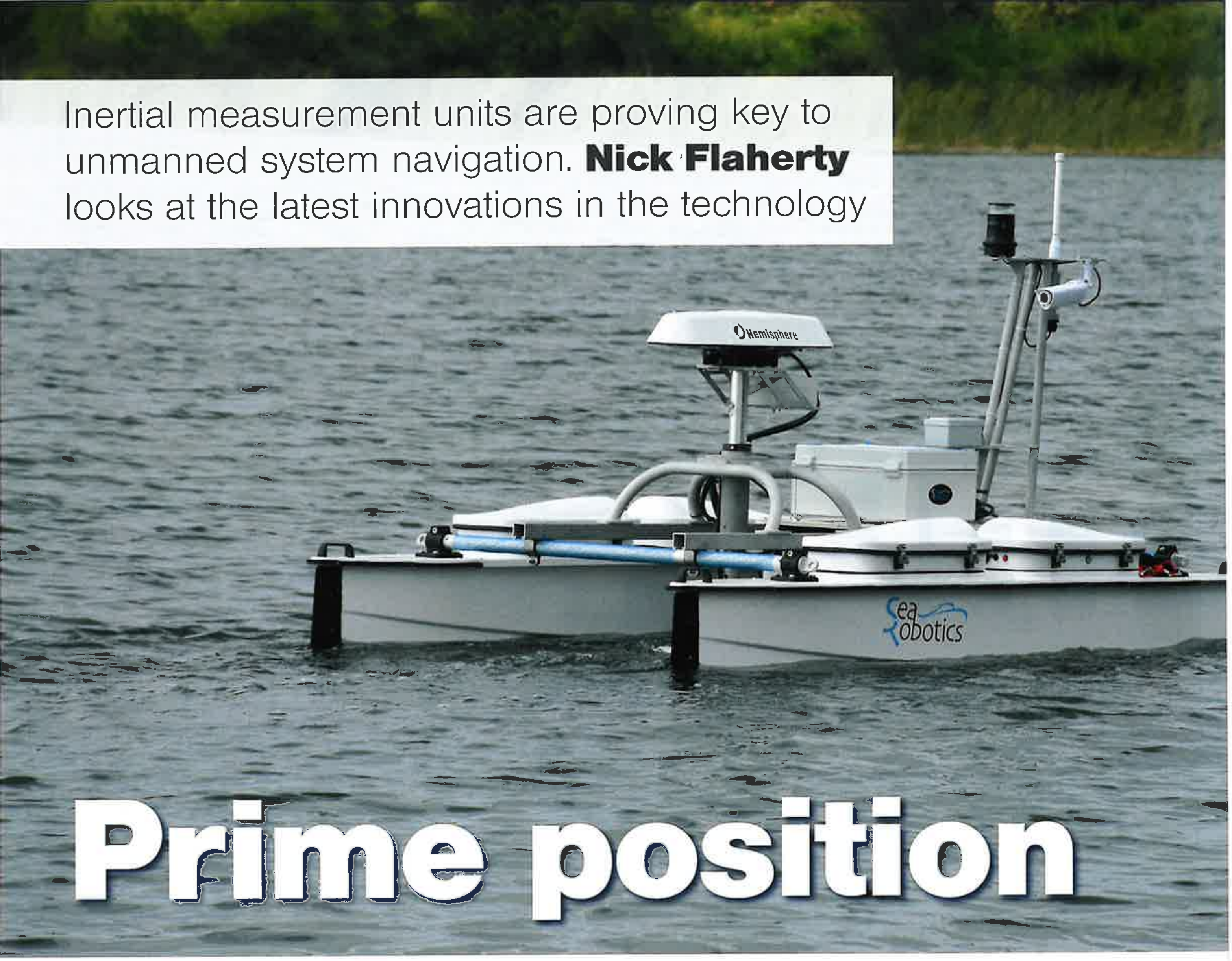
Inertial measurement units are proving key to unmanned system navigation. **Nick Flaherty** looks at the latest innovations in the technology



Prime position

In these days of global satellite networks, it may seem that inertial navigation is an old-school technology, but the need to know the exact location of an unmanned system has never been more important, and inertial measurement technology is an essential element in the system's design, no matter which realm it operates in. Driverless cars for example need reliable data that is accurate to the nearest centimetre, while UAVs need data in all three dimensions, and at sea the height of the waves becomes a vital data point.

