thousands of tags.

Systems consulting for a health maintenance organization (HMO) sparked the authors' interest in this technology. As patients' files were often impossible to find, doctors were forced to see about one in five persons unaided by a medical record. Attempts to bar-code the records did not solve the problem, as HMO staff frequently forgot to scan critical files when passing them between offices. Not surprisingly, the files most often misplaced concerned compli-

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cated cases with multiple caregivers. At one site, the authors saw several record room employees out in clinical areas, consulting lists of desperately needed records as they sifted through piles of paper.

Several physicians wondered if there was anything like the GPS devices used to help pilot aircraft that they could use to track the records through the facility, "like those badges everyone wears on Star Trek." But a technology search found nothing targeted at this problem.

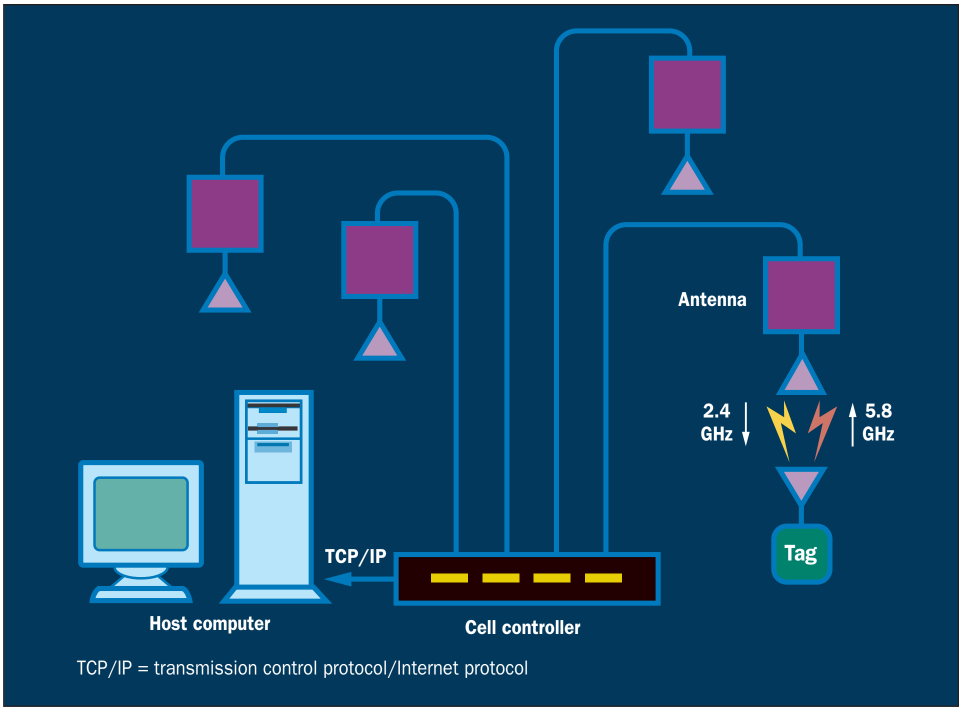
In the course of several months, convinced that a technological solution was within reach and that the range of possible applications was vast, the authors (with others) formed PinPoint Corp.; designed its product trademarked the PinPoint 3D-iD local positioning system (LPS); and filed a related set of patent applications. The name 3D-iD emphasizes two fundamental characteristics of the technology. First, it covers an entire three-dimensional indoor, or otherwise boundaried, space, not just doorways, conveyor belts, or other fixed points. Second, it is capable of determining the 3-D location of items within that space.

The design process that resulted in the 3D-iD system started with a general idea, a market opportunity, and a blank piece of paper.

An indoor positioning system's goals

The requirements of enterprise-wide asset-tracking systems are fundamentally different from those of GPS, and their basic design differs accordingly. Certain LPS characteristics are critical:

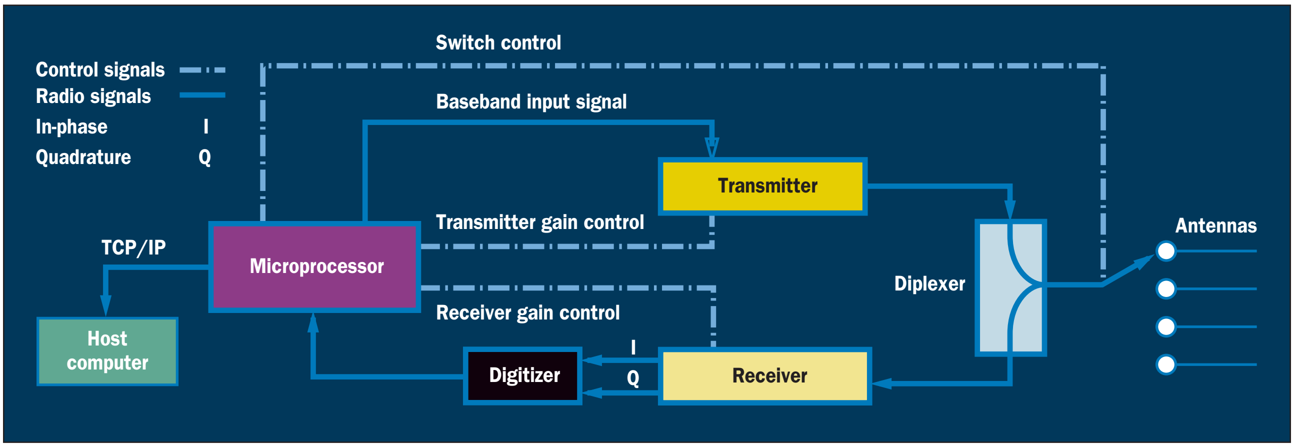
- So-called tags, physical devices associated with the people and assets being tracked, which should be as small and light as possible for the widest applicability.
- Tags that are inexpensive, for broad appeal and applicability, and therefore far simpler in design than GPS receivers.
- An infrastructure that tracks thousands of tags, whereas in GPS, a mobile device must determine its own location in reference to an infrastructure. A tag need not "know" its own position—a difference that opens the door to the necessary design simplification.
- Accuracy of 10 meters for most indoor applications, though some require 2-meter accuracy



