High Performance Inertial Sensors Propelling the Internet of Moving Things

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As the proliferation of quality sensors, reliable connectivity, and data analytics combine to create new industrial efficiencies, there is a parallel benefit from also making these intelligent nodes increasingly autonomous and mobile. In these cases, precision motion capture and location tracking of the sensor node become central to the application's success. Smart farms are then able to leverage autonomous land and air vehicles in concert to more effectively guide ground operations based on rich geolocated sensor content and analytical learning. The smart operating room brings classical navigation techniques to the surgical table for precision guided robotic arms that employ sensor fusion to ensure accurate guidance under all conditions. In numerous fields, motion-based sensors become a value multiplier to applications on the move.

The ubiquity of consumer inertial sensors in mobile phones has led to a widespread underwhelming opinion of their accuracy, and, thus, have been ineffective to date at propelling the concept of the Internet of Moving Things (IoMT). However, new generations of high performance industrial sensors are capable of supporting subdegree pointing accuracy and precise geolocation, while also providing the size and cost efficiencies necessary, and are now primed to move the IoMT forward.

Drivers for Intelligent Sensing in Industrial Systems

The most valuable advancements in industrial machinery and processes are focused on tangible, system-level benefits that typically pose design and implementation challenges, which in turn resolve into new solution approaches and business models. Three such system-level drivers are the pursuit of resource efficiencies, critical accuracy, and improved safety. Applications eyeing these enhancements are spread across industries and span air/land/sea, indoor/outdoor, short-term/long-term, and human/machine, but regardless, they all rely on common attributes; namely precision, reliability, security, and intelligent processing and analytics, as summarized in Table 1.

Sensors of multiple types become central to the design task of the targeted applications. The system complexity of the designs being addressed results in a requirement for careful consideration of sensor quality and robustness across widely varying conditions. While some industries may have the ability to choose sensors out of convenience (for example, leverage the suite of sensors already existing in a mobile phone), others will define a sensor suite from the ground up, choosing them based on precision and intelligently combining them to allow full and reliable coverage of the intended system states.

Table 1. Valuable System Attributes in IoMT Applications Translate to Challenging Design Needs

System Drivers	Example Applications	Critical Needs
Resource efficiency	Precision farming; inventory/asset control; industrial surveillance; equipment predictive maintenance	Multiparameter sensing; geolocation; databasing/referencing
Critical accuracy	Factory robotics; surgical instruments; construction; vehicle guidance	Precision; stability; repeatability; all-condition operation
Improved safety	Unmanned vehicles; condition monitoring; autonomous machines; first responders	Reliability; environmental immunity; ruggedness; predictive analysis; fail-safe modes