All these different requirements are driving innovation in both the sensors and the software of the latest inertial measurement units (IMUs). IMUs can also be used in payloads such as cameras or Lidar laser mapping systems to provide a separate source of location data.

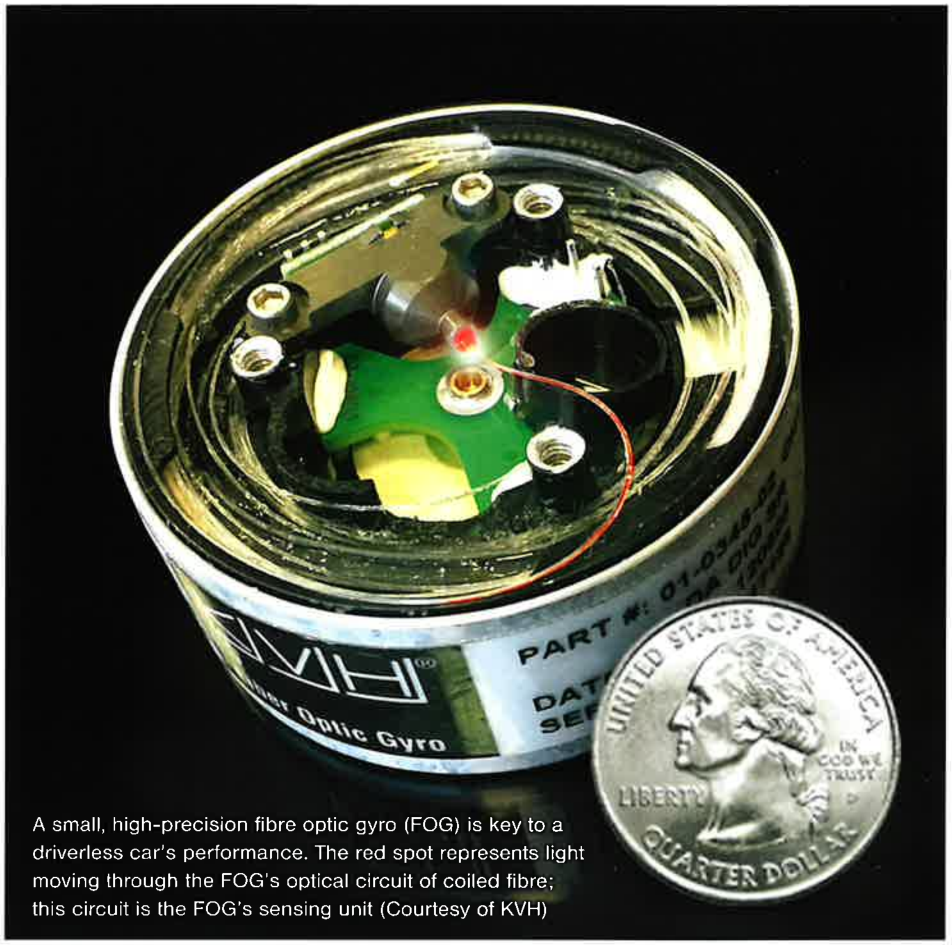
That allows the payload to be separate from the craft's navigation system, making installation easier by requiring fewer connections between the navigation system and the payload. It also allows the payload to have a higher accuracy for the positioning data from the craft, for example for surveying in environments where data accurate to the centimetre or even the millimetre may be needed and satellite navigation isn't good enough.

An IMU consists of several elements, and is based around an accelerometer for measuring acceleration and a gyroscope for measuring rotation to provide position data relative to a known point. Other elements such as a magnetometer, to measure the local magnetic field, and temperature and pressure sensors – and even an altimeter – can also be added to boost the accuracy of the data coming out of the device.

