UNMANNED systems TECHNOLOGY

Critical intelligence for land, sea and aerospace engineers

It's all panning out

Focus on new gimbal technologies

Is everything OK?

What autonomy means
for performance monitoring

Tool of the trade

How Reference Technologies' Hummingbird XRP
has been designed as the workhorse of UAVs

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Reliably informed

In this issue we look at the challenges of developing reliable unmanned systems for a wide range of applications. With legal operations beyond visual line of sight (BVLOS) on the way, UAVs will become suitable for a greater variety of tasks, as we highlight on page 46, looking at how new technologies are being integrated into existing platforms to enable new use-cases.

Our cover story on the Hummingbird XRP takes that forward, by looking at the way a platform can be developed using many rounds of testing to reach the most flexible design. We also discuss a new radial engine design for helicopter-type UAVs, on page 64.

When autonomous systems are used for so many applications, monitoring the platforms becomes even more important to ensure the systems can be used reliably. As we explain on page 82, machine learning and connections to the cloud are playing a growing role in monitoring the performance of ground systems and for tapping into the battery packs and autopilots of UAVs.

There is an irony here though that this is increasing the complexity of the system, and therefore potentially lowering its reliability. But monitoring the performance of an unmanned system in more detail, regardless of the application, gives engineers greater confidence that it can predict when it needs to return to base before a problem occurs.

That confidence will be a key part of the roll-out of unmanned systems for many applications in the coming years.

Nick Flaherty | Technology Editor

Editorial opportunities

Do you have a strong technical knowledge of one or more aspects of unmanned systems? As we grow we are on the lookout for experts who can contribute to these pages. If that sounds an interesting challenge then don't hesitate to explore the possibility of writing for us by emailing: **ian@ust-media.com**

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Editorial Director
Ian Bamsey

Assistant Editor
Guy Richards

Technology Editor
Nick Flaherty

Contributors
Peter Donaldson, Rory Jackson

Technical Consultants
Paul Weighell
Ian Williams-Wynn
Dr Donough Wilson

Design
Andrew Metcalfe
andrew@meticulousdesign.com

UST Ad Sales
Please direct all enquiries to
Simon Moss
simon@ust-media.com

Subscriptions
Freya Williams
freya@ust-media.com

Publishing Director
Simon Moss

General Manager
Chris Perry

Office Administrator
Frankie Robins

For all enquiries relating to unmannedsystemstechnology.com please contact:

EchoBlue Media Online Publisher
Caroline Rees
caroline@echobluemedia.com

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High Power Media Limited
Whitfield House, Cheddar Road,
Wedmore, Somerset,
BS28 4EJ, England
Tel: +44 (0)1934 713957
Fax: +44 (0)20 8497 2102
www.highpowermedia.com

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ALSO FROM HPM

Reaping reward of r&d

Ground vehicles

Researchers at Cambridge University have developed a vegetable-picking robot that uses machine learning to identify and harvest lettuce, a crop that has been difficult to harvest effectively (writes Nick Flaherty).

The Vegebot was initially trained to recognise and harvest Iceberg lettuce in a lab setting, but has now been successfully tested in various field conditions. Iceberg is the most common lettuce grown in the UK, but it is easily damaged and grows relatively flat to the ground, presenting a challenge for robotic harvesters.

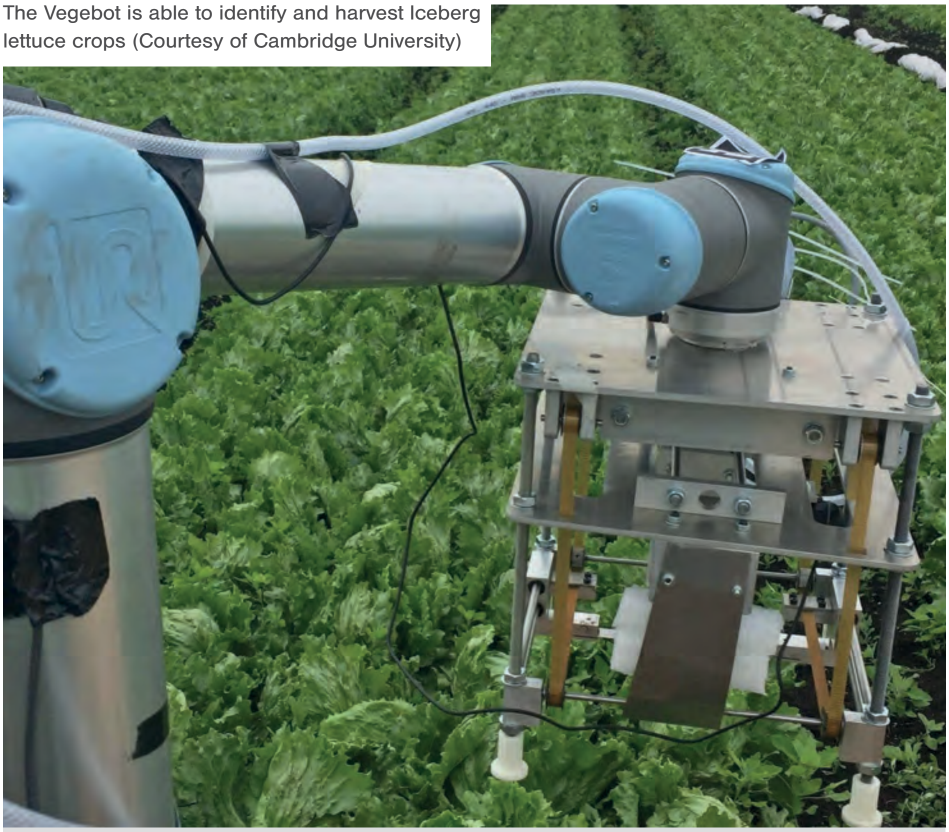
"Every field is different, every lettuce is different," said researcher Simon Birrell from the university's Department of Engineering. "But if we can make a robotic harvester work with Iceberg lettuce, we could also make it work with many other crops."

Julia Cai, who worked on the computer vision components of the system, added, "At the moment, harvesting is the only part of the lettuce lifecycle that is done manually, and physically it's very demanding."

An overhead camera in the Vegebot first identifies the 'target' crop in its field of vision, then determines whether a particular lettuce is healthy and ready to be harvested. It then cuts the lettuce from the rest of the plant at a height of 2 cm from the ground without crushing it.

"For a human, the entire process takes only a couple of seconds, but it's a really challenging problem for a robot," said researcher Josie Hughes.

The Vegebot is able to identify and harvest Iceberg lettuce crops (Courtesy of Cambridge University)



"We're also collecting lots of data about lettuce, such as which fields have the highest yields, which could be used to improve efficiency.

"We still have to speed up the Vegebot to the point where it could compete with a human, but we think robots have lots of potential in agritech."

The researchers developed and trained a machine learning algorithm on example images of lettuces. Once the Vegebot could recognise healthy lettuces in the lab, it was then trained in the field, in a variety of weather conditions and on thousands of real lettuces.

A second camera on the Vegebot is positioned near its cutting blade, to help ensure a smooth cut. The researchers were also able to adjust the pressure of the robot's gripping arm so that it held the lettuce firmly enough not to drop it, but not so firm as to crush it. The force of the grip can be adjusted for other crops.

The system also reduces food waste, as each field is typically harvested only once, and any unripe crop is discarded. It could be trained to pick only ripe vegetables, and since it could harvest round the clock, it could perform multiple passes on the same field, returning at a later date to harvest the vegetables that were previously unripe.

Swarm endurance boost

Airborne vehicles

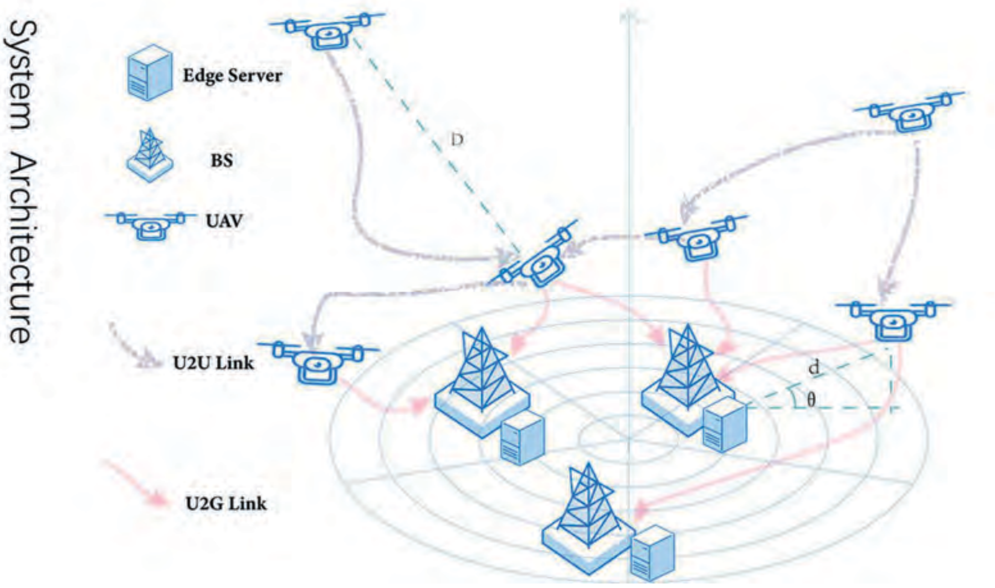
An energy-efficient data routing algorithm developed by an international team could keep UAV swarms flying for longer (writes Nick Flaherty).

In disaster support-and-recovery scenarios, when the local comms infrastructure has been destroyed, UAV swarms can be linked to one or more local base stations to provide comms links. Maintaining these links for as long as possible is essential.

"The battery capacity of UAVs is a critical shortcoming that limits their use in extended search-and-rescue missions," said team member Wuhui Chen, a researcher at China's Sun Yat-Sen University.

There is a major trade-off between the bandwidth requirements and the transmission time. So the team developed a data routing algorithm that uses multiple hops between members of the swarm.

This hybrid computational approach combines mainstream linear programming (LP) with a genetic algorithm. The adaptive LP-based genetic algorithm (ALPBGA) identifies the lowest energy route within a swarm in real time and simultaneously balances out the individual UAV power use, for example by determining which UAV will send information to a base station.



The data routing algorithm minimises energy use for comms across a swarm of UAVs (Courtesy of Wuhui Chen)

"By balancing power consumption among the UAVs, we can significantly boost the ability of the whole system," said Patrick Hung, a researcher at the University of Ontario Institute of Technology in Canada, and another member of the team. "Simulations show that our approach can outperform existing methods."