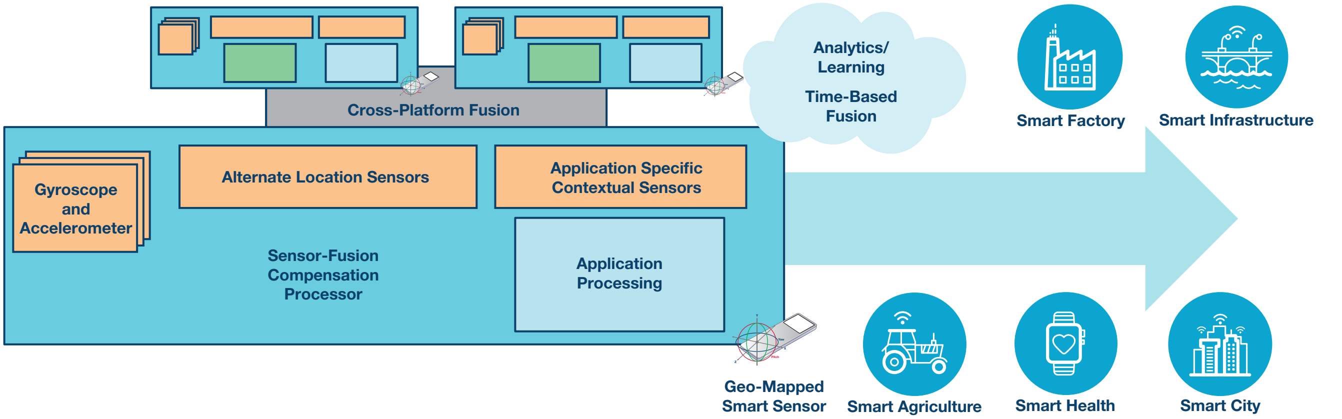

Figure 1. Emerging industrial requirements combine contextual plus motion sensing and multiple layers of fusion.

Smart Sensing

With sensor rich context, these intelligent and accessible systems are revolutionizing what would otherwise be mature industries, turning agriculture into smart agriculture, infrastructure into smart infrastructure, and cities into smart cities. As sensors are deployed to gather relevant contextual information in these environments, new complexities arise in database management and communication requiring sophisticated fusing not just from sensor-to-sensor, but across platforms and across time (for example: cloud-based analytics of an infrastructures' condition over time, last year's crop yield, or traffic conditions and patterns), as seen in Figure 1.

The resolution to which information can be reliably extracted from the equipment and the environment becomes the primary gauge of the ultimate utility and growth of these new ventures. Accuracy drives efficiency, translating into the necessary economics, while it also is central to safe and reliable operation. While a simple feature addition may be possible with the most basic of sensors, this minimal added value falls short in the subject IoMT applications, where yes/no, up/down, or on/off gets replaced with infinitely finer resolution, and the addition's implications on sensor choice.

Where Motion Matters

In most cases, the IoT is in motion. Even when it is not—for instance a stationary industrial security camera—precise pointing can still be essential, or perhaps knowledge of unwanted motion (tampering) can be valuable. A drone capturing crop images with an optical payload can deliver results better and faster if accurate pointing angles can be maintained under rugged flight conditions, and it can allow historical comparisons of data and trends if the optical data is accurately geo-mapped. Smart vehicles, whether they be land-, air-, or sea-based, increasingly rely on GPS guidance. However, GPS is also increasingly under threat whether it be intentional or natural (buildings, trees, tunnels, etc.). If chosen with precision, additional sensors can reliably dead reckon in between outages. Table 2 offers a sampling of things that put the M in IoMT, noting the relevance of the motion to the utility of the application.

Table 2. Knowledge of Motion or Even Lack Thereof Is Critical to Success in Many Applications

Industrial Equipment	Motion Relevance
Smart tractors	Geolocation, antenna stabilization
UAVs/drones	Geolocation, swarming, payload pointing
First responder	Geolocation, mapping, activity monitor
High value assets	Geolocation, inventory control
Trains, other transports	Geolocation, safety
Augmented reality	Geolocation, pointing
Smart vehicles	Geolocation, sensor-positioning, dynamics
Robotics, machinery	Geolocation, controls, stabilization
Antennas, cameras	Pointing angle, installation/calibrations, stabilization

The significance of the extracted system-state knowledge is enhanced if given an opportunity and the means to capture the natural inertia of the equipment or person, and can properly fuse it with the available, contextual information. This is displayed in Table 3.

Table 3. Position Sensing as a Value Multiplier to the IoT

Position Sensors		IoT Contextual Sensors		
Inertial		Temperature		
GPS		Optical		
Magnetometer	+	Chemical	=	IoMT
Barometer		Gas		
Ranging		Vibration		
Other		Other		

Reliable and Secure IoMT Nodes

The validity and value of the output of the IoMT node is most dependent on the quality of the core sensors and their ability to capture the application's context with high fidelity. Fusion processing is then necessary for continual sensor corrections/enhancements and for ideal sensor-to-sensor state dynamics (for example, which sensor is most reliable at any given point in time). Application-level processing is layered into the solution and optimized to the specifics of the environment, including appropriate boundary conditions. Though autonomous, in some cases these nodes are working in collaboration, such as in swarmed unmanned vehicles on land or in air. In these cases, secure communication links are deployed, emphasizing reliable transmissions and protected unique identities, as seen in Figure 2.