An inertial measurement system (IMS) meanwhile adds in satellite navigation elements such as receivers for the GPS, Galileo or GLONASS systems. The GNSS data can feed either into the IMU, creating an IMS, or directly into a craft's navigation system.

That means there are many different specifications for an IMU depending on the application, which gives opportunities

IMUs for marine systems sometimes need highly accurate measurement of the height of a craft above water level, requiring more complex signal processing algorithm design (Courtesy of SBG)



A small, high-precision fibre optic gyro (FOG) is key to a driverless car's performance. The red spot represents light moving through the FOG's optical circuit of coiled fibre; this circuit is the FOG's sensing unit (Courtesy of KVH)

for developers to differentiate the design; it also has an impact on the design of the sensors. For example, driverless car IMUs will need two-axis accelerometers and gyros because the third axis, height, is less relevant. By contrast, accelerometers developed for safety applications where early notification of tipping (as in a change in height) is essential will need a three-axis sensor.

This design approach can be extended to using different types of sensors on different axes. For example, a marine IMU may need more accurate height information from the motion of waves (called the 'heave') so the vertical axis would have a sensor with higher accuracy but a lower dynamic range (as the wave height doesn't change very quickly). That is very different from a UAV where the height can change quickly, and here the height data can be supplemented with an altimeter or pressure sensor.

Technologies

All of this means there is room for many different types of sensor technology in an IMU's design, depending on the performance and reliability requirements. IMU makers therefore regularly assess the various sensors on the market, often choosing technologies depending on the application and even the axis being measured.

These technologies can range from the early laser-based ring gyros to more modern fibre optic gyros (FOGs) and oscillating piezoelectric gyros, as well as micromachined MEMS devices. Similarly, accelerometers can be designed in different ways, based around quartz crystals or different MEMS structures.

While MEMS devices are smaller and lower power than other accelerometer and gyro technologies, they have struggled in the past to reach the performance levels required for IMU designs, although that is changing. At the other end, FOG devices – while highly accurate and reliable, having no moving parts – have been too large and costly for many mobile applications, but that too is changing.

The performance of an IMU is a complex combination of sensor technology, the packaging of the sensors, the accuracy of the test and calibration data and the associated algorithms, as well as the algorithms and software implementation in the navigation system. Changes in sensor design, the type of packaging and the software all have an impact on the performance of the overall system.

For example, specific design skills are needed when integrating sensors in more rugged, ceramic

A cylindrical gyroscope uses a quartz crystal with no moving parts to achieve higher reliability (Courtesy of Innalabs)

packages. While they provide more protection against vibration, their use is not as straightforward as with plastic encapsulated devices, as designers need to consider the thermal effects. Ceramic will not expand as much as the printed circuit board underneath, which can cause the connections between the package and the board to break if there is a thermal mismatch.

Fibre

The advent of the semiconductor laser has dramatically reduced the cost, size and power consumption of the FOG. The laser uses two opposing beams in the same fibre optic cable, which can be up to 5 km long, and changes in the rotation of the device can be detected through an interferometer. These have been used in larger unmanned aircraft but have often been too heavy and costly for smaller systems.

Modern semiconductor processes allow the fibre to be easily connected to the laser cavity (self-aligned), eliminating a costly step in the manufacturing. A key advantage of a FOG is that it has no moving parts, so the reliability is higher than with MEMS devices.

> Researchers have been able to build quantum sensors that cool a cloud of ions so that the quantum states are entangled

In one development, a FOG has been combined with low-noise MEMS accelerometers for an IMU with a diameter of 88.9 x 73.7 mm (3.5 x 2.9 in), a weight of 700 g and a typical power consumption of 5 W. While this level of technology is used for weapons systems, the same FOG is used in several prototype driverless vehicles and unmanned underwater systems.

These provide precise azimuth measurements that an autonomous car's logic processing unit and control systems need in order to determine motion through a curve. One IMU includes a FOG and accelerometers in a compact, lightweight package to provide six degrees of freedom and acceleration data to precisely track the position and orientation of the car, even when GPS is unavailable, helping the car stay on course.