The simulations show that as swarm size increases from tens to hundreds of UAVs, the ALPBGA algorithm reduces the number of UAVs that stop communicating by 30-75% compared with other swarm communication algorithms.

The next move is to extend the ALPBGA research to different swarm flying trajectories to see how the positioning of the UAVs in the swarm can further reduce the overall energy consumption.

Cool idea for gas turbines

Propulsion

Engineers at Southwest Research Institute, in the US, have developed a 3D-printed impeller for a cooled, radial gas turbine (writes Nick Flaherty).

They say it can provide thousands of hours of electricity to a UAV – a significant improvement on current UAV turbines that operate for only a few hundred hours before wearing out.

The problem with current small turbines is that during the combustion process the turbine has to withstand the high-temperature gas, which can cause damage.

"We've designed a turbine that has tiny airflow passages that cool the turbine without sacrificing the power," said David Ransom of the institute's Mechanical Engineering division. "Normally with small turbines you have to choose between performance or reliability, but we're making it possible to have both."

The engineers used the internal passages of large, high-temperature turbines found in power plants and passenger aircraft. To create the small, intricate design with internal air passages, they used selective laser melting, which builds metal parts layer by layer.

Intelligent Energy's 2.4 kW fuel cell

Weight gain for hydrogen

Fuel cells

Intelligent Energy has developed a hydrogen fuel cell power module for unmanned vehicles up to 25 kg (writes Rory Jackson).

"It's a 2.4 kW fuel cell power module," said the company's Andy Kelly. "Much of the same technology has been used in it as in our 800 W product, but this one is aimed at much bigger UAVs, such as those with MTOWs of roughly 55 lb or 25 kg.

"It will give a UAV of that weight roughly 2 hours of flight when paired with an 11 litre 350 bar hydrogen gas cylinder."

The new system weighs 3250 g, measures 430 x 230 x 130 mm, and is rated to a peak power level of 4.8 kW (with 2.4 kW being the maximum continuous power output). It is being tested to operate at temperatures from -5 C to 40 C, up to a ceiling of 3 km.

It uses the same AC64 fuel cell stack technology as the company's other UAV power modules but with 144 cells integrated into the energy stack, compared with the 34 cells in the 800 W unit.

As this also means more heat being generated, and concentrated within the thicker cell volume, the 2.4 kW module comes with two cooling fans of 15 cm diameter each, compared with the two smaller fans of about 7.5 cm diameter each and a smaller overall vent area on the 800 W module.

> As this means more heat being generated, it comes with two cooling fans of 15 cm each

"That also means the 2.4 kW unit's cooling is more efficient overall, and is lighter and has a lower material cost just because there's more open space on the housing," Kelly added.

"We did a bit of CFD to check the cooling fans would be sufficient to dissipate the heat generated by the stack, but that was a relatively short test. We quickly moved on to real-world flow measuring equipment, which allowed us to judge exactly how to control the fan given the amount of heat we are dealing with."

The fans are driven by a T-Motor F40 Pro II electric motor and propeller, which has a 2400 kV rating, measures 23 mm across and uses a resin on the stator wires to insulate against temperatures of up to 240 C.

Also, and unlike Intelligent Energy's other systems, the 2.4 kW module is designed with a higher peak power range, allowing approved compatibility with VTOL aircraft. The system's two hybrid batteries have a peak power rating of 4.8 kW each by default, but technically the module can produce up to 8 kW and end-users can pair it with a larger battery if they so choose.

Each default battery has a capacity of 2700 mAh and weighs 340 g.

GNSS-free navigation

Airborne vehicles

Researchers at the Technical University of Munich (TUM) in Germany have demonstrated a system that eliminates the need for GNSS satellite navigation, and instead uses optical cameras for navigation and fully automated landing (writes Nick Flaherty).

Using an optical system allows UAVs to operate safely from smaller sites that do not have sophisticated equipment. The development is part of the C2Land project.

TUM's optical cameras provide automated aircraft landings without using ground-based systems (Courtesy of C2Land)

At large airports, the Instrument Landing System (ILS) allows commercial aircraft to land automatically with great precision. Antennas send radio signals to the autopilot to make sure it navigates to the runway safely.

Procedures are also currently being developed that will allow automatic landing based on satellite navigation. Here too a ground-based augmentation system is required.

However, such systems are not available for general aviation at smaller airports, which is a problem if visibility is poor, as aircraft simply cannot fly.

"Automatic landing is essential, especially in the context of the future role of aviation," said Martin Kugler, research associate at the TUM Chair of Flight System Dynamics. This is especially so for automated aircraft transporting freight and automated flying taxis, he said.

In the C2Land system, the autopilot uses GNSS satellite signals to navigate, but these are susceptible to measurement inaccuracies, for example owing to atmospheric disturbances, so pilots currently have to land a UAV craft by remote control.

To achieve a fully automated landing, a team from one of the project's partners, the Technical University of Braunschweig, therefore designed an optical reference system.

This consists of a camera operating in the normal visible range and an infrared camera that can also provide data under conditions with poor visibility. The researchers developed customised image processing software that lets the system determine where the aircraft is relative to the runway according to the camera data it receives.

The TUM team then used the optical reference system as part of a fully automatic control system in a research aircraft, a modified Diamond DA42. The aircraft has a fly-by-wire system, enabling control by means of an advanced autopilot, also developed by the TUM researchers.

To make automatic landings possible, additional functions were integrated into the software, such as comparison of data from the cameras with GPS signals, calculation of a virtual glide path for the landing approach as well as flight control for various phases of the approach.

The Photon 601 uses machine vision to identify landmarks to navigate without the need for a GNSS satellite signal (Courtesy of University of Samara)

In a similar development to that by TUM, researchers in Russia have also unveiled a UAV that uses optical cameras.

The Photon 601 was built by a team at Samara University to be independent of navigation systems such as GPS and GLONASS. Its navigation system recognises 'support points' such as landmarks on a map that are set beforehand along the route using gyro-stabilised optical and infrared cameras. These points are identified using machine learning in an image recognition system to provide course corrections.

The researchers have tested the 50 kg UAV, which has a range of 400 km and can fly up to an altitude of 5000 m. The video link has a range of 120 km.

The insect-inspired quadcopter's pivoting arms help to optimise its energy efficiency (Courtesy of Purdue University)

Insects help UAV design

Airborne vehicles

A team from Purdue University's School of Engineering Technology in the US has taken inspiration from insects to come up with a novel design for a quadcopter that involves actively pivoting the arms on which the rotors are mounted (writes Peter Donaldson).

Researchers Xiumin Diao, Jin Hu and Hao Xiong have published a paper describing their approach to optimising the energy efficiency of a quadrotor UAV by rotating its arms to positions derived from a dynamics model of the vehicle and the power-thrust curve of its rotors.

The design was inspired by the wings and flight patterns of insects, and includes folding arms that can make in-flight adjustments, said Diao. Pivoting the arms moves the centre of lift with respect to the centre of gravity, which stabilises the aircraft and, because it allows the use of the full range of rotor thrust, increases energy efficiency.

The researchers calculated the conditions under which the UAV can optimise its energy efficiency in steady-state flight, and analysed its efficiency in various scenarios. One scenario involved calculating the arm rotation approach that produced the best energy efficiency for a UAV in a steady hover with an offset centre of gravity.

In simulation, they demonstrated the ability to reduce energy consumption by 13% compared with a conventional design, and said experiments have shown that the same vehicle can make larger savings in practice.

The team plotted the power consumed by a rotor against the thrust generated by it, to gauge its efficiency. With torque sensors on each motor, they were able to measure bias torque along the *x* and *y* axes, plotting them against each other, against total thrust and against power, with low bias torque figures indicating greater efficiency.

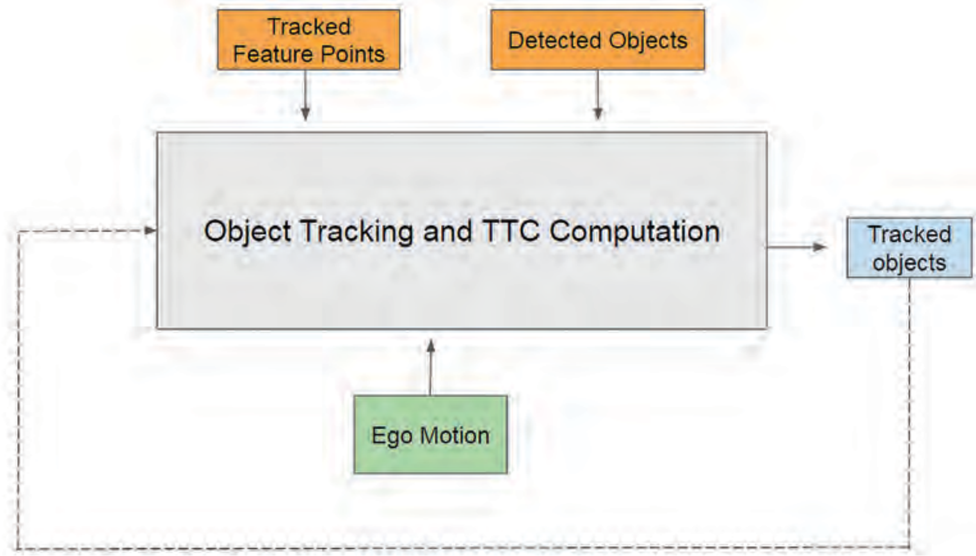
For example, comparing bias torque along the *y* axis for a conventional UAV with one with rotatable arms showed that the curve for the latter is much shallower, and rises to a lower peak of less than 300 W at 5 Nm compared with almost 350 W.

To each object its own ID

Vision systems

Nvidia has developed a six-camera system that tracks detected objects as they appear in consecutive camera images by assigning them unique ID numbers (writes Nick Flaherty).

Camera object tracking is an essential component of the surround camera vision pipeline of an autonomous vehicle, as it plays a critical role in robust distance-to-object and object velocity estimations. This can also mitigate missed and false-positive object detections and prevent them from propagating into the planning and control functions of a self-driving car. These functions are used to make decisions about stopping and accelerating.



Object tracking and TTC computation diagram of Nvidia's camera system

The system uses six cameras to avoid blind spots around the car. The software in it tracks objects in all six camera images, and associates their locations in image space with unique ID numbers as well as time-to-collision (TTC) estimates.

The surround camera object tracker predicts the object scale change, translation and TTC using specific points on the objects, and allows a latency of around 90 ms. This enables the car to respond properly to sudden stopping conditions, even in high-speed driving.

It also addressed the problem of ghost tracks of objects moving out of the scene, which are the main cause of false-positive braking. The tracker removes ghost tracks within 30-150 ms without causing object track misses.

