John Edwards

New Directions in Navigation and Positioning

Signal processing-enabled technologies pinpoint people, places, and things

In an era of same-day product deliveries, interplanetary space probes, and autonomous vehicles, transporting something—or someone—from here to there quickly, directly, and precisely is becoming increasingly important.

An array of navigation and positioning technologies are now available to help guide and locate vehicles, people, and almost endless number of objects. The satellite-based global positioning system (GPS), for instance, now lies at the heart of an almost endless array of location, navigation, timing, mapping, and tracking tools. Real-time location system (RTLS) technologies, meanwhile, rely on resources such as GPS, Wi-Fi, Bluetooth, near-field communication (NFC), and radio-frequency identification (RFID) to detect the current location of a target, which may be anything from a vehicle to an item in a manufacturing plant to a person.

With navigation and positioning technologies continuing to fuel the development of innovative commercial, industrial, consumer, and scientific applications, researchers are turning to signal processing methods and approaches to tweak the performance of existing systems as well as to pioneer completely new tools and services.

A GPS alternative

Researchers at the University of California, Riverside (UCR), have developed a new navigation system that is based entirely on existing terrestrial signals, such as cellular and Wi-Fi, rather than GPS. The new technology, which the researchers claim is both highly reliable and accurate, can function as a standalone alternative to GPS or as an alternative to satellite signals to enable highly reliable, consistent, and tamper-proof navigation in autonomous systems, such as robots, driverless terrestrial vehicles, and unmanned aerial vehicles (UAVs).

"GPS is unreliable for anytime, anywhere navigation, including indoors and in deep urban canyons," says team leader Zak Kassas, an assistant professor of electrical and computer engineering in UCR's Bourns College of Engineering. He notes that GPS signals are also highly vulnerable to interference, jamming, and spoofing. "However, in most GPS-challenged environments, there are dozens of signals of opportunity (SOPs) that are available at various frequencies, geometry and transmission protocols, and whose received power is much higher than GPS," Kassas says.

By exploiting abundantly available SOPs, the new approach reduces the sensory payload that's typically used to compensate for GPS's shortcomings. "Current and future vehicles, whether manual, semiautonomous or fully autonomous, ground and aerial, would benefit from this research," Kassas says.

The system can be used by itself or to supplement inertial navigation system data in the event of GPS failure. The researchers' approach include theoretical analysis of SOPs in the environment, building specialized software-defined radios (SDRs) that can extract relevant timing and positioning information from SOPs, developing practical navigation algorithms and, finally, testing the system on ground vehicles and unmanned drones.

"We have designed state-of-the-art specialized SDRs for cellular code division multiple access and long-term evolution (LTE) signals," Kassas says. "We mounted our SDRs on ground vehicles and UAVs and demonstrated experimentally these vehicles navigating to an unprecedented level of accuracy only with cellular signals." The trajectories produced by the SDRs were within a few meters from a trajectory produced with traditional GPS receivers (Figure 1). "To my knowledge, we were the first to demonstrate UAVs navigating exclusively with cellular signals," Kassas remarks.

Kassas notes that the system uses signal processing in all of its stages. "We start by studying the SOPs and deriving theoretical signal models for what useful position-navigation-timing information we can extract from these signals," he says. "We then design SDRs that process these signals and output useful information [then] fuse the extracted information with signals from other sensors to achieve an accurate and robust navigation solution." The SDRs contain phase-locked loops, delay-locked loops, frequency-locked loops, fast Fourier transforms, inverse FFTs, and

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FIGURE 1. The simulation results for an unmanned drone flying over downtown Los Angeles showing the true trajectory (red line) with GPS navigation only (yellow line) and GPS aided with cellular signals (blue line). (Figure used courtesy of UCR.)

numerically controlled oscillators. "Our integrated navigation filter uses extended Kalman filters," Kassas says.