A FOG IMU was also an integral part in a competition designed to showcase robots capable of intervening for and even replacing humans in high-risk situations such as fires, earthquakes and other natural disasters. This highlights that FOG gyros continue to have a major role to play in many unmanned system designs.

Fibre ring laser gyros are also still used for IMU systems, although more so in maritime applications as these can be large and power-hungry. They use multiple lasers in a cavity to detect changes in rotation.

Quartz

A quartz-based accelerometer can provide higher reliability for navigation applications as it also has no moving parts, relying on the response of an electrically stimulated crystal. This can deliver a mean time between failures of 500,000 hours, or 17 years, compared with five years for a FOG.

Bias stability (the measure of the bias performance) is one of the key factors in the choice of an accelerometer. This is the offset for the sensor, and should be as linear and repeatable as possible, as hysteresis in the bias leads to errors that cannot be resolved by compensation.

The accelerometer, while larger than a MEMS sensor, also provides a bias of less than 4 mg and less than 160 µg for repeatability, which is a big difference from a MEMS accelerometer. A crystal accelerometer is also more resistant to shock and vibration than a MEMS sensor.

Quantum sensors

The next level of accuracy for gyroscopes comes from quantum effects. Researchers have already been able to build wafer-level quantum sensors that assemble a cloud of ions, confine them and cool them down with a semiconductor laser and diffraction gratings so that the quantum states become entangled. Tiny changes in acceleration can be detected by the entangled ions, providing an accelerometer or a gyro.

A standard MEMS process is used to build channels and cantilevers with gold electrodes that confine the ion cloud on a series of chips on a 4 in silicon wafer that can be used as a single-axis gyro. A prototype unit, the size of a shoebox, uses semiconductor lasers to cool a million rubidium ions for use as the sensor and has been tested at sea in a submarine. The sensitivity of the sensor is such that it is affected by the mass of any nearby undersea mountain ranges.

MEMS

The biggest advance in IMU technology in recent years however has been the improvement in MEMS sensors.

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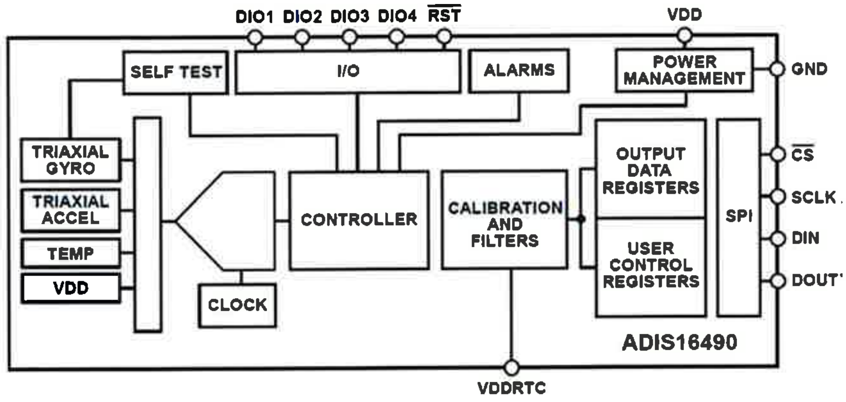
Controlling the design of the IMU from the manufacture and packaging of the MEMS sensor all the way through to the compensation electronics enhances the performance of the overall system (Courtesy of Silicon Sensing)



Compensation of the MEMS-based accelerometers and gyroscopes in a tactical-grade IMU can be handled by a dedicated digital signal processor (Courtesy of Analog Devices)

MEMS-based accelerometers and gyro sensors can use similar structures, although the gyro sensors are made to resonate in order to pick up changes in orientation, so advances in the design of the MEMS structures benefits both types of sensor.

The automotive industry has driven the development of MEMS sensors, particularly accelerometers, which are used to trigger airbags in a crash, and for stability control. While this has delivered high-volume production though, the packaging is optimised for the automotive environment and may not be suitable for the higher performance requirements of an IMU.