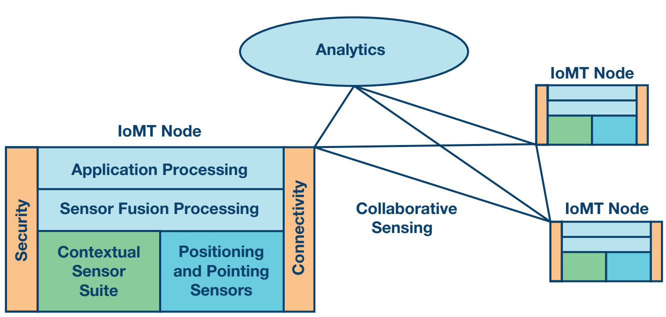

Figure 2. Connected and secure sensors combining context plus position.

Table 4. Starting with a Base of Quality Sensors, Increasing Integration and Intelligence Drives Autonomy and Human-Machine Convergence

		Measurement	Control	Autonomy	Convergence Human/Machine
Sensor	Basic, single, sensing element	•			
Multisensors	Identification of multiple sensing types to fit application need	•			
Fused Sensors	Using one sensor to correct another or state-driven, hand-off between sensors	•	•		
Smart Sensors	Localized embedded processing, supporting real-time analysis and decisions	•	•	•	
Connected Sensors	Communications links support cross-platform information sharing	•	•	•	
Intelligent Sensors	Leverage of information across time (for example, cloud, databasing) to adapt/learn	•	•	•	•

Table 5. Quality of Sensor, Not the Sophistication of Sensor Fusion, Drives Accuracy and Utility

Inertial Sensor Quality	Characteristics	Role in Sensor Fusion	Accuracy After Sensor Fusion	Suitable for:
High Precision	Ultralow noise, stable operation under all conditions	Primary sensor, heavily relied on, capable of supporting rugged/unpredictable conditions	~0.1°	Complex motion, long life, mission critical
Low Precision	Low to moderate noise, poor stability, unspecified drift under vibration/temp/shock	Backup sensor with low weighting, restricted or conditional reliability	3° to 5°	Simple motion, short life, error tolerant use cases

Sensors at the Core of Autonomy

As with the human body, the autonomous IoMT node relies on multiple sensing inputs to achieve the needed awareness to act independently and optimize its outcome to random and even chaotic events, ultimately improving over time. As Table 4 notes, the transition from basic measurement, to control, to autonomy requires increased sophistication at the sensor merging level, as well as in the embedded intelligence. As these nodes also achieve high levels of interconnectivity and adaptive learning, they trend toward a convergence of human and machine.

Location Without Infrastructure

GPS is everywhere, unless there is a satellite blockage or outage. Wireless ranging techniques can be precise if accessible. Magnetic field readings are always there, if not disturbed. Inertia is uniquely self-reliant. Clearly, inertial MEMS sensors have their own deficiencies (drift), but these can be manageable and new generations of industrial inertial measurement units (IMUs) provide unprecedented stability in small, cost-effective packages.

Inertial MEMS devices leverage standard semiconductor processes, sophisticated packaging, and integration approaches to directly sense, measure, and interpret their motion, typically in the form of linear acceleration (*g*) or angular rotation (°/sec, or rate), as seen in Figure 3. Because all but the most benign of applications have what is called multiple degrees of freedom (essentially, motion can be on any and all axes, and the equipment is relatively unconstrained in its motion), the *g* and rate measurements must be captured for each of x, y, and z; or, in some cases, termed roll, pitch, and yaw axis. Combined, these are sometimes referred to as six degree of freedom inertial measurement units.