However, running object detection on all six camera feeds for each image frame can increase the system's overall latency. Depending on the application, developers can choose to reduce object detection frequency and run the object detector once every three frames, for example. That would free up resources for other computations.

The system successfully tracked another car at a distance of 150 m with a 100 mph relative velocity differential, with the object detection running once every three frames.

The surround object tracking system has been successfully tested for more than 20,000 miles with a car in autonomous mode. The tests were performed in various seasons, routes, times of day, illumination conditions, highways and urban roads. No disengagements owing to object tracking failures were observed or reported.

Nvidia's DriveWork software development kit contains the object tracking module, which can run on a CPU or GPU to provide flexibility in the overall resource scheduling for the software pipeline.

The GPU implementation is seven times faster than the CPU implementation, but the software is flexible enough to have the object tracker on a CPU for one camera and on the GPU for the other five.

Radar can spot mini-UAVs

Detection

Researchers at the Daegu Gyeongbuk Institute of Science and Technology in South Korea have developed a radar system that can detect miniature UAVs at a distance of over 3 km (writes Nick Flaherty).

The system, developed by researcher Daegun Oh and his team, operates at between 12 and 18 GHz, and uses a combination of an active electronically scanned array with a type of neural net called a generative adversarial network (GAN). The GAN has two neural nets that compete to produce the best results to pick up UAVs weighing as little as 500 g.

Rangefinder plays it safe

Sensors

Attollo Engineering has unveiled a laser rangefinder called the WASP-200 LRF, which comes in two variants – one with Ardupilot/Pixhawk flight controller compatibility, the other for CAN bus systems (writes Rory Jackson).

The WASP-200 LRF incorporates a 905 nm laser source with a 56 Hz update rate and a very sensitive receiver circuit. The system is FDA-certified as a Class 1 laser device, meaning it is safe for normal use including the use of typical magnifying optics.

This is an important distinction, as many other rangefinders in this range class are designated as the less safe Class 1M. Attollo also offers a higher repetition rate of 10 kHz and multi-emitter systems to meet a variety of customer needs.

"It has also been designed as a single-shot system – one laser pulse is sent and received, and we know exactly how far away the object being detected is with that single pulse," the company's Tony Vengel explained. "Most laser rangefinders in this industry need to use several pulses, then let the signal dwell and build up before giving a reading.

"Our speed and accuracy comes partly from the design of the receiver and laser transmitter circuits, and from the signal processing algorithms we've developed. We can also algorithmically accommodate for excessive solar background radiation and obscurants."

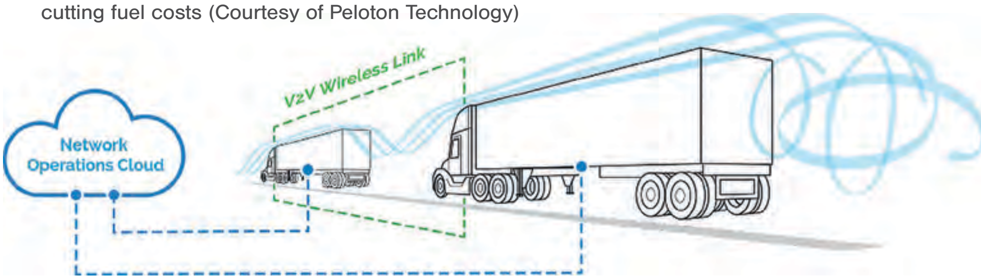
Unusually for the industry, the WASP-200 LRF is a single-shot system

These features allow the WASP-200 to be used for range measurements over water and in dusty environments, such as for industrial survey, sense-and-avoid systems, and other missions. It is housed in an ABS enclosure and weighs 26 g in its Ardupilot/Pixhawk configuration or 44 g in its CAN bus configuration, which includes IP67 protection.

Platooning via the cloud

Platooning

The technology allows one truck to follow another, cutting fuel costs (Courtesy of Peloton Technology)



Peloton Technology has launched a Level 4 ‘automated following’ system for trucks based on access to remote servers in the cloud (writes Nick Flaherty).

It uses 802.11p DSRC at 5.9 GHz to enable a single driver to control a pair of vehicles with a separation of less than 50 ft (15 m).

The PlatoonPro system has a driver in both the lead and following trucks in case the two need to separate. The driver in the following truck steers, but the system controls the powertrain and brakes to manage the following distance precisely and provide immediate reaction to whatever acceleration or braking the lead truck performs.

A V2V link allows the human-driven lead truck to guide the steering, acceleration and braking of the following truck and connects the safety systems between the trucks.

The two trucks are connected to a network operation cloud (NOC) via an encrypted 4G cellular link. The NOC supervises the Peloton system, approving and authorising driver pairs to form a platoon.

The Peloton cloud monitors real-time traffic, weather, construction and other driving conditions, to make sure platooning happens only if it’s safe to do so. If it isn’t, the cloud will withdraw the ability to platoon for a particular segment of the route, which still requires the driver in the second vehicle.

It also provides information and alerts to truck drivers about any traffic slowdowns ahead.

A key element of the NOC is coordinating the platooning. Even when the two trucks are from the same fleet and are leaving at roughly the same time, coordinating them is a critical feature to maximise platooning mileage and minimise or eliminate delays.

Fleet managers use the NOC as a matching service for platooning, pairing trucks and drivers according to various factors. The Peloton cloud determines whether the trucks and drivers trying to platoon are compatible before pairing them, looking at whether the intended routes are similar and how much overlap they have in their schedules and choice of roads.

The NOC is also built to tie in to fleet management systems and in-house systems of fleet operators. This allows it to combine data from the platooning with third-party data to develop analytics for fleet customers about safe driving conditions as well as fuel use, driver evaluations and other platooning statistics.

PlatoonPro has now been used by six customers, and additional customer fleet trials are underway. Tests have shown fuel savings averaging more than 7%, with 90% of the miles travelled in platoon mode, up to 700 miles per truck.

3D-printed parts can stand the heat

Manufacturing

CRP Technology has developed the first flame-retardant polyamide material for 3D-printing components that can withstand temperatures of up to 180 C (writes Nick Flaherty).

The Windform FR (Flame Retardant) 1 material is the first such material with carbon fibre reinforcement that is qualified to the UL 94 V-0 burn rating, making it suitable for aircraft and aerospace applications.

It has also passed the 12 and 15 s FAR 25.853 horizontal flammability tests as well as the 45° Bunsen burner test. This allows it to be used in 3D printers for aerospace designs such as interior parts, cockpit, air conditioning piping, air ducts and air outlet valves as well as vehicle interiors, housings and enclosure assemblies in automotive designs.

3D-printed air conditioning piping produced using Windform FR1

The company said the material is also suitable for manufacturing components with detailed surface resolution.

The Kar-go uses 'terrain training' to allow fleets of them to be operated autonomously

Fleet expert in deliveries

Driverless vehicles

Kar-go has launched a production version of its autonomous delivery vehicle (writes Nick Flaherty).

Kar-go uses a 'terrain training' approach to enable each vehicle to become an expert in its particular route so that it can then focus on any abnormalities in that route. The vehicles will operate in fleets, each one delivering within a dedicated local area, so it never needs to drive too far in an untested environment.

The system has been designed by the Academy of Robotics in Wales, UK, for delivery applications.

It continuously scans under other vehicles on the road to determine if there is a moving object on the other side and what direction it is moving in. This is intended to enhance safety in busy residential streets by avoiding pedestrians.

The terrain training uses landmarks to get the exact position on a local route. For example, identifying a clearly visible bank 10 m away, a lamp post 10 m away and a cell tower 50 m away gives three points the Kar-go can use to triangulate its exact position, rather than relying on GNSS satellite navigation.

The system uses modules rather than a single controller for functions such as lane and object detection. This modular structure means the final outputs relating to speed, steering and braking are not processed from a single module, but are the result of integrating perception and decision outcomes of multiple modules. That makes the system less sensitive to disturbances and noise.

Each module is designed to operate individually as well as collaboratively, as any module can take control in case another one fails.

A decision-making convolutional neural network (CNN) runs on Nvidia's Drive graphics processing unit. However, this is not sufficient for effective operation, as it is a static, passive-vision system that perceives the world one frame at a time with no knowledge of prior frames. The CNN is also trained using a mathematical optimisation process, which is not how intelligence emerges in nature.

Instead the Kar-go uses a technique called long short-term recurrent networks, which are used in other domains such as natural language processing. They use a sequence of preceding frames to predict a new frame and then compare that predicted frame with the incoming data.

The controller also uses a 'continuous time-recurrent neural network' that also takes previous frames as the input. This algorithm changes on the basis of the content of the images it uses, evolving into a more accurate algorithm.

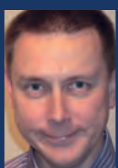
Addressing the challenge of communicating with humans and other autonomous vehicles, the vehicle's outer body is fitted with reflective screens and LED rings that can light up and change appearance in different scenarios. These help the Kar-go to communicate with other drivers and pedestrians during deliveries.

Unmanned Systems Technology's consultants

Dr Donough Wilson
Dr Wilson is innovation lead at aviation, defence, and homeland security innovation consultants, VIVID/futureVision. His defence innovations include the cockpit vision system that protects military aircrew from asymmetric high-energy laser attack. He was first to propose the automatic tracking and satellite download of airliner black box and cockpit voice recorder data in the event of an airliner's unplanned excursion from its assigned flight level or track.

For his 'outstanding and practical contribution to the safer operation of aircraft' he was awarded The Sir James Martin Award 2018/19, by the Honourable Company of Air Pilots.

Paul Weighell
Paul has been involved with electronics, computer design and programming since 1966. He has worked in the real-time and failsafe data acquisition and automation industry using mainframes, minis, micros and cloud-based hardware on applications as diverse as defence, Siberian gas pipeline control, UK nuclear power, robotics, the Thames Barrier, Formula One and automated financial trading systems.



Ian Williams-Wynn
Ian has been involved with unmanned and autonomous systems for more than 20 years. He started his career in the military, working with early prototype unmanned systems and exploiting imagery from a range of unmanned systems from global suppliers.

He has also been involved in ground-breaking research including novel power and propulsion systems, sensor technologies, communications, avionics and physical platforms.

His experience covers a broad spectrum of domains from space, air, maritime and ground, and in both defence and civil applications including, more recently, connected autonomous cars.

The OpenIMU300RI CAN bus IMU has an open source comms and navigation stack

IMU with CAN-do

Sensors

Sensor maker Acienna has developed an IMU with an interface to the CAN system commonly used in autonomous systems (writes Nick Flaherty).

The OpenIMU300RI is a nine-axis MEMS-based IMU that includes a CAN interface, an RS-232 interface, and an ARM Coretex M4 CPU. The OpenIMU's CPU can run both standard and custom algorithms created using an open source set of development tool.