MEMS-based IMUs can now compare with FOG-based systems in terms of accuracy, and do not necessarily have the export restrictions that can apply to FOG sensors.

This advance in MEMS-based sensor performance has been achieved through a combination of packaging and the software algorithms. By moving to packaging that allows the sensor to be in a hard vacuum, the sensor's quality factor (also called the Q) can be boosted from 500 (in standard plastic packaging) to 30,000.

This high Q gives a bias of 0.1°/hour, comparable to FOG-based systems, and compares to a bias (or drift) of degrees per second for commercial devices. Developing that packaging technology for mass production was a major step forward in its own right.

There are many different types of structure for MEMS sensors, although all MEMS gyroscopes make use of the Coriolis effect, which can be detected more easily on small structures than large ones. By resonating a micromachined structure so that its mass is vibrating towards and away from the centre of rotation, any tangential movement can be measured to provide the angular velocity.

Some MEMS sensors use a large mass that responds to the change in direction, some have rings that are excited by permanent magnets, while others use ceramic piezoelectric materials to provide the resonance. These all have different responses, from linearity to dynamic range.

Using semiconductor manufacturing techniques allows several devices to be built on one piece of silicon with the associated control-loop signal processing. While that may be suitable for developers who control the sensor's design and manufacturing to produce an IMU though, it may not suit a third-party IMU integrator who uses different types of sensor on different axes of a unit.

Controlling the entire process allows developers to optimise each element of the IMU, however, from the design of the sensor to the feedback loop and signal conditioning for the sensor data, as well as the packaging of the sensor and the IMU. It also allows more knowledge of the performance of the sensor over time, which is a key element in building a calibration model of the IMU.

Many MEMS sensors have an open-loop output, which means they just provide the raw data from the sensor. Sensor makers though are moving to a closed-loop output to improve the accuracy, adding in signal processing alongside the sensor to compensate for known effects.

Operating in a closed-loop mode gives better scale-factor performance for navigation calculations by minimising errors, and this is currently a major focus for IMU designers. The closed-loop performance of MEMS IMUs is approaching that of open-loop FOGs but still not challenging closed-loop FOG units.

Size

The advantage of MEMS sensors is that they allow a smaller IMU design. They are down to 5 cm^3 for an 82 cm^3 module, and even under 2 cm^3 with a housing of 29 cm^3. There is a trade-off however between IMU size and performance, as larger sensors provide higher performance. That means there is pressure on the supporting electronics to be made even smaller to reduce the overall size of the housing.

One sensor and IMU maker has been working with a US research agency to get the sensor design under 1 cm^3 to meet the target of an IMU that is under 100 mm^3 (that is, less than 5 mm on a side). This can be achieved with chip-scale MEMS sensors where the silicon sensor is not packaged and mounted directly on the board, with packaging around the whole IMU.

The issue with that though is the manufacturing yield of the IMU, because the construction is more like a chip module than a printed circuit board. A lower manufacturing yield drives up the cost of course, which is already higher for such a small system.

Coupling accelerometers, gyroscopes and GPS/GNSS data through an extended Kalman filter in an IMU provides position, velocity and attitude that can be orders of magnitude better than a standard navigation system (Courtesy of Vector Navigation)

Other sensors

There are some cases where magnetometer information can be used for heading, orientation or spin rate but that can be very challenging in real-world conditions when dealing with the metal on the platform, such as in the motors. MEMS-based magnetometers with a U-shaped cantilever beam also provide a comparison with the gyros by checking how often the craft turns.

MEMS-based pressure sensors can also be used as altimeters, again checking that the results of the IMU's output are correct.

Building an IMU

Selecting the best type of sensor for a given application is a key part of building an IMU, and that can mean using several different types of sensor.

In a high-end IMU for example, two different MEMS gyros are used on each of three axes, with each using different technologies to give different resolutions and dynamic ranges. The IMU then blends the data from each of those sensors to give the result for that axis.