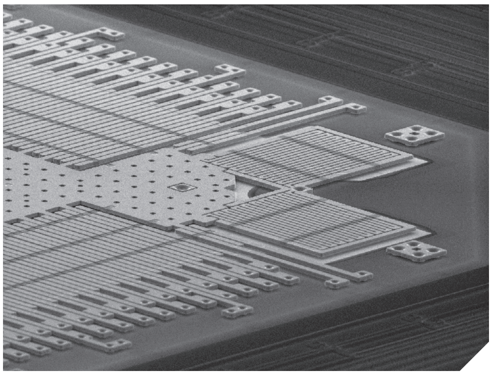

Figure 3. Microelectromechanical structure used for precision motion determination.

While economics naturally drive a MEMS designer to employ the least amount of silicon area to extract these multiple sensing types (*g*, rate) on each axis (x, y, z), a more deliberately balanced view of designing for performance is necessary to meet the more challenging industrial sensing profile. In fact, there are MEMS structures that attempt to measure all six modes with a single MEMS mass. Before examining the validity of such an approach to high performance sensing, it is important to understand that while there are motions for which a MEMS device is required to capture, it is equally important that the same device be capable of dismissing (or not being perturbed by) other forms of motion that translate into error. For instance, while a gyroscope is measuring angular rate, it should also be capable of ignoring acceleration or gravitational effects on that angular rate measurement. A simple MEMS device that tries to measure everything with one small structure is by nature (by design) also fully susceptible to these other distracting error sources, and unable to distinguish wanted motion from unwanted motion. Ultimately, this translates into noise and error in the navigation or pointing application.

For the IoMT to deliver on its promise of valuable resource efficiencies, safety enhancements, or critical accuracy when needed, it requires a higher level of precision than available from the ubiquitous simple sensors available in today's mobile devices. Designing for performance translates to designing for each sensing mode and each sensing axis independently, but with a view towards fusion and integration. Finally, it is important to know that designing for performance does not have to be at the expense of designing for cost-effectiveness.

Feature or Performance

Some applications can imply substantial value from feature additions (gesture/orientation of a device for mode switching) that are relatively easy to extract with simple MEMS devices. An industrial or professional device may be more apt to measure value, as the difference between several degrees of orientation accuracy vs. subdegree or the ability to discern better than an order of magnitude more accurate position, while also operating in a high vibration environment. The differences in performance between low and high end sensors are not subtle and, in fact, are vast enough to warrant careful consideration during component selection.

The end application will dictate the level of accuracy required, and the quality of sensor chosen will determine whether this is achievable. Table 5 contrasts two solution options illustrating the significance of sensor choice to not only the design process, but to the equipment precision. A low precision sensor may in fact be suitable if it is only relied on in limited instances and if the application has tolerance for error—

in other words, if it is not safety or life critical, or if relatively imprecise accuracy is good enough. Though most consumer-level sensors have low noise and perform adequately in benign conditions, they are not suitable for machinery subject to dynamic motion, including vibration, which in a low performance inertial measurement unit cannot be separated from the simple linear acceleration or inclination measurement that is desired. To achieve accuracy of better than one degree while operating in an industrial environment, the selection focuses on sensors that are designed specifically to reject error drift from vibration or temperature influences. Such a high precision sensor is then capable of supporting a larger span of the expected application states and over longer time periods.

Table 6. Industrial MEMS Devices Offer Extensive Characterization of All Known Potential Error Sources and Achieve More Than Order of Magnitude Precision Improvement vs. Consumer

Parameter	Typical Industrial Spec	Units	Delta Improvement over Typical Consumer Device
Gyroscopes			
Dynamic Range	Up to 2000	°/sec	~
Noise Denisty	0.004	°/sec/√Hz rms	2×
Angular Random Walk	0.2	°/√Hr	2×
In-Run Stability	6	°/hr	3×
Bias Repeatability	0.2	°/sec	100×
–3 dB Bandwidth	465	Hz	2×
Accelerometers			
Dynamic Range	Up to 40	*g*	3×
Noise Denisty	25	μ*g*/√Hz	10×
Velocity Random Walk	0.03	m/s/√Hr	10×
In-Run Stability	10	micro-*g*	10×
Bias Repeatability	25	mg	100×
–3 dB Bandwidth	500	Hz	2×
Axial Alignment	0.05	deg	20×
Linear Acceleration Effect	0.01	°/sec/*g*	10×
Vibration Rectification	0.004	°/sec/g^2	10×
Sensitivity Tempco	25	ppm/°C	10×
Bias Tempco	0.007	°/s/°C	10×