In an autonomous vehicle, CAN is used to pass IMU data to other sensors as well as the main vehicle control, and some designs are using CAN bus to share IMU data with up to 20 other vehicle subsystems in parallel, such as Lidar, image cameras and radar.

The CAN specification has two standards for messages: CAN 2.0A with an 11-bit message identifier, and an alternative standard, CAN 2.0B, with a 29-bit message identifier. Both message types have a maximum data payload of only 8 bytes.

Standard CAN data rates are 250 kbit/s, 500 kbit/s and 1 Mbit/s. Driverless cars tend to use custom-defined messages with 11-bit identifiers, whereas heavy equipment vehicles more commonly use the 29-bit identifiers and define messages according to the J1939 standard. Recently some applications have started to use a newer CAN FD (Flexible Data-rate) protocol that supports data payloads up to 64 bytes.

That makes a CAN interface an increasingly convenient and reliable way to pass IMU data to one or more subsystems on the vehicle.

The open source approach allows engineers to write an application that can 'listen' to other messages on the bus. For example, Acienna's Dynamic Tilt algorithm could be enhanced by listening to messages such as odometer or vehicle speed to better compensate for the influence of linear acceleration on dynamic roll and pitch.

The application could also take data from the RS-232 port on the IMU from a GNSS satellite positioning sensor. This data can then be fused with the OpenIMU300RI's internal IMU data for full GNSS/INS sensor fusion.

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Industry

Defence & Security Equipment International (DSEI) remains the single largest exhibition and conference for governments, armed forces and industry leaders to gather together and discuss the latest issues and requirements of the global supply chains for defence and security technology.

The biennial event, being held on September 10-14, will host 1600-plus exhibitors from more than 60 countries, with a huge array of vehicle and technology manufacturers among them.

The newest unmanned vehicles are expected to continue being displayed prominently among the systems being exhibited and launched. The ability to efficiently and persistently acquire intelligence, surveillance and reconnaissance imagery using advanced UAVs and other unmanned systems is prized by security forces worldwide.

Furthermore, improvements in autonomy enable reductions in work burdens and personal risk to soldiers as well as police, firefighters, first responders and other key public services.

As ever, the event will be held at the ExCeL, in London's Docklands, and inside the many exhibitions halls, vehicles and tech will be arranged across zones corresponding to theatres of operation, with aerospace, land, naval, security and joint zones available. Outside on the Thames, there will be a naval zone for static displays and live demonstrations of new USV and UUV systems.

In addition, DSEI 2019 will hold its first ever 'Manufacturing Hub', which will showcase the materials, parts and services from Tier 2, 3 and 4 companies for engineers from the defence sector to investigate. The latest in CAD software, connectors, additive manufacturing and many other key technologies will be exhibited there too.

The conferences will feature more than 300 speakers from governments, militaries and companies to present up-to-date announcements and analyses on critical strategic and technological topics.

For more details go to **www.dsei.co.uk**

Intergeo and EDS 2019

Industry

Intergeo is the world's biggest trade show for geo-spatial and geo-referencing technologies, and has been held annually in various German cities since its inception in 1995.

Intergeo 2019 will run from September 17 to 19 in the Messe Stuttgart, and following the trend in the past few years, unmanned aerial and ground vehicles will feature more heavily than ever.

With last year's iteration of the event bringing together 640 exhibitors from 41 countries, as well as nearly 20,000 visitors, this year's Intergeo is expected to be larger still, particularly with Stuttgart's long-running history as a hub of cutting-edge vehicle engineering.

The show has consistently broadcast the capabilities of unmanned systems not only for agriculture and infrastructure inspections, but for a huge range of other industries and applications, such as real estate, construction, water management and environmental conservation.

Among the various sections of the show floor, Interaerial Solutions will be dedicated to UAV manufacturers, developers of software for geo-spatial survey and analysis, and producers of critical supporting components such as GNSS, data links and sensor payloads.

And this year's Intergeo will play host to the first ever European Drone Summit, a new conference programme dedicated to topics such as the safe integration of unmanned aircraft into national airspaces, security concerns and provisions, and vital urban applications of UAVs such as medical services.

For more information, go to **www.intergeo.de/intergeo-en**

UAV Technology Conference 2019

Industry

The 4th annual UAV Technology Conference will be held in London's Copthorne Tara Hotel from September 30 to October 1.

Dedicated to showcasing, discussing and analysing the latest capabilities of unmanned aircraft in multi-domain mission environments, the event will include presentations from dozens of high-ranking military personnel representing NATO and its member countries.

A range of strategic and technological issues will be discussed, including counter-UAS, ISR capabilities, swarming technology developments and the latest systems for guidance, navigation and comms.

For more details go to **www.uav-technology.org**

UST diary

Unmanned Systems – Defense. Protection. Security
Tuesday 20 August – Wednesday 21 August
Washington, DC, USA
www.thedefenseshow.org

UAS Summit & Expo
Tuesday 27 August – Wednesday 28 August
Grand Forks, ND, USA
www.theuassummit.com

InterDrone
Tuesday 3 September – Friday 6 September
Las Vegas, USA
www.interdrone.com

DSEI 2019
Monday 10 September –Thursday 13 September
London, UK
www.dsei.co.uk

Interaerial Solutions and Intergeo
Tuesday 17 September – Thursday 19 September
Stuttgart, Germany
www.interaerial-solutions.com

UAV Technology
Monday 30 September – Tuesday 1 October
London, UK
www.uav-technology.org/ustmag

Commercial UAV Expo Americas
Monday 28 October – Wednesday 30 October
Las Vegas, NV, USA
www.expouav.com

Advanced Engineering
Wednesday 30 October – Thursday 31 October
Birmingham, UK
www.easyfairs.com/advanced-engineering-2019/advanced-engineering-2019/

Unmanned Systems Canada
Wednesday 30 October – Friday 1 November
Ottawa, Canada
www.unmannedsystems.ca

The Commercial UAV Show
Tuesday 12 November – Wednesday 13 November
London, UK
www.terrapinn.com/exhibition/the-commercial-uav-show

TUS Expo
Tuesday 14 January – Wednesday 15 January 2020
Rotterdam, The Netherlands
www.tusexpo.com

UMEX
Sunday 23 February – Tuesday 25 February 2020
Abu Dhabi, UAE
www.umexabudhabi.ae

Oceanology International
Tuesday 17 March – Thursday 19 March 2020
London, UK
www.oceanologyinternational.com

Japan Drone
Wednesday 25 March – Friday 27 March 2020
Chiba, Japan
www.japan-drone.com

Global Robot Expo
Wednesday 1 April – Tuesday 2 April 2020
Madrid, Spain
www.globalrobotexpo.com

SOFIC 2020
Monday 11 May – Thursday 14 May 2020
Tampa, FL, USA
www.sofic.org

Unmanned Maritime Systems Technology
Wednesday 13 May – Thursday 14 May 2020
London, UK
www.smi-online.co.uk/defence/uk/conference/Unmanned-Maritime-Systems

DRONE Berlin Exhibition
Tuesday 26 May – Wednesday 27 May 2020
Berlin, Germany
www.drone-berlin.de

Eurosatory
Monday 8 June – Friday 12 June 2020
Paris, France
www.eurosatory.com

Autonomous Ship Technology Symposium
Tuesday 23 June – Thursday 25 June 2020
Amsterdam, The Netherlands
www.autonomousshipsymposium.com

Farnborough International Airshow
Monday 20 July – Sunday 26 July 2020
Farnborough, UK
www.farnboroughairshow.com

Based on a Jetstream regional airliner, the Surrogate UAV demonstrated technologies including sense and avoid, synthetic aperture radar and satcom for unmanned use (Images courtesy of BAE Systems)

For future reference

This futurist and technology strategy executive at BAE Systems shares his views on what lies ahead for UAVs with **Peter Donaldson**

Tornado jets sparked a passion for flight in a boy from Preston, in England's north-west. The fighters' charisma, combined with a passion for the natural world and a love of science fiction, steered Nick Colosimo towards a successful career as an engineer and futurist with BAE Systems.

Now 47, he has worked on various UAV programmes, including the Astraea airspace integration effort and the Mantis UAV technology demonstrator, and is now involved with the UK's Team Tempest future combat air system project, which is being designed to be optionally piloted and control groups of UAVs.

His love of nature had an engineering side to it, and he talks of obsessing over how nature solves problems such as the evolution of passive and active stealth by the hatchet fish. When it rises into shallow water in daylight to feed, this animal is in a position to be attacked from below by predators targeting its silhouette, but it has evolved highly reflective silvery sides.

"So the hatchet fish is in zero contrast against the pale background and can't be seen from any angle other than vertically underneath," he explains. This active measure eliminates the remainder of the silhouette with bioluminescence. "Its underbelly lights up as it rises up the water column."

Prof Colosimo regards these 'problem-solution analogies' drawn from nature as powerful and important in engineering. Faced with a problem, he asks whether there is another sector or domain in which a similar problem exists, how it was solved and how the solution might be transferred to the current problem.

Seen here in an anechoic chamber, the Mantis armed ISTAR UAV benefited from integration and testing work carried out by Colosimo's team aboard the Surrogate UAV

Futurist

The role of futurist involves identifying important trends across the political, economic, sociological, technological and environmental landscapes.

"These trends must be interpreted, allowing actions to be taken to mitigate future threats and to seize future opportunities early. It is really a scientific pursuit, as opposed to crystal ball-gazing," he says. "The wisdom of crowds and drawing on multiple sources of information are the keys to success."

Colosimo's involvement with robotics began as a boy studying computers and control technology at school in the 1980s, in a course he enjoyed for its mix of theory and hands-on construction. "I remember building a multi-layered security vault system as a project. That was all relays and transistors in terms of the control technology," he says.

After completing his schooling, at 18, he opted for an apprenticeship with BAE Systems instead of a full-time university course. "I wanted to study part-time and apply knowledge on a day-to-day basis in the workplace, so the scheme was ideal for me," he says. "These days we would call this a Modern Apprenticeship, and the company offers various ones."

He soon began to work with cutting-edge technology. One project, involving the Typhoon fighter, was to simulate complex new actuators in hardware and software to 'fool' the flight control system into behaving as though it were airborne, using real actuators so that they could be tested safely and affordably.

Surrogate satisfaction

The project that gave him the most satisfaction as his career advanced was the Surrogate UAV. Developed in cooperation with Cranfield University and Cranfield Aerospace, a modified Jetstream twin-turboprop regional airliner served as a manned test bed that demonstrated a range of autonomous UAV capabilities in a very short time on a tight budget, he says.