[1] The Local Positioning System subdivides the interior of a building into cell areas that vary in size with the desired level of coverage [top]. The cells are each handled by a cell controller, which is attached by coaxial cable to up to 16 antennas [four are shown].

[2] On the transmit side, the cell controller modulates a 40-MHz baseband input onto a 2.44-GHz carrier, filters the output to comply with legal (FCC) requirements, and transmits the signal through a selected antenna [bottom]. On the receive side, the cell controller demodulates and extracts the in-phase (I) and quadrature (Q) components of the 5.78-GHz tag response, and digitizes the result for processing.

The cell-controller radio system, under microprocessor control, enables software to modify the baseband input sequence in order to support assorted signal-processing techniques; to modify the transmit gain of the radio transmitter or receiver or both in order to support operation at very varied distances; and to switch among antennas at high speed in order to collect data from assorted antennas.



or better. For many outdoor GPS applications, accuracy in the range of 50 meters is ample.

• Counteraction of indoor multipath effects, a challenge when combined with the higher accuracy requirement. A GPS receiver, owing to its great distance from the satellite, must take into account multipath and also other effects, like atmospherics and relativity, that are irrelevant to a ground-based system.

• A radio system in compliance with Part 15 regulations of the Federal Communications Commission (FCC), so that a customer may install and run the system without a license in the United States and elsewhere.

These system characteristics were chosen for their feasibility and in the light of informal discussions with potential end-users. In the process, the focus shifted from tagging folders to tagging people and assets.

Existing short-range technologies

The design process started with a review of existing products, the hope being to integrate some of them and launch a system without further ado. Instead, a new technology had to be designed and implemented from the ground up, as nothing available measured up to Pinpoint's technical goals.

Since the invention of the microprocessor a variety of short-range radio-based technologies have been employed to track items indoors. They identify objects with a sensor having a range of a few centimeters to about 3 meters, depending on the technology.

Most people are familiar with electronic article surveillance (EAS) systems, which are widely used in retail and library settings. They deter amateur theft, but little else. The tags are simplicity itself, responding to a matched electronic field by resonating: when the resonance is detected, an alarm sounds. EAS tags must be extremely low cost to be commercially viable. As a result, the products have a restricted range, lack identification codes, and are of limited reliability.

A newer technology, radio frequency identification (RFID), has been emerging over the past decade as a substitute for bar codes. Detectable up to about 3 meters away, RFID tags are identified as they pass fixed sensors. Consumers encounter RFID systems handling gas payment and automated toll collection on highways. Industry exploits them for a wide variety of purposes, including hands-free access control and as a replacement for bar codes in dirty or environmentally challenging environments.

RFID tags may be broadly categorized as active or passive. The distinction is that passive tags require no battery, so that they tend to cost less but have shorter range. Passive RFID tags vary widely in design details, but all lack a battery and share the challenge of extracting operating power from the air. As they pass within range of an interrogator (tag reader), their circuitry is charged either inductively (typically at 125 kHz) or electromagnetically (most commonly at 13.56 MHz). Once powered, passive RFID tags identify themselves to the interrogator using a proprietary technique, such as frequency shifting, half-duplex operation, or delayed retransmission.

The range of passive RFID systems is limited by the need for a nearby power source. Tiny RFID tags, such as the rice-sized devices injected beneath a pet's skin to identify it, have a read range measured in centimeters. Larger tags, some the size of license plates, can be read across a meter or more.

Active RFID systems, thanks to their battery, support longer read ranges and a broader set of features. They also usually operate at higher frequencies—typically in the unlicensed 900-MHz or 2.45-GHz bands—and are more expensive than passive systems.

Defining terms

Chip time: the duration of a single bit in the pseudo-random code sequence used to spread the spectrum of an information signal.

Chipping rate: the inverse of chip time; the rate at which the coded information signal bits are transmitted as a pseudo-random sequence of chips.

Delayed retransmission: the delayed response of tags, typically implemented using surface acoustic-wave devices with different delay settings, from which the interrogator can infer tag identity.

Frequency shifting: the translation of a signal of one frequency into a signal of another frequency.

Half-duplex operation: in the case of the tag, its being charged intermittently by the interrogator. When the interrogator's charging circuit turns off, the tag uses stored power to respond.

In-phase: the portion of a signal that is not phase-shifted or has the same phase as a reference signal.

Modulated backscatter: the process whereby a tag responds to a reader/interrogation signal or field by modulating the response signal and re-radiating, or transmitting, it at the same carrier frequency.

Multipath: the phenomenon exhibited by radio-frequency energy when it takes multiple routes between the transmitter and the receiver. Multipath signals can cancel or reinforce one another.