This keeps the dynamic range very low to get better resolution. If the IMU is rotated too quickly, data is lost from the precision gyro, but the less accurate one has a higher dynamic range so the data is still captured.

That is particularly useful for vehicles that need guidance but which are not turning or accelerating quickly. These high-end systems are providing a bias stability of 0.1°/hour and an angular random walk of 0.01°/route-hour.

This level of performance is necessary in autonomous cars that need positional data that is accurate to a centimetre over a 500 m stretch, especially in an urban canyon where no navigation satellites are ‘visible’. The car needs to keep moving even if there is uncertainty over the position, as it cannot just stop in the middle of the road.

> Selecting the best type of sensor is a key part of building an IMU, and that can mean using several different types of sensor

Calibration

Calibrating an IMU is an essential part of its development. To evaluate its response to acceleration and turns, the unit is tested on an arm that accelerates and rotates in two axes in a custom chamber.

The resulting data, with temperature response and bias stability, is used to build a model of the unit's performance, rather than just using a look-up table from the raw data. The model, built with second- or third-order polynomial equations or Kalman filters, is then used to provide the data for temperature compensation in the device.

That means the linearity of the sensors is an essential parameter so that the model can be as accurate as possible. This feeds back into the design of the sensor's structure to enhance the linearity of the response over other factors such as dynamic range.

Temperature compensation is handled by signal processing within the IMU. It can be implemented by a dedicated digital signal processor (DSP), but the increasing performance of low-power embedded microcontrollers from ARM is providing sufficient performance. The latest Cortex-M4 processors with floating-point and DSP extensions are suitable for this, and are available from a range of chip suppliers.

The microcontrollers can run a

combination of control code and DSP code, which also allows an IMU developer to innovate with software. In addition, a real-time operating system (RTOS) can run on the microcontroller to provide a range of other data fusion capabilities.

The controller board and RTOS can be used with different accelerometer and gyro sensors to provide a range of IMUs with different performance characteristics.

The range of chips with the same controller core also support different interfaces such as SPI for UAVs or CAN for autonomous vehicles; the chips can include a single or dual core to handle a wider range of tasks.

With this processing power the IMU can then act as the data fusion controller, taking in GNSS data and other information to provide more accurate position data.

The calibrated output of the sensors is fed into a Kalman filter, and combined with the GNSS signal position and velocity data to provide the best position data. Everything is done in the Kalman filter using kinematic equations; one IMU developer provides different motion profiles as presets for the Kalman filter depending on the application.

A larger IMU can provide more accurate position data, but the challenge for designers is to provide higher accuracy in smaller packages (Courtesy of SBG)

The RTOS can also be used to implement filters that reject outliers of the GPS signal: when an incorrect

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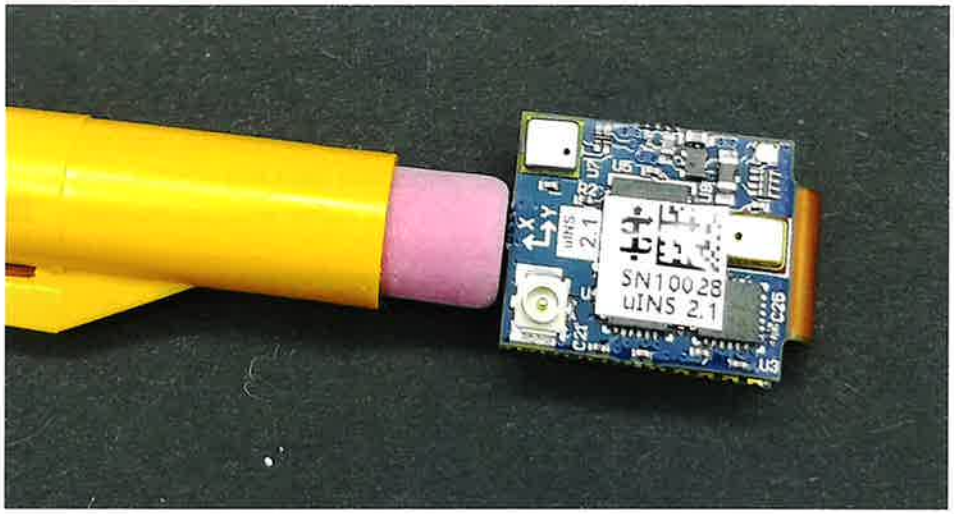
MEMS-based IMUs and IMSs that include GNSS satellite navigation are shrinking in size (Courtesy of Inertial Sense)



The processing power of dual-core controllers is allowing software to add more features while allowing complex calculations

data point that lies outside the range of previous readings is detected, it can be discarded and the inertial data used instead.