He attributes this success to having a small multidisciplinary team with diversity of thought that included academics and people from BAE Systems as well as small-to-medium enterprises.

Systems tested included airspace integration technologies such as sense and avoid, which was later used in the Autonomous Systems Technology Related Airborne Evaluation and Assessment (Astraea) programme. As Astraea progressed, Colosimo's team integrated more systems and expanded the scope of the trials to include real 'intruder' aircraft.

> The role is really a scientific pursuit, rather than crystal ball-gazing. The wisdom of crowds is key to success here

"We had safe vertical separation in the air but took it out in the software to convince the algorithms that the intruders were co-altitudinal, then put them on courses that would violate each other's safe operating bubble," he says. "Then the sensors and algorithms would

The Tempest Future Combat Air System concept could result in a manned aircraft capable of managing several unmanned versions of itself

> Any decisions involving lethal effects are the preserve of humans, but routing, detecting and avoiding threats and so on, the machine can do that

work out whether we were on a collision course, and we'd instigate an avoidance manoeuvre in accordance with good airmanship and the rules of the air.

"Ultimately, what we were doing there was to replicate human see-and-avoid capabilities to a high level of performance and ultimately equivalence. I think we exceeded equivalence."

The Surrogate was also used to reduce the technical risk in a mission system for the Mantis medium altitude long endurance unmanned air vehicle demonstrator, which included a prototype synthetic aperture radar (SAR) from Selex-ES (now Leonardo) and a new Inmarsat broadband satcom system.

"We could have the machine fly a route, operate the SAR, generate images, find objects of interest autonomously within the images and then push the image 'chips' back to a human analyst through satcom," he says. The analyst would then classify the object or ask the aircraft to take another look.

Progress has been rapid in the decade since this project. "Artificial intelligence is getting to the point where neural networks can start to classify many of those things," Colosimo says. "But how much you can trust that, I'm not so sure.

"It depends on what you are trying to achieve in terms of the military task. If it is imperative to distinguish one object from another, then you still need to put it in front of a well-trained human analyst."

Mentors and bugs

Among the many people he regards as mentors is technical innovation engineer at telecoms testing company Spirent, Dr Rafal Zbikowski. When he was professor of control theory at Cranfield, Zbikowski changed Colosimo's perspective on problem-solving through his work on insect flight.

Before aerodynamic theory caught up, the joke in circulation was that bees shouldn't be able to fly but hadn't seen the memo. Zbikowski's work on aero-servo elastics showed how insect wings bend radically with airflow to exploit techniques including vortex generation to provide lift and control.

Aero-elasticity had long been considered a resonance-inducing nuisance that had to be mitigated in aircraft, but Zbikowski turned that on its head in what Colosimo describes as a light bulb moment for him.

"If you start out to make aero-servo elasticity work in the design of the vehicle, you might not simply avoid creating problems but could also capitalise on it in ways analogous to what flying creatures do. And it's not limited to low-speed flight or low-mass aircraft," he says.

Team Tempest

The project with which Colosimo is most closely involved these days is Tempest, the future fighter intended to replace the Typhoon when it is retired from RAF service in 2040. The main goals at this stage, he says, are to develop the intellectual property, skills and technologies required for a new generation of combat aircraft.

An optionally unmanned version of the aircraft is a possibility. "Getting the command and control right between a manned aircraft, which may be commanding what is a semi-autonomous craft, is extremely important," he says. "Any decisions involving lethal effects are the preserve of humans, but routing, detecting and avoiding threats, gathering imagery and sending it back for analysis and so on, the machine can do that.

"We're working at the very edge of technology, trying to predict what will be possible in 10, 20, 30 years' time and how we can plan for that. That's as difficult – and as exciting – as it gets. Our philosophy is to fail fast, learn and develop."

Since its existence was announced at Farnborough 2018, the outline case for the Tempest programme has been approved by the government, and UK industry, and the RAF has made major strides in developing enabling technologies; discussions with potential international partners are ongoing as well. "We're hoping for some big announcements and updates soon, so watch this space," Colosimo says.

He regards the qualification and certification of such complex systems as the industry's greatest challenge, one exacerbated by machine learning exploiting neural networks. This is the 'black box problem' in which although engineers can monitor the inputs and outputs of a system, they don't necessarily understand the process that turns one into the other. Such opaque complexity, he says, could increase the probability of failures such as undesirable emergent behaviours.

"At some point in the future we may pass a complexity threshold that current mitigation methods can no longer cope with," he explains. "We may all need to think more radically about how we design, develop, manufacture, test and deploy unmanned technologies."

Radical thinking is the essence of the job. "I don't think I will ever get bored," he says.

Nick Colosimo

Professor Nick Colosimo is technology strategy executive, principal technologist, global engineering fellow at BAE Systems in Warton, Lancashire. His education began at Larches Country Primary School and continued at Ashton-on-Ribble High School in Preston, north-west England.

He joined BAE Systems in 1990 as an apprentice, and continued his education part-time at institutions including the Central Lancashire and Manchester Metropolitan universities. Over about 11 years he studied mechanical and production engineering, mechatronics, applied physics and electronics, computing and avionics.

In his current role, he looks after technology strategy and planning, which has involved setting up and mobilising a number of strategic technology themes and their associated road maps, including AI and autonomous systems, space, near space and so on. He is also principal technologist responsible for disruptive technologies, which combines his role as a futurist with leadership of technology proof-of-concept demonstrations.

As a global engineering fellow he is called upon to address difficult engineering problems and to help promote engineering and company capabilities and values.

He has held various positions within BAE Systems, including strategy & planning executive for future capabilities, principal technologist – disruptive technologies (2016-18), and executive manager, advanced systems & innovation (2009-16). Before that he had various engineering and specialist roles.

The Hummingbird XRP with its inventor Allen Bishop in Reference Technologies' home state of Colorado, where it has access to a large block of airspace for flight test operations (Courtesy of Reference Technologies)

Development of this UAV provides an object lesson in how to cater for an extensive range of applications. **Peter Donaldson** reports

Utility player

With eight rotors on outriggers around a vertical ducted fan, the Hummingbird XRP is a distinctive-looking UAV developed by Reference Technologies in Lafayette, Colorado. The 225 lb multi-copter has a hybrid combustion-electric power plant, a claimed mission radius of 150 miles with 30 lb of payload, plenty of spare electrical power to run mission equipment, and 400 lb of thrust.

Eight hard points support sensors or cargo, and the vehicle is offered at a price of around $400,000 for surveillance, mapping, payload delivery and more. Company founder Allen Bishop hopes it will become the UAV equivalent of the Ford F-150 pick-up, a popular and powerful general-purpose truck.

The story began in 2011, when Bishop saw a gap in the market for a VTOL UAV that would fit into Group 3 of the US Department of Defense's five-group taxonomy, in which higher numbers indicate larger aircraft. Group 3 covers vehicles of between 55 and 1320 lb take-off weight, nominal operating altitudes below 18,000 ft and speeds below about 250 knots. Most are priced at around $1 million, he notes.

He says he felt that in terms of price, performance and complexity, Group 3 vehicles represented a sweet spot in the margin between the commercial and military sectors. "I didn't want to be limited by offering either only military or only commercial products," he says. "There were also too many battery-powered systems on the market.

"Even now, I don't know many multi-rotor systems that can offer more than an hour of flight time on batteries with a substantial payload, as in a large camera or multiple sensors."

After incorporating Reference Technologies in 2011, he spent about 18 months researching power sources, and soon decided that only a hybrid power system would meet his needs, which were at least 7 and preferably more than 10 kW of 48 V DC power for the propulsion system, the utilities and the mission equipment.

"We went through a period in which everybody said they could meet those needs, but nobody actually

Like the external rotors, the one in the central duct is electrically driven, but it is controlled by the power management system rather than the flight control system (Courtesy of Reference Technologies)

produced," he says. "So while the world was working on a better compact hybrid power source, I ventured into designing the vehicle."

The initial concept coalesced in his mind at the start of a meal in a restaurant: the trigger was the cylindrical form of a water tumbler placed before him on the table. "On a napkin I drew a cylinder and put out six arms and then put propellers – little Xs– on the end of each arm, drew some landing gear with the curvature you see on the Hummingbird, then drew two propellers inside the main duct."

The first series hybrid proof-of-concept vehicle was just called the Hummingbird, and took the form of a hexacopter with ducted 17 in outboard rotors and a 24 in diameter central duct, which housed a two-cylinder two-stroke engine. That was coupled to a Sullivan starter/alternator and power system running KDE Direct electronic speed controllers (ESCs) and brushless DC motors for the outboard rotors as well as the counter-rotating rotors in the duct.

"That allowed us to do a number of experiments and show that a compact power system was capable of producing the thrust we needed," Bishop says.

In this form, the Hummingbird did the rounds of the trade shows. Within a year, potential customers were asking for more range, endurance and payload, he says. That drove the development of the current, larger vehicle with the eXtended Range and Payload that gives it its XRP moniker.

This has a central duct 30 in in diameter with twin, counter-rotating 30 in rotors and eight 27 in diameter outboard rotors that are no longer in ducts. Power is provided by a Sky Power (formerly 3W International) 180 cc, 20 kW SP-180 rotary engine with an integral starter-generator, supplemented by a lithium-polymer battery pack.

> We tried about 200 different rotor designs but in the end we came back to two-blade rotors on the inboard and outboard

Achieving 400 lb of thrust from this power plant required aerodynamic optimisation work beyond Bishop's abilities as a self-taught aerospace engineer, so he turned to the University of Colorado, hiring interns to do the calculations that would allow him to minimise the power required to generate each pound of thrust.

Getting the rotor design right was crucial. "Initially we tried our own design," he recalls. "We did a lot of 3D printing using carbon fibre-infused plastics, and we tried about 200 different designs of rotors with dual, triple, quadruple and octuple blades. In the end, we came back to two-blade rotors inboard and outboard."

"Efficiency was our real Achilles heel at the beginning: we were looking at 100-130 W/lb of thrust," he says. "We just couldn't put enough power in the system – even with batteries added – to achieve a reasonable payload and endurance."

After asking several aerospace engineering firms to design the rotors, without success, the company went back to KDE Direct and asked it to design a propeller to match its motors and ESCs, which it achieved within six months. "We found their efficiency was roughly 30-40 W/lb of thrust – KDE almost tripled the efficiency."

The Hummingbird XRP now uses KDE's 8218xf-120 motors and UAS125UVC ESCs. The outboard rotors use the same company's CF275-DP blades, which are 27.5 in in diameter and have an 8.9 pitch. Their twist ensures a consistent pressure along the length of each blade, says Bishop, while

The Hummingbird XRP's major components conform to the vehicle's general annular theme, including the fuel cell, girdle, central duct and electronics bays and covers (Courtesy of Reference Technologies)

the aerofoil design ensures a consistent stress factor from the root to the tip, maximising the overall thrust production along the entire length.