Quadrature: the portion of a signal that is phase-shifted by 90 degrees from a reference signal.

Several of the best-selling active RFID systems use modulated backscatter to communicate: the tags modulate their radar cross-section in a pattern to identify themselves to the interrogator. The design uses very little power and is simple to fabricate. Unfortunately, modulated backscatter tags have limited range, around 3 meters for the most part, and some products cannot be detected if blocked by a dense enough attenuator, such as a partition wall or a human body.

Evidently, current RFID offerings were designed to cover doorways, where a read range of 3 meters is adequate. In the early stages, the authors tried to implement a modulated backscatter tag, but found reliable detection at long range difficult. Backscatter reflections from the tag were overwhelmed by reflections from file cabinets, white boards, fluorescent lights, and other objects.

Today, most of the commercially exciting developments in RFID focus on size and cost reductions. Numerous vendors are struggling to design passive RFID tags that will cost almost as little as EAS tags. There is also much interest in passive inexpensive RFID tags with a read and write capability. New products with US $1 tags are becoming available, probably decreasing to about $0.25 within three years. Still, the devices remain tied to a nearby power source—a seemingly unshakable handicap, even as these technologies become inexpensive commodities. A paradigm shift is needed to move from portal coverage to coverage of a large zone or full indoor coverage.

Current mid-range technologies

A variety of products can be read from a distance of 15 meters or more. Mostly narrowband devices, they wake up periodically and transmit a unique code to identify themselves. If a receiver is in range, it detects the tag's presence and notifies a software application. If the tag signal is not received when expected, the system triggers an alarm.

A mature instance of this technology is produced by BI Inc., Boulder, Colo., for Electronic Home Arrest Monitoring (EHAM). The systems monitor the homes of persons under court-ordered supervision, to check whether they are there or not. A radio-frequency transmitter fastened around the client's ankle emits a signal, and a field-monitoring device picks it up. The signal contains the transmitter's identification number (ID), plus an indication of its tamper and battery status. The transmitter is designed to be worn continuously by the client throughout his or her house arrest. Similar technology has been used by other vendors to detect whether Alzheimer patients have wandered away, or to confirm that infants have not been illegally removed from a hospital.

More recently, radio frequency emitters have been embedded into what are sometimes called smart pallets, to track goods through a distribution process. The products the authors identified, however, were all designed to be detected when in range of a receiver, and did not appear easily upgradable to an LPS approach.

The U.S. Department of Defense also deploys a tagging system, based on high-end tag technology developed by Savi Technology, Mountain View, Calif. Containers of the kind usable on any form of transport have two-way superheterodyne radio tags attached to them, and their contents recorded in the tag's memory. Persons with hand-held interrogators can find the approximate location of a tag by monitoring its increasing radio signal strength as it gets closer. The exact location is found by activating a beeper in the tag. Moreover, fixed interrogators up to about 180 meters away can read tags and pass the information around the world quickly by satellite communications. While apparently well-suited to use by a global military operation, the approach lacked the simplicity the authors were seeking for an extremely low-cost LPS tag. It also lacks a key capability—it cannot accurately locate assets in a facility without human intervention.

Relatively long-range technology is also used for highway toll collection. These products focus on reliable communication with tags as they pass fixed points at a rate of about 100 km/h. Readers are typically installed over a highway to cover just one lane, tags in the windshield must be installed in a particular way, and cars are assumed to be traveling in the direction of traffic.

Several products for identifying locations of objects employ infrared technology, called IRID. The tags periodically transmit their identification codes by emitting infrared light to readers installed throughout the facility. In a survey of users and resellers, PinPoint found that users are not wholly satisfied with these systems. The tag prices are relatively high, and installation is complicated by the large number of readers required to ensure a line of sight to every possible tag. Users also complain about reliability. IRID systems do not work at all under various common lighting conditions. The user's cooperation is needed to avoid blocking the tag's IR emitter: a scarf or tie in the wrong position (or a party with balloons) can disable an IRID personnel tag. Nonetheless, IRID systems are currently being sold, mostly for health care applications.

The 3D-iD system design

The 3D-iD system was envisioned as the equivalent of a GPS for a location fixed by boundaries—a building, say, or a parking lot, or an amusement park; hence the term local positioning system (LPS). The system uses the concepts of GPS, but with a proprietary infrastructure to communicate with inexpensive tags.

In GPS, each satellite transmits a unique code, a copy of which is created in real time in the user-set receiver by the internal electronics. The receiver then gradually time-shifts its internal code until it corresponds to the received code—an event called lock-on. Once locked on to a satellite, the receiver can determine the exact timing of the received signal in reference to its own internal clock. If that clock were perfectly synchronized with the satellite's atomic clocks, the distance to each satellite could be determined by subtracting a known transmission time from the calculated receive time. In real GPS receivers, the internal clock is not quite accurate enough. An inaccuracy of a mere microsecond corresponds to a 300-meter error. This clock bias error, as it is called, can be determined by locking on to four satellites, and solving for X, Y, and Z coordinates, and the clock bias error. Interestingly, GPS has been used simply to determine the current time with high accuracy.

The same concepts apply to one possible design of an "indoor GPS" system. A tag can be designed to transmit a code for simultaneous arrival at three receivers installed in the facility. If the Z (height) position is assumed to be fixed, three receivers are enough to simultaneously solve for the tag's X-Y position and clock bias error. However, this design has three drawbacks.