Designers of precision instrumentation are typically most interested in working with inertial measurement units (IMUs), which output calibrated *g* and rate rather than angle or distance traveled, as this system-level information is highly application-specific, and thus is the focus activity of the system designer, rather than the inertial sensor designer. The issue this creates is in discerning, for instance, pointing accuracy from an inertial sensor specification table.

In Table 6, the specifications of a mid-level industrial device are shown in comparison to a typical consumer sensor that may be found in a mobile phone. Note that higher end industrial devices are also available, which are an order of magnitude better than those shown. Most low end consumer devices do not provide specifications for parameters such as linear acceleration effect, vibration rectification, angular random walk, and other parameters that actually can be the largest error sources in industrial applications.

This sample industrial sensor is designed for use in a scenario anticipating relatively rapid or extreme movement (2000°/sec, 40 *g*), where a wide bandwidth sensor output is also critical to enable best discrimination of signal. Minimum drift of offset during operation (in-run stability) is desired to reduce the reliance on a larger suite of complementary sensors to correct performance, and, in some cases, minimization of turn-on drift (repeatability) is critical in applications that cannot afford the time required for back-end system filtering corrections. Low noise accelerometers are used in cooperation with gyroscopes to help distinguish and correct for any *g*-related drift.

The gyroscope sensors have actually been designed to directly eliminate the effect of any *g*-event (vibration, shock, acceleration, gravity) on the device offset, providing a substantial advantage in the linear-*g* term, and via calibration, both temperature drift and alignment have been corrected. Without alignment correction, a typical multi-axis MEMS device, even when integrated into a single silicon structure, can be misaligned to the point of being the major contributor to an error budget.

While noise has become less of a distinguishing factor among sensor classes in recent years, parameters such as linear-*g* effect and misalignment, which are most costly to improve either through silicon design approach or through part-specific calibration, become noise adders in any application beyond simple or relatively static motion determination.

Can Sensor Fusion Fix a Poor Quality Sensor?

Simply, no. Sensor fusion is filtering and algorithms that merge or manage the sensor combination, relative to the environment, motion-dynamics, and application-state. It can provide for deterministic corrections such as temperature compensation and it will manage the hand-off from one sensor to another based on system-state knowledge. However, it does not fix inherent deficiencies in sensors.

The most critical task in a sensor fusion design is first developing a deep knowledge of the application-state to drive the rest of the design process. The selection of appropriate sensors for a given application is followed by detailed analysis to understand their weighting (relevance) during different phases of the overall mission. In the example case of pedestrian dead reckoning, the solution is dictated primarily by available equipment (for example, embedded sensors in a smart phone), rather than by designing for performance. As such, there is a heavy reliance on GPS with the other available sensors such as embedded inertial and magnetic, offering only a small percentage contribution to the task of determining useful position information. This works reasonably well outside, but in a challenged urban environment or indoors, GPS is not available, and the quality of the other available sensors is poor, leaving a large gap, or in other words, uncertainty in the quality of the position information. Though advanced filters and algorithms are typically employed to merge these sensors without either additional sensors or better quality sensors, the software does little to actually close the uncertainty gap, which ultimately significantly lowers the confidence in the reported position. This is conceptually illustrated in Figure 4.