Ducts ducked

The most immediately noticeable thing about the Hummingbird XRP's outboard rotors is that they are no longer in ducts. Despite being quieter and having an efficiency advantage of between 10 and 14% in vertical flight over open rotors – thanks to their suppression of vortex formation – aerodynamic problems in transition and forward flight meant the ducts had to go.

The issue is the angle at which air enters the ducts when the vehicle pitches forward to accelerate and adopts a nose-down attitude in forward flight. (The autopilot limits pitch and roll angles to a maximum of 20° to avoid losing lift and, consequently, altitude.)

The airflow delaminates on the lower edge of the duct, while air that impinges on the curve of the upper edge generates aerodynamic burble through the duct. Furthermore, some of the air is deflected up and out, never making it into the duct. All of that is bad for efficiency, Bishop explains.

"The air that does go in becomes a burbling air mass that goes into the rotors," he says. "Not only do we lose the calculated efficiency of the duct, we lose more efficiency overall because the rotors can't maximise their thrust capability. So we dispensed with the external ducts."

Lidar is intolerant of shakes and bumps; I wanted an aircraft that could still be a good imaging platform in fairly rough weather

The arms on which the outboard rotors are mounted emerge from the sides of the central duct at an upward angle, creating dihedral that adds stability because it tends to return the aircraft to level flight after a disturbance.

"We wanted an extremely solid platform for imaging such as Lidar, which is very intolerant of shakes and bumps," he says. "I wanted an aircraft that could still be a good imaging platform in relatively rough weather."

The rotor configuration in the central duct also contributes to stability, as counter-rotation cancels out the yaw moment that a single rotor would produce and would require a separate anti-torque system to eliminate.

Bishop considered using a single-rotor plus a stator system to straighten out the airflow within the duct, as used in some other ducted fan vehicles, but rejected that owing to weight and reliability concerns.

"Every pound of plastic or metal we put on the aircraft is a pound of fuel we don't have. Second, it's a mechanical device with pivots, bearing surfaces and servos, and they all become single points of failure," he says.

Each rotor in the duct is driven by its own electric motor; the generator is the only device that is mechanically driven by the engine.

Less-than-ideal aerodynamics can be tolerated in the central duct because airflow through it is more important for cooling the engine, the generator and the power electronics than it is for thrust. However, the duct does contribute about 50 lb of thrust, and it still works reasonably efficiently in a hover.

"If there were two rotors and nothing else inside the duct, we would be closer to 70 lb," Bishop says. "We lose about

20-25 lb of thrust purely because of the 'dirtiness' of the duct itself."

That dirtiness is caused by the presence of the engine and alternator along with their mounting arms, which consist of four carbon fibre tubes, and the heat sink that draws heat away from the inverters and power supplies, even though its fins align with the airflow through the duct.

The rotors in the duct are directly controlled by the power management system rather than the autopilot. This arrangement ensures that the speed of the central duct fans is controlled by cooling requirements as the priority rather than thrust.

That is important if, for example, the Hummingbird is being used in 'perch and stare' mode, sitting on a hill or building with the external rotors turned off and the sensors operating on battery power. As the batteries discharge, the power management unit senses when they need recharging, and the hybrid system starts doing that, he says.

During that process, the power management unit starts the central ducted fans and regulates their cooling effect by controlling their speed until the batteries are recharged, while the mission continues.

Generating 13 kW of three-phase electrical power and converting it from AC to DC through an inverter means there is a lot of heat to get rid of. Although the power electronics manufacturers offered their own heat sinks and cooling fans, Bishop wanted a more efficient and lighter solution, so he designed a heat sink shaped to conform to the inside curvature of the main duct.

Mounted in the power bay – one of eight electronics bays arranged around the top of the aircraft – the 8 x 6 in aluminium alloy heat sink dissipates heat from the power electronics through fine fins that protrude through a window in the upper duct into the airflow.

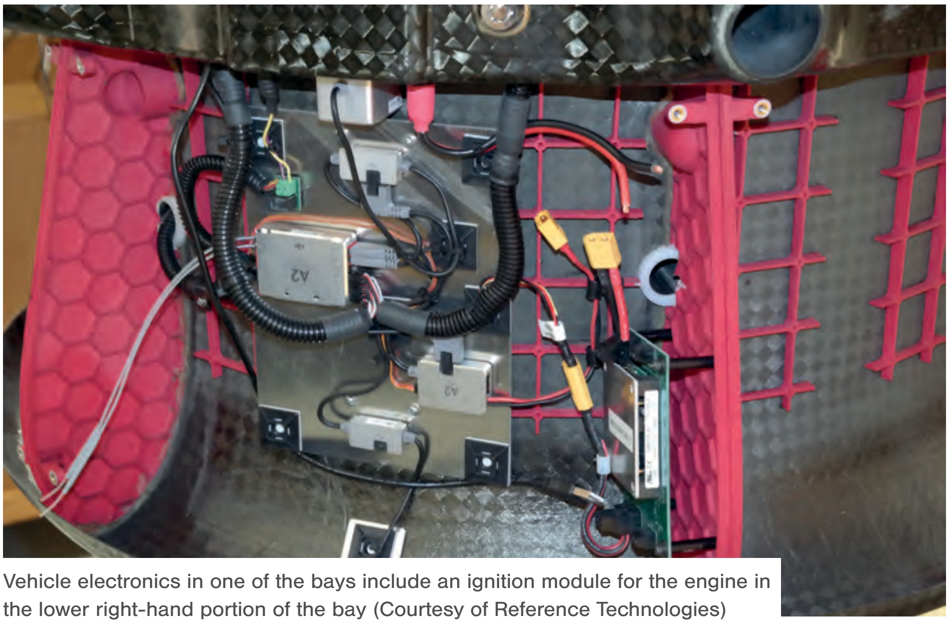
Moulds, lay-up and 3D printing

Reference Technologies also chose an external supplier to build the airframe. Adam Works, formerly Adam Aircraft, has built corporate jet airframes from carbon fibre-reinforced plastic (CFRP).

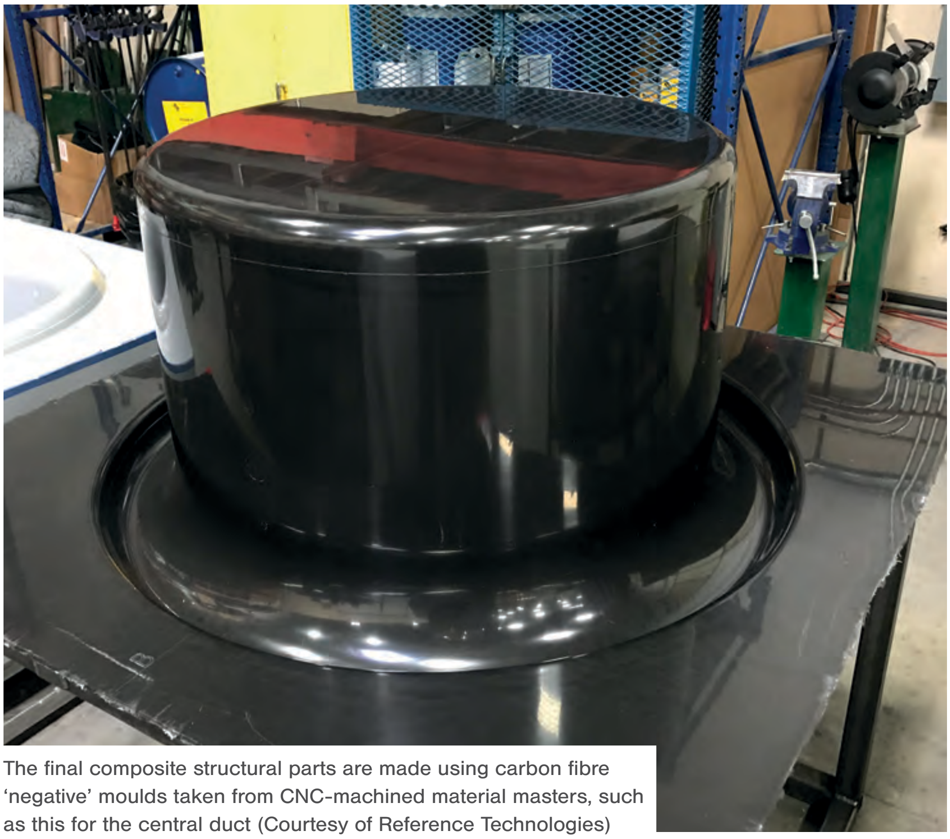
Early on, Bishop invested heavily in tooling to make CFRP parts. For the original Hummingbird, with its 24 in diameter duct, all the tooling for the structural components was CNC-machined from aluminium billet, with a price tag to match – he says the moulds for the main duct alone cost more than $100,000.

When construction of this early version began in 2015, Adam Works used wet lay-up techniques, manually applying resin to dry carbon fibre cloth before putting the parts into vacuum bags and curing them in a 400-600 F oven.

With such expensive tooling, changes to the design were consequently also very expensive. "We made major



Vehicle electronics in one of the bays include an ignition module for the engine in the lower right-hand portion of the bay (Courtesy of Reference Technologies)



The final composite structural parts are made using carbon fibre 'negative' moulds taken from CNC-machined material masters, such as this for the central duct (Courtesy of Reference Technologies)

changes, and many times had to toss them out and start over," he says.

By the time he had decided to build the Hummingbird XRP, Adam Works had switched to a different, cheaper and more flexible way of making moulds. This involves CNC-machining a hard, high-density compressed material to create a master 'positive' mould from which carbon fibre 'negative' moulds can be made that are used to make the final parts.

The company now uses pre-preg carbon fibre cloth instead of manually applying resin to fibre. "This is very efficient and cost-effective, and these moulds are good for more than 100 final parts before they need replacing," Bishop says.

"Also, when we go to full-scale production and are building a vehicle every two days or so, we will need multiple moulds. We can produce as many moulds as we need for basically the same cost as producing the final aircraft parts, or a little more because the moulds have thicker cross-sections for more rigidity."

This process is also flexible enough to allow them to incorporate changes quickly and relatively inexpensively. "The few changes we made to the structure at the very end were simply done in the master high-density material moulds, and then we created the production moulds as needed," he says.

"Adam Works produces the entire Hummingbird airframe – all the carbon fibre, landing gear, arm joints, upper and lower duct and the main girdle.