First, the need to solve for the tag's clock bias error adds to the number of good readings required to find a tag, which in turn adds to both infrastructure cost and installation complexity. In a cluttered indoor environment, a clear signal may be unobtainable from more than one or two of the antennas, unless they are installed in huge numbers. One design option would support an independent solution for each distance reading, providing more opportunity to heuristically reconstruct a tag's position from clues such as knowledge of the facility and typical patterns of movement. For example, tags tend to move along corridors at walking speed, not through walls or floating 50 meters above the pavement.

Next, if a tag's clock is unknown, all the receivers need to share a precisely calibrated time base. No cost-effective way to reliably accomplish this seemed to exist, other than by wiring the receivers together.

Lastly, for reasonable location accuracy, intuition suggested that the tag would need to generate codes at a baseband rate of 10 MHz or better (presumably modulated onto a 915-MHz or 2.4-GHz carrier). This requirement seemed likely to increase both the cost and power consumption of the tag. Research into the signal processing literature and experiments with 10-MHz baseband signals indoors indicated that the system would in fact need to operate far more quickly to achieve the target of 3-meter accuracy.

These considerations motivated the search for an alternative approach, and a transponding-tag design emerged as the favorite. Like GPS satellites, 3D-iD readers emit codes that are received by the tags. Unlike GPS, the tags do not include sophisticated circuitry and software to decode this signal. Instead, they simply change the signal's frequency and transpond it back to the reader with tag ID information phase-modulated onto it.

The reader extracts the tag ID from this return signal, and also determines the tag's distance from the antenna by measuring the round trip time of flight. Since the reader generates the signal, there is no need to calibrate the tag's clock. Since the distance to each reader is determined independently, there is no need to synchronize the clocks on the various readers. And since the tag is not generating the code, it is practical to send a baseband signal at 40 MHz, which makes for reasonably accurate location.

A 3D-iD system requires its own indoor antenna infrastructure [Fig. 1]. The system is organized as cells within a building. Each cell is handled by a cell controller, which is attached to up to 16 antennas [Fig. 2] by means of coaxial cables—no further antenna power source is required. Both the cell controller and the tag are designed to comply with FCC Part 15 regulations so that no license is needed for operation.

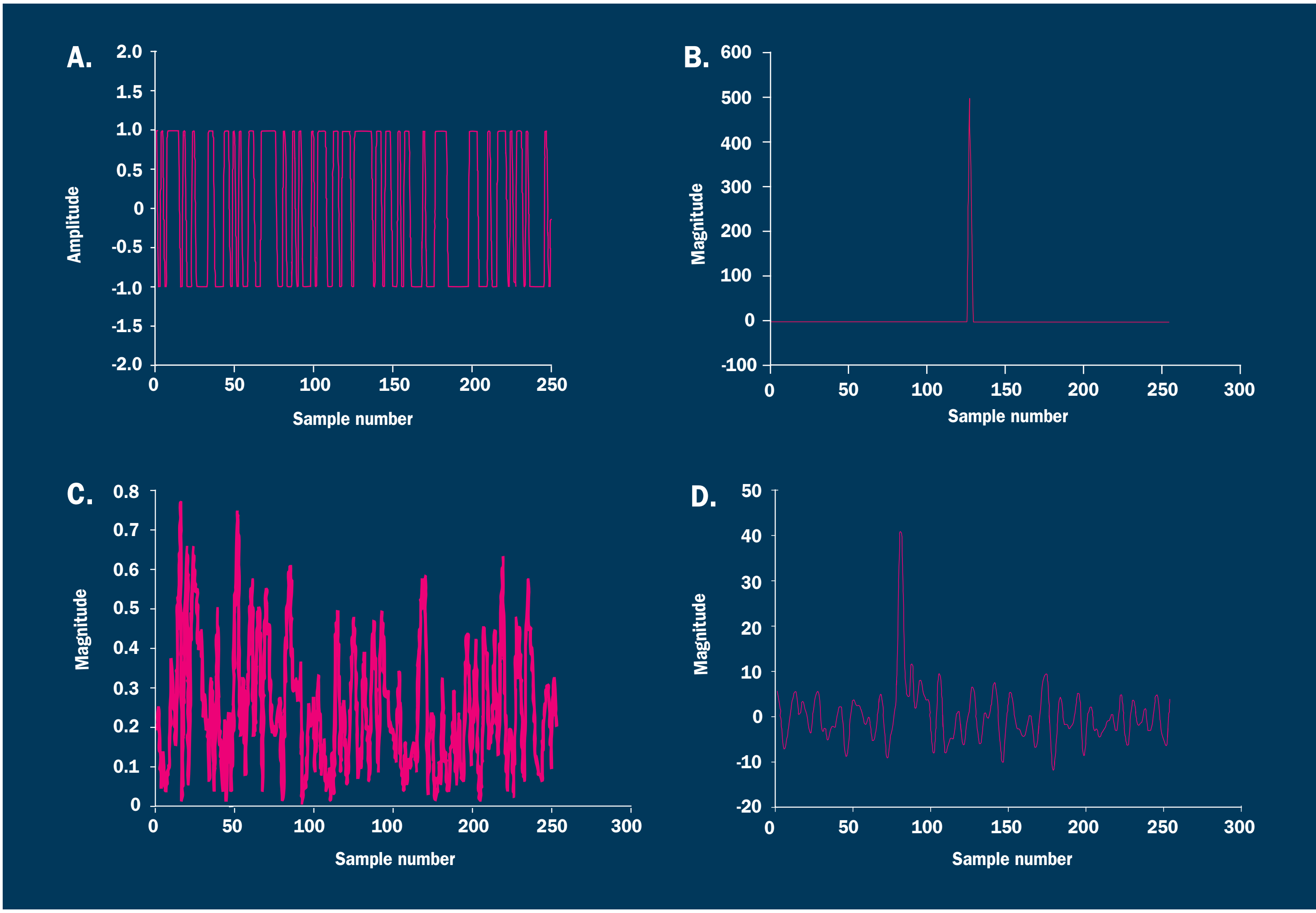
Early commercial versions of the tag emit about a milliwatt, so that the tag can be detected reliably from about a 30-meter distance. A tag about the size of a double-thick credit card can therefore operate for over a year with a small battery. For future applications where battery life may not be critical, higher-power tags will support much longer ranges—they could achieve 300-meter ranges in an unlicensed system.