SOPs have been extensively analyzed for communication applications, yet are still not well understood as potential PNT sources. "We have been deriving theoretical signal models capturing phenomena that were never discovered prior to our research, because these signals were not intended for PNT purposes," Kassas says. "For example, we discovered that the observed clock bias corresponding to different sectors in the same base transceiver station cell is not the same." The difference turned out to be on the order of nanoseconds. "While the difference is not harmful for communication purposes, it introduces positioning error of tens of meters if not modeled and accounted for appropriately," Kassas explains.

Kassas says that autonomous vehicles are likely to benefit most from his team's research. "Autonomous vehicles will inevitably result in a sociocultural revolution," he says. "Our overarching goal is to get these vehicles to operate with no human in the loop for prolonged periods of time, performing missions such as search, rescue, surveillance, mapping, farming, firefighting, package delivery, and transportation."

Space optical communication and navigation

In 2013, the U.S. National Aeronautics and Space Administration (NASA) demonstrated the Lunar Laser Communication Demonstration experiment, a laser communication prototype that achieved record-breaking data download and upload speeds between Earth and the moon. Now, a NASA optical physicist claims he can equal those speeds and create extremely precise distance and speed measurements using a single compact package (Figure 2).

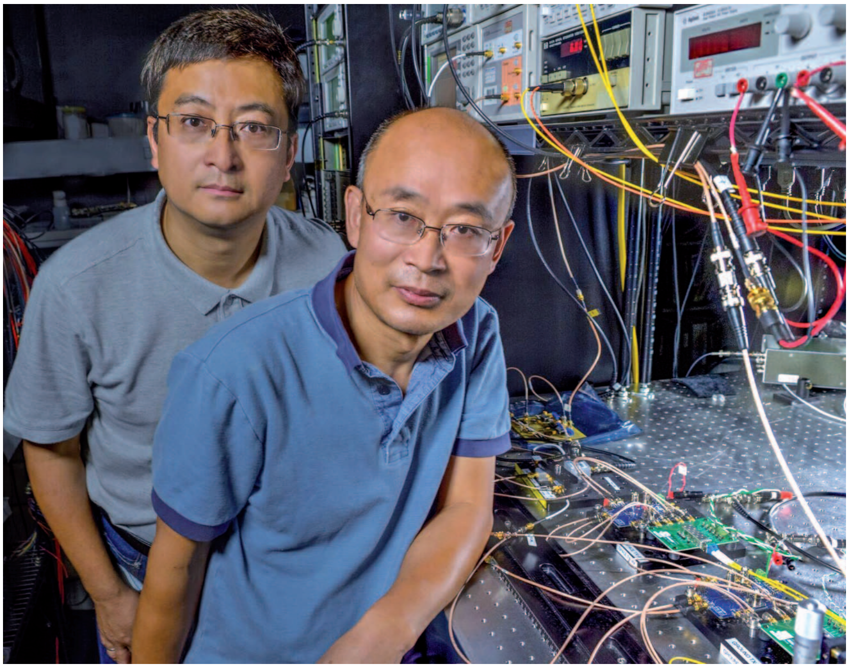

FIGURE 2. NASA optical physicist Guan Yang (right) and research associate Wei Lu pose in front of the lasercom breadboard they created to demonstrate high data-rate download and uplink speeds as well as highly precise distance and speed measurements all from the same, relatively small package. (Photo used courtesy of NASA.)

The new Space Optical Communication and Navigation System is a miniaturized lasercom transceiver comprising commercially available components that simulate both ground and space terminals. In recent laboratory tests, the system showed that it could provide micrometer-level distance and speed measurements over a 622 Mb/s laser communication link. "This technology decreases ranging and range-rate errors by orders of magnitude," says Guangning Yang, an optical physicist at NASA's Goddard Space Flight Center in Greenbelt, Maryland. "We can more precisely determine a spacecraft's orbit relative to an absolute location." Besides transmitting data at LLCD's record-breaking rate of 622 Mb/s, the new transceiver measured speed within a precision of less than 10 μm/s and distances within 20 μm. The system achieved the precise measurements by incorporating a Doppler frequency enabled by an FFT.