"The girdle is our main structural element. It goes around the middle of the aircraft and on it we attach the landing gear, external fans, hard points and other optional accessories. It is a U-shaped channel that also houses the cabling, control lines and fuel lines so that they are all hidden and protected."

The Hummingbird also makes extensive use of 3D printing for parts including mounts and enclosures for electronics and even secondary structure. Reference Technologies' partner here is iFuzion in Denver.

Materials used include several types of plastic, some infused with carbon fibre reinforcement, and metals including aluminium, stainless steel and titanium. The covers for the electric motors that drive the rotors in the centre duct, for example, are 3D-printed. "They fit perfectly, like they came out of a plastic injection moulding machine," Bishop says.

One of the most important 3D-printed metal parts is the autopilot enclosure that fits inside the upper front electronics bay. Although Bishop wouldn't reveal what the material is, he says the enclosure's purpose is to hold the autopilot securely in the bay and act as a Faraday cage to protect it from deliberate RF interference.

Quest for power

Finding a suitable engine proved a fraught process. Bishop had wanted to use a rotary originally because of its mechanical simplicity and high power-to-weight ratio. However, the UK company he chose to supply the engine filed for bankruptcy two weeks after accepting Reference Technologies' deposit.

That frustration motivated him to seek an alternative, a search that led to 3W International/Sky Power and its air-cooled two-stroke twins, first the 17 hp SP-170, which provided enough power for prototype flight testing and validating all the aerodynamic calculations.

However, it was soon clear that better fuel efficiency and more power would be needed for the XRP version, and Sky Power's new SP-180 SRE Hybrid seemed a natural fit. Bishop stresses that its power figures have been validated on a dynamometer, giving him confidence that it will perform as advertised. Combined with an article this magazine ran on the engine (*UST* 25, April/May 2019), this influenced his decision to invest in the development and integration of the SP-180 SRE Hybrid.

Mounted on CFRP tubes that attach to the duct walls, the engine draws in air through an upward-pointing intake and sends spent gases through the exhaust pipe to a silencer in the form of a perforated annular aluminium tube attached to the bottom of the duct.

"The engine is very reliable, and achieves significant time between overhauls," Bishop says. "And it has logged hundreds of hours of test time in all environments."

The SP-180 SRE Hybrid's integral generator was also an important factor in choosing it, he says. In a 48 V electrical system, the generator can produce about 13 kW to power the propulsion motors, utilities and payloads, although Bishop emphasises that 15 kW will be available with a new, higher voltage inverter that will reduce the current. As it is, he notes, 13 kW at 48 V works out at 270 A, which is a large current for the main power bus of a relatively modestly sized vehicle. ▶

The Sky Power SP-180 SRE Hybrid is packaged with an integral alternator and produces all its power in electrical form (Courtesy of Reference Technologies)

Power from the alternator can be supplemented by a Grepow/Tattu or Panasonic lithium-polymer battery pack. In response to a large power demand from the control system, the battery pack powers the propulsion motors in parallel with the engine-driven generator. As the vehicle approaches the commanded speed, and power demand falls, the generator can handle the propulsion requirement and recharge the batteries.

"We have designed the system so that the batteries provide starting power and then, once the engine is running, the direction of power flow reverses," Bishop says.

With lithium-polymer chemistry, it is important to pay particular attention to battery management, he says. Before every long flight, which could be up to eight hours, the checklist recommends that the batteries are replaced with a fully charged set.

"We can run a number of missions and let the system recharge the batteries, but at some point you remove them and do a balance charge to make sure you always have balanced batteries going into a long flight," he adds.

"We are looking at [lithium] iron chemistry for a more consistent power output, but the downside there is that when you're out of power, you're out.

"The power graph for lithium-polymer will decline in a nice, predictable curve, but the iron chemistry delivers high power until nearly exhausted and then in a couple of milliseconds you're empty. That's not good for an emergency descent because it's very hard to predict, but we are looking at different battery chemistries as they become available."

As well as starting and hybrid boost power, the batteries also provide a measure of redundancy. "If the engine were to die, we have enough stored energy to take us from about 3000 ft above ground level [AGL] to a safe landing," he says.

Redundancy and parachute

One benefit of using multiple electric motors and a large reserve of thrust over weight is the opportunity to build in some extra redundancy, Bishop notes. "We can tolerate the loss of up to three motors," he says.

"There is a caveat though, in that you can't lose all three on one side. You could have two together and then skip and lose another one on the other side. If you run everything at maximum you can get it on the ground safely. If you lose only two, you can continue the mission, but you are going to really tax the remaining six outboard motors and duct motors."

A parachute can be fitted as an insurance policy for the aircraft and whatever expensive sensors it is carrying. On the Hummingbird XRP, it is housed in a cylindrical container mounted on one of the hard points. The lines supporting the UAV under the parachute are attached steel 'leader' cables that in turn attach to fittings on each landing gear leg, close to where they mount to the structural girdle.

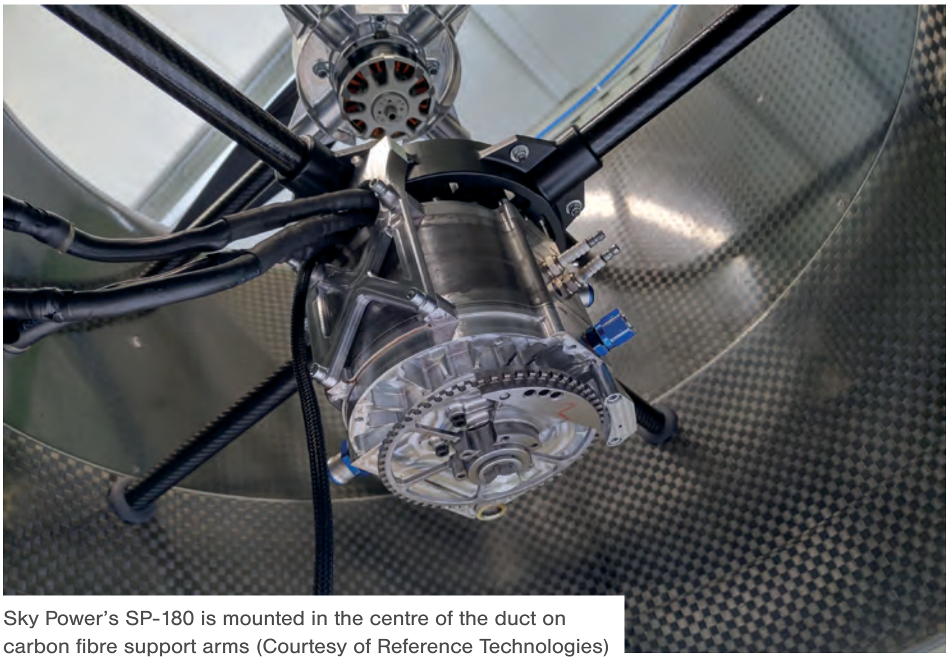
The cables are attached using Velcro along the upper duct covers and come across the top of the lip, staying out of the airflow, and attach to the parachute harness. As the parachute deploys, the cables and the parachute itself are forced upwards to clear the rotors.

Flight testing of the parachute installation is planned for later this summer at a site in southern Colorado, in which the company is cleared to operate at up to 15,000 ft above mean sea level, and where the Hummingbird will be accompanied by a manned spotter aircraft.

Comms suite

The basic comms system for command & control and telemetry includes radios operating in the 900 MHz, 1.2 GHz and 2.4 GHz bands, with 2.4 GHz suitable for still images and lower resolution video, and 5.8 GHz preferred for transmitting live video.

In terms of output power, they normally operate at 1 W depending on



Sky Power's SP-180 is mounted in the centre of the duct on carbon fibre support arms (Courtesy of Reference Technologies)

Datasheet

Hummingbird XRP

Maximum take-off weight: 225 lb
Thrust: 400 lb
Payload: 30 lb with six-plus hours' endurance
Fuel capacity: 12 gallons
Endurance: more than six hours
Range: about 300 miles one-way
Width: 9 ft
Duct diameter: 30 in
Outrigger propeller diameter: 27.5 in
Engine: 20-28 kW, 180 cc rotary
Power available from generator: 13 kW

Some key suppliers
Airframe: Adam Works
Engine: Sky Power
Motors, ESCs and propellers: KDE Direct
Batteries: Grepow/Tattu
Batteries: Panasonic
Ballistic parachute: Para Zero
Additive manufacturing: iFuzion

Federal Communications Commission requirements. However, says Bishop, they can use more powerful transmitters in special circumstances. To date, the Hummingbird has flown with various off-the-shelf radios transmitting from 5 mW to more than 5 W.

He says the Hummingbird XRP's format makes it a good comms platform, as the square aluminium alloy frame that acts as a brace for the landing gear legs – preventing them from splaying out on a hard landing – also serves as the antenna farm. Normally, it is home to omnidirectional antennas covering all the above frequencies.

With dish and patch antennas on the ground station and a clear line of sight, this arrangement enables comms ranges of 8-15 miles. For longer line-of-sight ranges – Bishop talks of operating a vehicle at 1000 ft AGL and up to 50 miles away – patch antennas can be mounted on the frame, either at a fixed angle of 45° of depression or on servos so that they can be steered to aim constantly at the ground station's GPS coordinates.

The ground station can also use tracking antennas, taking the GPS feed from the aircraft and putting it into a controller that points a high-gain antenna at it. These are normally dish antennas with gains of between 12 and 20 dBi.

Another option for long-range comms involves a second Hummingbird 'repeater' fitted with directional high-gain antennas and 'parked' at altitude, providing a 300-mile range for up to eight hours.

For integration into air traffic, the company is working with suppliers to fit a Mode-S transponder and provide an ADS-B Out capability initially, so that air traffic control facilities and other aircraft with ADS-B equipment will be able to see the UAV on their displays.

After that, the plan is to integrate an ADS-B In capability plus sense-and-avoid software that would allow it to fly in congested airspace and autonomously avoid other aircraft.

Other emerging technologies, such as audio sensing and low-power radar and long-range Lidar are also being considered for integration. Reference Technologies plans to test these and other capabilities later this summer.

Bishop has security as well as safety in mind for the comms and navigation system. He says, "We have designed the vehicle to be as impervious as possible to anti-drone technology that uses extremely high-power RF signals" to jam or overwhelm the internal electronics, which is the purpose behind housing the autopilot in the Faraday cage mentioned earlier.

However, the comms antennas will still provide a path into the system for hostile RF signals, so the company is considering patenting what Bishop calls an electronic guillotine device that, on command from the ground once a hostile signal has been detected, will isolate the autopilot and the rest of the control system from interference. Naturally that would mean the vehicle would no longer be able to communicate, so it would have to execute some protocol that would take it to safety autonomously.