In operation, the cell controller quickly cycles among antennas, determining distances to whichever of them are in range of the tag. Once this is done for at least three antennas, the tag's location in space can be estimated. In many situations, a good estimate of tag location can be obtained from fewer than three antennas. A grocery store aisle can be covered by two antennas, one at either end, and most hallways can be similarly covered. In more open environments, an installer can, with thought, place cell controllers and antennas so that the location of a tagged asset can be derived from just two distance measurements.

Without developments in four parallel underlying technologies, 3D-iD technology would not have been practical. First, the availability of parts for, and engineering expertise and field experience with, microwave frequencies is growing. Next, digital hardware advances make it possible to digitize and process high-frequency output from these radios in real time. Third, a broad and evolving signal-processing literature provides techniques to extract useful information from these signals. Finally, the widespread adoption of corporate intranets supplies a means to distribute and display 3D-iD data enterprise-wide. Thus, while 3D-iD has been theoretically possible for well over a decade, it has been difficult to imagine its commercial implementation until quite recently.

Conceptually, determining tag location is not complicated. The tag signal is received at a time that is the sum of: transmission time by the cell controller; known fixed delays in the cell controller circuitry and its cables; known fixed time delays due to the tag's circuitry; and the time for the signal to travel through the air. Once time of arrival is known, it is a simple matter to subtract out the known fixed system delays, and the distance through the air is the remainder multiplied by the speed of light. Since the signal travels to and from the tag, the distance to the tag is half of the air distance traveled.

As a practical matter, nonetheless, extracting the distance to the tag is a signal-processing challenge, particularly if the levels of accuracy must be high [Figs. 3A–3D]. To a degree, the 3D-iD system architecture removed three of the main complexities that enmesh a GPS receiver. For one, in order to determine time of flight from a satellite, a GPS receiver needs to synchronize its clock with the satellite's clock; but with 3D-iD, transmission time is a given because the cell controller originates the signal. Next, a GPS receiver must first roughly frame its location—hence



[3] The signal changes as it passes through stages of the cell controller. As idealized, a pseudo-random sequence enters the cell controller modulator [A] and, if correlated at this stage, would exhibit an idealized autocorrelation peak [B]. In the actual 3D-iD system, a real-world demodulated signal from a tag in an office environment looks different [C]. Note that the I and Q components are numerically combined for clarity. The signal-to-noise ratio is high but distorted, chiefly by multipath effects. The same signal when digitally correlated has a clear peak but is subject to multipath effects [D].

the long synchronization time usual when the devices start up; but with 3D-iD, the search can be limited to a relatively small window because the tag is known to be in the general vicinity of the cell controller. Last, a GPS signal runs into atmospheric and relativistic distortions on its 13 500-km journey from satellite to receiver, none of which affects a relatively short-range system.

Still, a very substantial challenge remains: how to extract tag distance amid the clutter of the indoors. Besides the signal received directly from the tag, there are the multipath signals reflected from objects such as steel beams, whiteboards, and fluorescent lights [Figs. 4A–4D]. Without multipath components, the time of arrival would be easily determined by finding the peak of the autocorrelation triangle. But multipath components distort most received signals.

The chief weapon against multipath is to speed up the clock of the pseudo-random sequence generator [Fig. 3A]. The triangular auto-correlation peak [Figs. 3B and 4A] is two chips (clock periods) wide at its base, and the time to rise from the noise floor to the peak is one chip. Radio waves travel at the speed of light, or about 30 cm/ns. If the chipping rate were 1 MHz, it would take 1000 ns to rise from the noise floor to the peak, providing a "ruler" with a thousand 30-cm increments. A 40-MHz chipping rate was chosen for PinPoint's 3D-iD system, providing a ruler of 25 ns. Since what is being measured is the round trip time of flight from reader to tag and back, this ruler provides real-world increments of about 3.8 meters, in range of the 3-meter marketing requirement. Because of regulatory restrictions in the 2.44- and 5.78-GHz bands, faster chipping rates are not easy to achieve, and signal-processing techniques must be used to improve accuracy further.

PinPoint has developed a proprietary approach for improving the reliability and accuracy of distance measurements. The model requirements were: half-chip accuracy (about 1.8 meters); high reliability; resistance to interference by narrowband jammers, especially microwave ovens; and low computational complexity.