> **Yang says that the biggest challenge faced so far has been conducting high-precision frequency measurements of a Doppler-shifted clock signal within a digital domain.**

NASA's current space communication and navigation systems, such as the tracking data and relay satellite (TDRS), provide two major services—communication and satellite tracking. Tracking keeps tabs on a satellite's location, speed, and orbit. "We do this by continuously measuring the spacecraft's distance and speed relative to a fixed reference point with an RF communication satellite, like TDRS," Yang says. "With these measurements, we can calculate the spacecraft's speed, distance, and orbit." Space optical communications promise to provide similar services, but with higher data bandwidth and enhanced tracking precision.

"With significantly improved satellite location and speed information, we will enable better scientific-data collection and processing," Yang says. "This high-precision instrumentation, which is low mass, consumes less power, is relatively small, and will enable many other scientific instruments that require high-precision ranging, such as flying information with a constellation of satellites."

The system's precise measurement capability is tied directly to high-precision frequency synthesizing, low-noise implementation of frequency and timing detection. "The final instrumentation will be carried out in a digital domain with lots of digital signal processing," Yang says. "The types of digital signal processing we used include digital frequency synthesizing, digital-phase detecting, digital-phase lock loops, digital filters, and digital-time interval counters for ranging measurements," he explains. The measurements are processed in a software tool that relies on an extended Kalman filter to produce high-precision orbit-state estimates.

Yang says that the biggest challenge faced so far has been conducting high-precision frequency measurements of a Doppler-shifted clock signal within a digital domain. "The obvious advantage with digital implementation is size and flexibility," Yang notes. "A single field-programmable gate array can accomplish much more in a small form factor."

Yang says that the project is moving ahead in two directions. "On one hand, we will try to implement the current version of this technology on an existing hardware platform, such as Goddard's NavCube (a spacecraft bus that is typically no larger than a shoebox), which is a powerful navigational technology," he remarks. "At the same time, we are pushing to further advance the technology into continuous optical-phase measurement."

Atomic gyroscope

U.S. National Institute of Science and Technology researchers have developed a compact, low-power atomic gyroscope design that promises to give precise navigational capabilities to spacecraft, submarines, and other vehicles hampered by size, weight, and power restrictions. The gyroscope can also simultaneously measure acceleration, enabling navigation by "dead reckoning" without reference to external landmarks or stars.

The gyroscope, an atom interferometer, is based on an expanding cloud of laser-cooled atoms, an approach first demonstrated at Stanford University. Traditional optical interferometry involves combining or "interfering" the electromagnetic waves in light and then extracting information about the original light paths from the resulting wave patterns. An atom interferometer leverages the ability of atoms to act as both particles and waves, interfering these waves to measure the forces exerted on atoms. When atoms speed up or rotate, their matter waves shift and interfere in predictable ways that are visible in interference patterns.

The basic concept behind the new gyroscope is similar to the principle underlying optical ring-laser gyroscopes, says Gregory Hoth, a postdoctoral research associate in NIST's Time and Frequency Division. "We take a wave and split it into two parts, he says. "We arrange for the two wave packets to travel along different paths and then recombine them and look at the amplitude of the wave that comes out." If the separated paths enclose an area, the output wave amplitude will depend on whether or not the device is rotating. "This is often called the Sagnac effect," Hoth says. For optical gyroscopes, the waves are light waves, and the amplitude corresponds to the intensity of the light. "For our gyroscope, the waves are matter-waves and the amplitude corresponds to the probability for an atom to occupy a specific energy state," Hoth says.

At the gyroscope's heart is a small glass chamber containing a sample of about 8 million cold rubidium atoms that are continuously trapped and released. As the atoms fall under gravity, a laser beam causes them to transition between two energy states. The process gives the atoms momentum and forces their matter waves to separate and later recombine to interfere. The cold atom cloud expands to as much as five times its initial size during the 50 ms (thousandths of a second) measurement sequence, which creates a correlation between each atom's speed and its final position. The interference effect on an atom depends on its speed, so rotations generate interfering bands of atoms across images of the final cloud (Figure 3).