In stark contrast, the industrial dead reckoning scenario is designed for performance with system definition and component selection guided by specific accuracy requirements. Significantly better quality inertial sensors allow them to take the primary role, with other sensors carefully leveraged to reduce the uncertainty gap. Algorithms are conceptually more focused on optimal weighting, hand-off, and cross-correlation between the sensors, along with an awareness of environment and real-time motion dynamics, than they are on extrapolating/estimating position between reliable sensor readings.

Accuracy in either case can be enhanced via improved quality sensors and while the sensor filtering and algorithms are a critical part of the solution, they do not by themselves eliminate the gap in coverage from limited quality sensors.

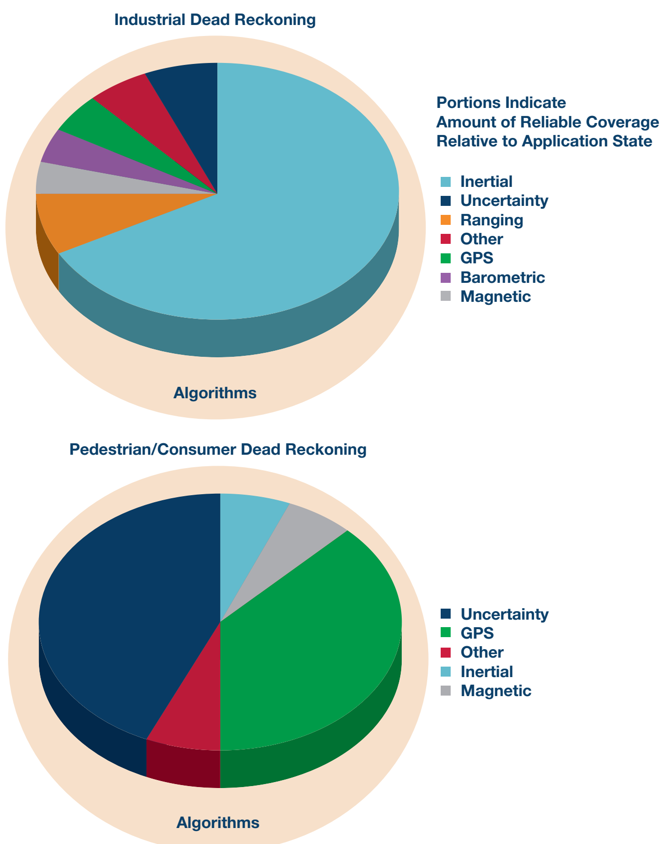

Figure 4. Application level precision determined by sensor quality, not by sensor fusion sophistication.

New classes of industrial sensors are providing performance nearly equal to that which was used to guide missiles in previous generations. Leveraging sensor architectures that were originally envisioned for reliable and precise use in automotive applications and built on economically viable and scalable processes, these new generation industrial sensors are fully unique in their performance-to-cost and performance-to-size ratio, as seen in Figure 5.

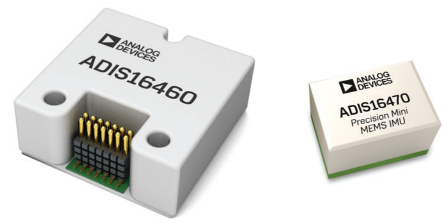

Figure 5. Industrial six degrees of freedom IMUs ADIS1647x and ADIS1646x, specified for precision even within complex and dynamic environments.

Precision motion sensing is no longer isolated to niche applications that had no choice but to afford investment in otherwise prohibitively expensive tracking solutions. With industrial grade precision available in mini-IMU form factors, IoT designers can now multiply the value they deliver through the integration of quality motion sensing, combined with their embedded contextual sensing to enable the IoMT.

About the Author

Bob Scannell is a business development manager for ADI's MEMS inertial sensor products. He has been with ADI for over 20 years in various technical marketing and business development functions, ranging from sensors to DSP to wireless, and previously worked at Rockwell International in both design and marketing. He holds a Bachelor of Science degree in electrical engineering from UCLA (University of California, Los Angeles), and a Master of Science in computer engineering from USC (University of Southern California).

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