A typical model [Fig. 4E] provides a value every 12.5 ns (or approximately every 1.8 meters), which corresponds directly to the system's 80-MHz sampling rate, namely, one value per sample. Note that the main multipath components are clearly discernible. On the basis of the model outputs, it is possible to interpolate peak location between the sample points. The approach works surprisingly well in practice, yielding distance measurements with about 1-meter accuracy. Thus, today's processors and techniques can determine tag location indoors in real time and with reasonable accuracy. With ongoing enhancements in both modeling techniques and processing speed, performance can only improve.

Implementation decisions

The first commercial version of the 3D-iD digital system uses an Intel Pentium II processor running an embedded version of the Unix operating system. The Intel Pentium has two indubitable points in its favor. First, its strong software development environment lets PinPoint get to market quickly even as signal-processing techniques evolve and are continuously upgraded. Second, the MMX instruction set is designed for 16-bit integer signal-processing operations. There are probably more cost-effective solutions, but for now, time to market is what counts.

The 3D-iD tags are designed for the least possible complexity and power consumption. For frequency translation from 2.44 GHz to 5.77 GHz, the 2.44-MHz received signal is simply mixed with the output of a 3.33-GHz phase-locked oscillator (PLO) within the tag. For communication back to the cell controller, the phase of the output can be flipped under microprocessor control. Simple versions of the tag are read only, and have no circuitry to demodulate the interrogation signal. A slightly more complex tag could be sent data by modulating the interrogation signal.

Readers familiar with microwave technology will note that a 3D-iD tag must include a variety of high-frequency components, hardly the way to meet aggressive cost objectives with off-the-shelf parts. But with the development of a custom application-specific IC (ASIC), all of the active components will be put on a single inexpensive chip, so that designs and processes already in place can be leveraged for high-volume cell phones and GPS receivers. Once this ASIC is available, the cost of other components and packaging will predominate.

To keep the design as simple and low-cost as possible, the tag is not required to decode the incoming signal. Instead, it simply wakes up periodically and transmits its identification code. For most of the time a given tag is in sleep mode, during which it can neither send nor receive information but merely count the time to the next transmission. When the tag wakes up, it emits a signal for about 5 ms. Thus, if it sleeps for 5 seconds, its duty cycle is 1/1000. At this level, tag battery life is primarily driven by the power requirements of the microprocessor sleep cycle.

Alternatively, where thousands of mostly stationary tags abound, motion detectors on the tags can make them transmit more often when in motion. Again, since tags are waking up according to a formula known to the cell controller, the cell controller can forecast most collisions, and the absence of an expected collision indicates that a tag has moved out of range. In the not-too-distant future, transmit times of 1 ms or less are probable. The main limiting factor today is the operating speed of the DSP hardware and software.

Tag transmissions may collide, especially if many tags are in the range of a given cell controller. Several approaches can be taken to limit the impact of packet collisions. Since collisions occur only within a given cell, cell controllers can be installed to cover a smaller area if there is a high density of tags. Slow-moving assets can be set to transmit infrequently. Where there are thousands of mostly stationary assets, motion detectors on their tags can help them transmit more frequently when in motion. Finally, in the not-too-distant future, with a modest increase in processing speed, signals should take less than 1 ms to transmit, yielding a nonlinear improvement in performance. In short, while some collisions are unavoidable, carefully crafted software can greatly mitigate their effects, helped by ever faster processors in the cell controller.

While the mass-produced 3D-iD tags are designed for minimal cost, one and the same infrastructure can be shared by a variety of tags for a variety of purposes. Most early adopters intend to use the technology for reading information from the tag. But the architecture can be extended to embrace two-way communication with the tag, with the tag being addressed while it is transmitting.

Once the 3D-iD infrastructure is in place, tags can be inexpensively packaged with other devices to support two-way digital communication. Several RFID products include the capability to connect the tags to other devices, but the limited range of these products limits their usefulness for general-purpose communication. In contrast, 3D-iD is designed to cover an entire indoor space, and as such is an ideal platform for inexpensive low-bandwidth communication with a range of devices. For example, hospitals and portable medical equipment manufacturers have expressed interest in a single system that is capable of asset and personnel tracking, as well as the ability to report telemetry and maintenance information from the equipment. Other examples are sure to emerge, limited only by customer creativity.

Installing 3D-iD

The flexibility intrinsic in the design of 3D-iD is best understood in the context of a real-world installation, such as a large teaching hospital. As a first step, most decision-makers are interested in a pilot installation, to see for themselves how the technology works in their particular environment. While it might seem logical to start out by covering a small area, the highest-value applications are justified by a need to track assets across a large facility. Usually, the first installation leverages a few cell controllers to cover a great deal of space, by detecting the passage of tags past a few fixed points.