The atoms are imaged by shining a second, weak laser beam through the cloud. Because atoms in different energy states absorb light of different frequencies, the final energy state of the atoms can be detected. The resulting images show interference bands of atom populations in the two different energy states. The rotation rate and axis are measured by analyzing the spacing and direction of the interference bands across the atom cloud. Acceleration is deduced from changes in the central band. The interferometer is sensitive to acceleration along the direction of the light and sensitive to rotations perpendicular to the light.

"The signal processing challenge in our experiment is to take images of the transition probability and estimate the wavelength of the fringe pattern," Hoth says. "To use the system as a gyroscope, you would use the wavelength of the fringe pattern to infer the unknown rotation rate." In experiments to date, the researchers' goal has been to quantify the relationship between the rotation rate and the wavelength of the fringe pattern so they can compare that relationship to theoretical predictions. "We do that by applying a known rotation rate and measuring the wavelength of the observed fringe pattern," Hoth says.

The process requires three images. "Each image has a fringe pattern with the same wavelength, but we vary the phase so that we see different parts of the fringe pattern," Hoth says. "By combining the three images, we can get the fourth image, which shows the spatial variation of the interferometer phase." The fringe pattern is equivalent to a slope or gradient in the interferometer phase. "By calculating the spatial phase, we solve both of our problems," Hoth continues. "The unwanted structure is suppressed and the hard problem of estimating a fringe wavelength has turned into the easy problem of estimating a best fit slope."

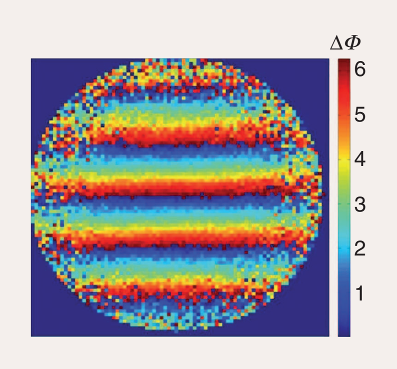

FIGURE 3. NIST's compact gyroscope measures rotation by analyzing patterns of interfering matter waves in an expanding cloud of atoms transitioning between two energy states. Each atom's speed determines both its final position in the cloud and the size of the rotational signal that shifts the interference patterns. Thus, rotations generate interfering bands of atoms across images of the final cloud. The color coding indicates how much the interference patterns shift in radians, the standard unit of angular measure. The orientation of the interfering bands (horizontal in the image) indicates the rotation axis. The rotation rate, determined by an analysis of the band spacing, is 44 milliradians/s. (Figure used courtesy of NIST.)

"The basic idea is that the part of the signal we're interested in changes when we modulate the phase, but the parts that we want to suppress stay the same," Hoth says. "So, by combining multiple images, we can separate the signal we want from the structure that we don't want."

Hoth goes on to say that the researchers are still experimenting with different ways of implementing the signal processing strategy. "It's mostly variations on the idea of modulating the phase and looking at the response," he says.

Although Stanford researchers were the first to demonstrate the technique of using an expanding cloud of laser-cooled atoms, they presented it in a 10-m-tall "atomic fountain" that was designed to be the world's most sensitive accelerometer. "In contrast to their work, our system was designed to be compact to open up the possibility of portable applications," Hoth says. The current experimental system is tabletop sized, but the researchers plan to eventually shrink the apparatus down to a portable cube approximately the size of a mini refrigerator. "There's a lot of very exciting work on atom interferometry being done all over the world," Hoth says.

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FROM THE EDITOR

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myself included, argued for a strategy that interacts with arXiv to put signal processing under a more appropriate topic branch, which may also need to be created. Thanks to the efforts led by SPS Vice President for Membership Dr. Nicholas Sidiropoulos, we learned that the arXiv scientific board has agreed to work toward creating an electrical engineering topic branch under which signal processing, information theory, and control theory will be hosted. This would be a wonderful development as SPS enriches its content ecosystem. Ultimately, our hope is that you, our readers and members, will find the content ecosystem beneficial to your professional development and be a regular contributor to the ecosystem.