This is particularly useful in harsh environments where there can be multi-path effects resulting from reflections of the satellite signal that are picked up at a slightly different time from the original, increasing the error of the position data.

The IMU can also take in other data such as odometer signals, which are accessed via a driverless car's existing CAN network. This signal is used as an external input to the IMU in the same way as GNSS to provide more data.

Marine applications for IMUs have additional challenges, particularly in accounting for the motion of waves. Called motion reference units, they are compensated and packaged specifically for the marine market for measuring much lower acceleration, typically 0.01-0.04 m/s^2, and surviving in much harsher environments.

The challenges include a 'heave output' – a measure of the instantaneous height of the craft compared to sea level, something that is required for sonar applications. While heave output can be delivered in real time, an RTOS can also be used to provide a highly accurate output.

This can take a few hundred seconds to deliver but the data is time-stamped by the RTOS so that it can be integrated into a survey and mapping system to improve the quality of the mapping data.

Another development is that IMUs with lower resolution but less drift are gaining interest in unmanned submersibles. The lower drift allows the craft to stay submerged for longer before surfacing to get a GNSS fix.

Conclusion

The next few years will see a change in the FOG market as MEMS-based IMUs become more precise, especially compared to FOG systems. Although closed-loop MEMS devices will provide higher accuracy, closed-loop FOGs will still be used for high-end compass applications.

Many IMU developers are focusing on providing ever-greater performance at a specific price point and size. Also, the additional processing power of dual-core microcontrollers is allowing software such as a RTOS to add more features, at the same time as allowing more complex floating-point calculations.

Advances in packaging are also key to IMU development. More cost-effective sealed packages boost the performance of the sensors, while the size of IMUs is being driven down as board-level packaging technology

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Some examples of IMU, gyro & accelerometer suppliers

AUSTRALIA

Advanced Navigation
+61 290 993 830 www.advancednavigation.com.au

CANADA

Novatel
+1 403 295 4500 www.novatel.com

FRANCE

SBG
+33 180 884 500 www.sbg-systems.com
Schneider Electric
- www.schneider-electric.fr
Texense www.texense.com
+33 386 212 718

GERMANY

Bosch Sensortec
+49 7121 353 5900 www.bosch-sensortec.com
Northrop Grumman LITEF
+49 7614 9010 www.northropgrumman.litef.com

ISRAEL

MTC Industries
+972 499 87772 www.mtcind.com

NETHERLANDS

Xsens
+31 88 97367 00 www.xsens.com

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Sensonor
+47 3303 5000 www.sensonor.com

REPUBLIC OF IRELAND

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UAV Navigation
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Oxford Technical Solutions
+44 1869 238 015 www.oxts.com
Silicon Sensing
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Epson
- www.eea.epson.com
Inertial Sense
+1 801 610 6771 www.inertialsense.com
Innovative Automation Technologies
+1 352 224 5115 www.iat-llc.com
Gladiator Technologies
+1 425 396 0829 www.gladiatortechnologies.com
Honeywell
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Lord Microstrain
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improves. That will bring higher levels of performance with smaller size to more applications, from UAVs and driverless cars to payload systems.

Acknowledgements

The author thanks Alexis Guinamard at SBG Systems, Eric Whitley at Silicon Sensing, Chris Lund at Honeywell, Bob Scannell at Analog Devices, Edel Griffths at Innalabs, Jakub Maslikowski at Vector Navigation and Sean McCormack at KVH for their help with this article. ☐