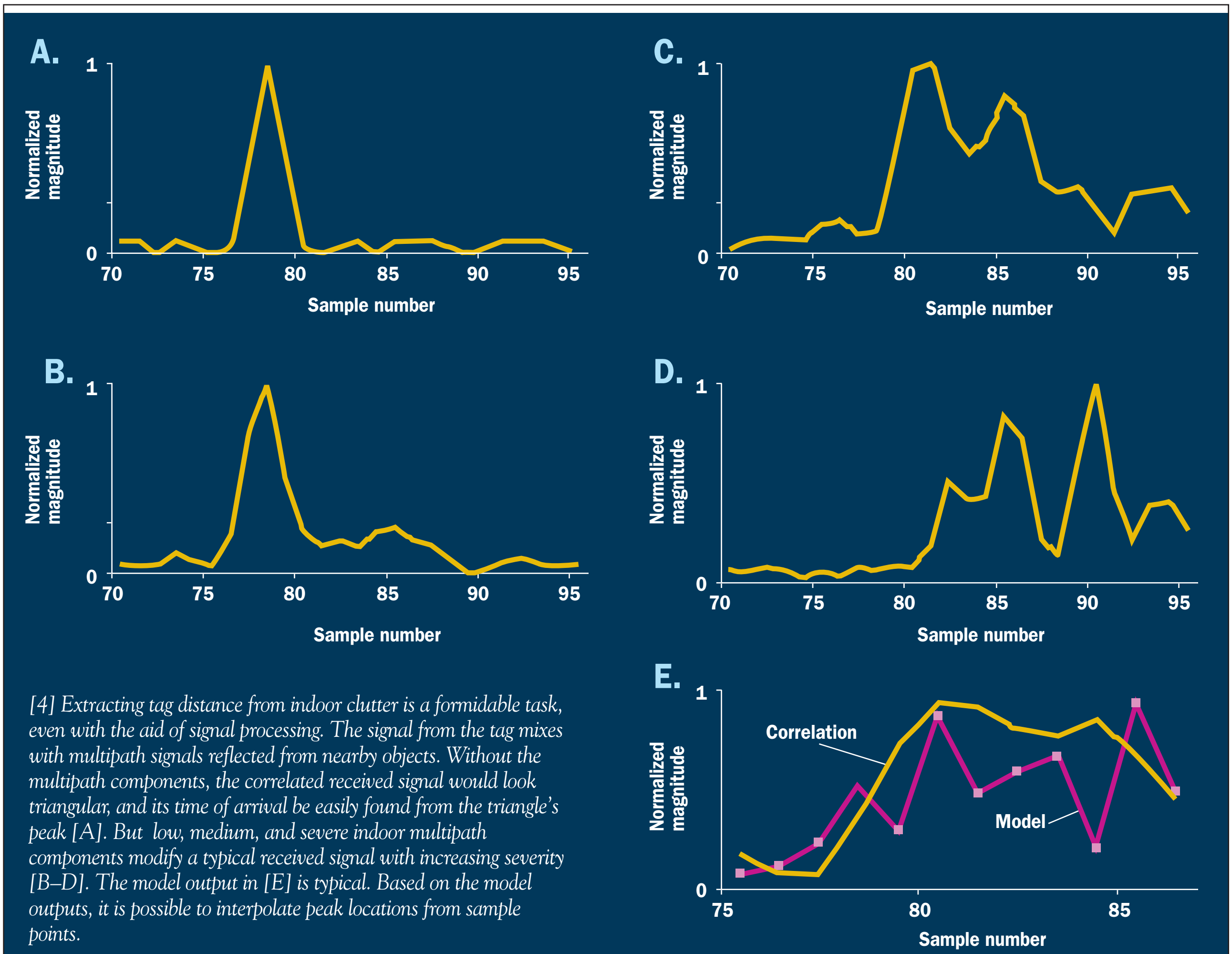
To illustrate, a hospital may start out by covering all elevator lobbies, and 15 meters in each direction. This configuration can track the movement of equipment such as wheelchairs and gurneys, which are too large to be carried up and down stairs. For this sort of entry-level installation, the asset's precise location need not be determined; but the distance from antennas still provides useful information. For example, from the observation that the distance to a particular antenna is increasing, it can be inferred that a tag was last seen moving away from the elevator into the east wing on the seventh floor.

After a pilot installation, the next logical step is to cover all hallways and stairwells, so that tags can be tracked whenever they are moved from one part of the facility to another. For example, an antenna can be placed at each end of a hallway, and a tag's location along that hallway can be estimated from its distance to each antenna. If a tag enters a room, its signal may become weak enough to elude either antenna, but the system will be able to report that a tag was last seen on the seventh floor in the vicinity of Suite 720. This information is enough in most circumstances to find a person or asset, and is a relatively inexpensive way to cover a complete facility.

At the next level of coverage, certain sections of the hospital may need to be more tightly covered for security purposes. If, say, valuable equipment is commonly pilfered from certain areas, antennas might be installed to cover those areas in their entirety. The extra antennas also have the side effect of adding to accuracy; so that the system could report that a tag was last seen near Room 723 in Suite 720. Additionally, the tag would be continuously monitored, reporting if it were tampered with or timing out if disabled or destroyed. A similar approach can be useful for tracking babies and Alzheimer patients.

Finally, certain areas of the hospital may require high-resolution location. Precise location would serve to quickly find small items such as telemetry monitors, or it might be helpful to know that a health care provider is with the patient in bed 723D, as opposed to being in the vicinity of Room 723. In such areas, extra antennas would again be installed to support full tracking.

One other nice feature of the system: the different levels of coverage can all co-exist in different portions of the hospital, depending on requirements and with a continuous upgrade path as needs evolve. Coverage and precision are purchased as needed.



[4] Extracting tag distance from indoor clutter is a formidable task, even with the aid of signal processing. The signal from the tag mixes with multipath signals reflected from nearby objects. Without the multipath components, the correlated received signal would look triangular, and its time of arrival be easily found from the triangle's peak [A]. But low, medium, and severe indoor multipath components modify a typical received signal with increasing severity [B–D]. The model output in [E] is typical. Based on the model outputs, it is possible to interpolate peak locations from sample points.

A more frustration-free future

Consider a day in the life, year 2003, when local positioning systems hopefully abound. Time to go to work, but you can't find your keys—again. But your new 3D-iD service, provided by your cable-television company, effortlessly locates them for you. You grab your laptop and go to work. Although your laptop is tagged, no alarm sounds because software recognizes you (with your keys) as an authorized escort. Drop the kids off at daycare. Since the children all wear 3D-iD bracelets, an alarm will sound if they wander off or are abducted.

At work, no time is wasted on looking for co-workers, whom you locate without effort. Phone tag is eliminated as incoming calls are directed your way. When you arrive at the elevator, it is waiting for you, since it sees you coming. Accordion folders of critical documents are tracked as they move from hand to hand. (Sorry, paper won't be eliminated until 2053.)

You've forgotten where you parked your car—again. Fortunately, your car is tagged, and the anti-theft system recently installed at your company's garage also locates your car for you in seconds.

At the grocery store, your shopping cart is designed for self-checkout. As you move through the store, a screen on the cart displays specials and shopping suggestions based on your location, and tailored to your shopping habits, culled from recent shopping trips.

On television, you are astonished to see the opening of a new highway in Japan, where the automobiles are controlled externally, based on precise location determined from a network of roadside antennas. Cars are closely spaced, mitigating highway congestion.

Hollywood has been demonstrating various versions of 3D-iD in films since the 1930s, and most people assume that the military has been using a product like this for years. Perhaps for those reasons, 3D-iD is one of the few emerging technologies that most people understand immediately and intuitively. But only now is it possible to turn such intuitive knowledge into workaday engineering solutions. *—J.W. & C.L.*

The 3D-iD software platform

Operationally, 3D-iD is designed to be helpful even in the absence of any process changes. Note the contrast with bar coding and RFID, which require that labels or tags be directed in the range of a reader or the other way around. In comparison, 3D-iD tags are tracked wherever the current and future processes happen to take them. In many applications, managers soon see that 3D-iD can streamline existing processes without massive re-engineering. Longer term, the 3D-iD infrastructure helps to fundamentally improve ways of doing business.

Although the benefits of 3D-iD can often be enjoyed without operational changes, it does of course require software and a system infrastructure. The 3D-iD customers pay for tags and cell controllers, but the system's value derives above all from the information it provides. Accordingly, PinPoint's software platform enables 3D-iD to be incorporated at a variety of levels.

The 3D-iD cell controllers, and by extension their tags, are designed as network devices. An open application programming interface (API) enables an application developer to extract data from the cell controllers using transmission control protocol/Internet protocol (TCP/IP). At a higher level, software is available to funnel cell-controller data into a Simple Query Language (SQL) database, making the data available to a wide variety of programmers and software platforms by way of open database connectivity (ODBC).

Broadly speaking, 3D-iD data is made available by either low-level API, or a stand-alone platform, or an enterprise platform. In low-level API, 3D-iD data from multiple cell controllers is collected onto a Windows NT workstation or server, and passed to applications over a TCP/IP interface. The publish/subscribe software paradigm used, like the approach used on Wall Street, quickly distributes large amounts of data to end-user applications. Client software provides a simplified interface to this same information through an ActiveX control. Third parties are encouraged to develop vertical market or custom applications or both using this API.

As for a stand-alone platform, it suits small-scale installations: 3D-iD data is archived into a Microsoft Access (Jet) database, which can then be accessed by a variety of applications using Visual Basic and other standard client tools.

Thirdly, an enterprise platform is best for large-scale and/or mission-critical installations. Here, 3D-iD data is archived to an ODBC-compliant database, which can in turn be accessed by much third-party software, including Web-enabled interfaces.

In most situations, the stand-alone platform will be used initially for pilot sites or small-scale installations or both. As the use of 3D-iD spreads through the enterprise, users will either turn to the API to incorporate the data into existing systems or else upgrade to the enterprise platform.

The flexibility afforded by this platform is critical in a world where there is no standard enterprise computing environment. The stand-alone platform and the API ease integrating the cell controllers into existing specialized systems that provide control of the corners of a business. Simultaneously, the enterprise platform and the application program interface make it possible to incorporate 3D-iD data into larger-scale solutions. ◆

To probe further

PinPoint Corp. maintains a World Wide Web page with information on 3D-iD at http://www.pinpointco.com.

For more on radio frequency identification (RDID), visit the Web site (http://www.rfid.org) of AIM International Inc., an international trade association for those involved with automatic identification systems. The site's basic primer gives a good overview of RFID technology.

BI Inc.'s Web site (http://www.bi.com) gives a good look at electronic home arrest monitoring devices and technology. Savi Technology also maintains a good and informative Web site (http://www.savi.com) for radio frequency identification.

Three texts in particular are excellent sources of more material and solid references on global positioning systems and spread-spectrum communications. Tom Logsdon's *Understanding the Navstar: GPS, GIS, and IVHS,* now in its second edition, aids readers in evaluating, applying, and benefiting to the full from the Navstar system; it was published by Van Nostrand Reinhold, New York, in 1995. The other two books focus on *Spread Spectrum Systems,* by Robert C. Dixon (second edition, John Wiley & Sons, New York, 1984), and *Spread-Spectrum Communications,* edited by Charles E. Cook and Fred W. Ellersick (IEEE Press, New York, 1983).

About the authors

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