The Hummingbird comes with a portable multi-screen GCS. Smaller and lighter handheld GCS units are also optionally available.

Autopilot training

Bishop's first choice of autopilot was the triply redundant DJI 3 Pro, but security worries about foreign content in a product aimed at the US government and other sensitive customers – particularly concerning the software and updates to it – led the company to work with an undisclosed US supplier on an alternative. This new autopilot is now being developed and will ship with the first customer aircraft.

During development, it was important to establish what a good centre of gravity would be so that the autopilot would not have to perform what Bishop calls "extraordinary calculations" to work out whether the UAV is level. In doing this, he also had to take into account the effects of fuel burn and payload deployment.

"If I have 50 lb of payload stashed in discrete packages around the periphery of the aircraft, and I am deploying them one at a time – perhaps two of them on one side at 10 lb each – what effect does that have on the horizontal stability of the aircraft via the autopilot?" he says.

The autopilot software includes code that runs the payload management system and advises the operator on load distribution during mission planning through the ground station's GUI. If a combination of payloads has to be delivered to different destinations in a particular order, the software will warn the pilot if the combination of payload positions, weights and sequencing will cause a balance problem and show how to distribute the loads to correct it.

To carry a single payload of 30 lb or more, the operator must use a sling to put it under the aircraft's centre of gravity. The sling system includes a harness that attaches to four hard points on the main girdle. The lines from these points meet 4 ft below the main duct in a coupling to which a 15 or 20 ft strop that carries the payload is attached.

A release mechanism can be installed either between the harness and the strop line or between the line and the payload, according to the needs of the mission. If the vehicle returns to base with the strop line, it lands sideways to keep it out of the way of the rotors.

The Hummingbird XRP is described as an open platform that can support a wide variety of payloads. For example, its four main hard points can each support two payloads, so it could deliver eight packages to eight separate locations.

It could land to deploy them or release them on parachutes, for example, or carry several different sensors or a combination of sensors and packages, Bishop says.

Tunnel detection and mosquito control

Each hard point is provided with a data and power connection, and up to 300 W of ancillary power is available for payloads. One of these is a ground-penetrating radar that an undisclosed government agency wanted to put on a UAV to detect tunnels, mines, IEDs and other buried threats in conflict zones.

Initially, the agency in question simply told Bishop it wanted to carry 40 lb of payload for six hours – 10 lb more than the vehicle could carry for that duration.

On further enquiry though, it emerged that the radar only drew a maximum of 200 W at 24 V, and that a significant proportion of its total weight was taken up by batteries, without which it would weigh only 24 lb, and that the Hummingbird's onboard power was more than adequate.

That sealed the deal, and Reference Technologies is now working with the agency, Bishop says.

With agricultural and related markets in mind, Bishop has also designed and built a spray bar system to dispense chemicals from nozzles at the end of four of the eight arms so that they discharge into the flow from the rotors.

The chemical payload is pumped to the nozzles from bottles attached to the hard points. That, he says, makes for a very efficient fogger.

Reference Technologies is now building the first few production vehicles for customers and is hoping for many more with a myriad missions in mind.

"The Ford Motor Company doesn't care what you are using your F-150 for; it's a utility, a tool, a platform, much like the Hummingbird XRP," Bishop says. ◻

The Hummingbird can be managed from a portable multi-screen GCS in the form of a rugged trifold computer from CP Technologies, although smaller and lighter handheld units are also offered as options (Courtesy of CP Technologies)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The quality of high-end payload gimbals is closely linked to the specialised techniques and equipment of each individual gimbal manufacturer (Courtesy of Ascent Vision Technologies)

Eyes on the prize

Rory Jackson looks at how gimbal manufacturers adopt the latest technologies to keep their systems optimised

The value derived from investing in a powerful imaging system will only be as high as the assembly in which the camera is packaged. As well as controlling and stabilising the pan, tilt and roll of the payload sensors, gimbal systems have to isolate and protect them from external forces, while also providing encoding and processing of the data being collected.

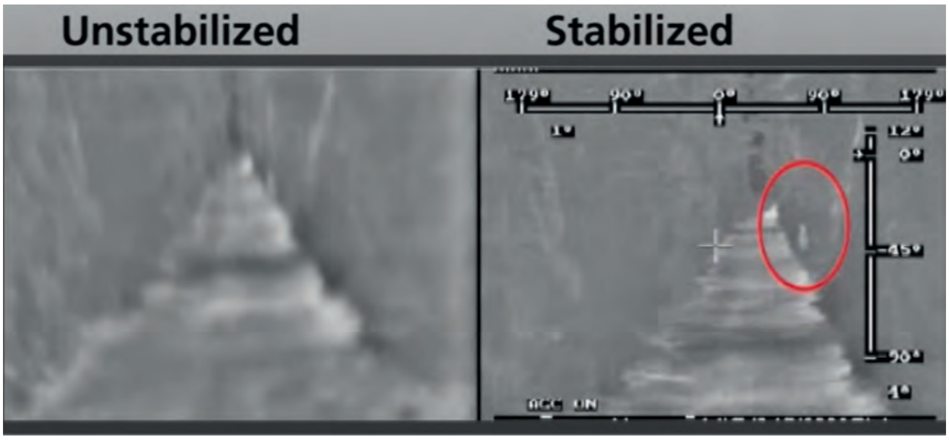
With the industry seeing a major drive for miniaturisation of high-end sensor packages to enable longer endurances for survey UAVs, as well as growing demand for intelligent object recognition and tracking, gimbal manufacturers are leveraging new technologies and investing in new processes for optimising the systems they produce.

Mechanical versus digital stabilisation

It is important to remember that the term 'gimbal' does not refer only to the mechanically operated enclosure in which a UAV's mission sensors are installed. It also signifies each of the mechanically rotational axes integrated into the overall gimbal system.

As a general rule, the more individual gimbals that are installed, the more the platform can be stabilised. As a minimum, one gimbal for elevation (pitch or tilt) and another for azimuth (yaw or pan) are typically incorporated. A third gimbal can be used to provide roll compensation, or additional elevation or azimuthing.

Having gimbals for the enclosure as well as integrated axes for a particular plane of rotation naturally gives more ways to isolate the visual feed from the various disrupting forces acting on the payload. It can also help overcome problems of gimbal lock when two axes are driven into a parallel configuration.



Improvements in a gimbal's mechanical and digital stabilisation contribute hugely to the level of mission-critical detail captured in images and videos, as seen in this comparison (Courtesy of Controp Precision)

For a 40 kg fixed-wing UAV with a two-stroke engine, say, which is to be regularly flown in all weather conditions, operators will probably want at least a four-axis turret with internal and external gimbals for pan and tilt.

Dedicating one axis to roll is particularly useful if the UAV will need compensation for buffeting by wind. This can also be accomplished digitally, essentially by post-processing the imagery to maintain a single angle in the roll axis, and cutting off unwanted parts of the picture. With well-written image processing software, a three-axis gimbal could be just as stable than a four-axis gimbal, if not more so.

Digital stabilisation can be vital, as adding gimbals generally means a larger overall footprint or less free volume for sensors.

The quality of digital image stabilisation is directly linked to the processing power available. In the past few years, powerful computing boards such as the Nvidia TX2 have become available that are sufficiently small and energy-efficient to be integrated into gimbal systems weighing less than 500 g.

Such processors can run highly demanding applications – 3D image stabilisation, for example – or machine learning-based detection and tracking software, which could help security operators track the licence plates of suspicious vehicles, say, or carry out commercial autonomous inspections for signs of wear in bridges, pipelines or other critical infrastructure.

Having more processing power also opens up the possibility of greater digital zoom, which may be preferable to greater mechanical zoom as that requires larger, heavier cameras with lenses of greater ranges of focal length. In addition to increasing the gimbal's power draw though, this would also make the gimbal more challenging to balance, owing to how the lenses shift back and forth while zooming in and out, altering the centre of gravity (CoG).

Previous attempts at such enhancement (and advanced tracking) capabilities have been made by installing FPGAs inside the housings. However, the hardware for that remains relatively expensive and complicated to develop software for, particularly when compared to the newest embedded computer processors.

Selecting (and thoroughly testing for) the right IMUs is critical for true gyro stabilisation. Inertial measurement technology has continued to be miniaturised and made more cost-effective over the past few years, with ongoing algorithmic reductions in gyro drift in terms of bias instability and angular random walk.

For gimbals that weigh more than 10 kg, fibre-optic gyros are still widely integrated for their higher accuracy than MEMS versions

Reducing these errors is critical to ensuring a gimbal's stability and accuracy, particularly as gimbals are increasingly expected to track moving targets. Also, an absolute minimum of gyro misalignment – in which the MEMS gyros are not perfectly oriented at 90º to each other – is needed to maintain an accurate flow of inertial measurements and thus keep gimbals pointed in the right direction.

For gimbals weighing more than 10 kg, fibre-optic gyros (FOGs) are still widely integrated for their higher accuracy than their MEMS equivalents. The development of FOGs using photonic ICs will provide greater performance still, while significantly lowering the costs associated with such systems, although their size and weight will still prohibit their use in miniature gimbals.

Motor control

Until a few years ago it was common for gimbal manufacturers to use open-loop control systems in their motors. That meant the motor was given a control signal and the required power to achieve the position commanded, and it was then assumed that the control action had been carried out as required.

This method is not energy-efficient though, as it typically uses more current than is truly necessary for the

Advances in motor control technology (and the motors themselves) can enable greater accuracy and the ability to retract gimbals into their UAV's hulls during flight or hard landings (Courtesy of Threod Systems)

required movement, to compensate for any error. This excess current also means the motors have to be unnecessarily large, at the expense of free space inside or around the gimbal.

Most gimbal manufacturers have therefore switched to closed-loop control. Here, the motor controller can test if the rotation mechanism has performed as commanded. If not, the current can be altered to compensate for the error, increasing gimbal precision and energy efficiency.

A position sensor, such as a Hall effect sensor or potentiometer, can be installed for this purpose, with its data feed being written into the gimbal's control algorithm to measure the motion and compensate accurately.

Closed-loop control also helps to compensate for changing loads, such as how zoom lenses dynamically alter the centre of gravity. Adding a sensor to the motor adds significant mechanical and algorithmic complexity though, particularly if slip rings are installed to provide 360° continuous turn in any of the axes – which is why closed-loop control has not been universally adopted.

New technologies are being developed and adopted to provide accurate and efficient gimbal control. For example, field-oriented control-based motor controllers are much more complex than those using trapezoidal control algorithms, but they provide faster speeds and better accuracy.

Also, brushless motors are widely replacing gear motors, as they use power more efficiently, providing more stable and precise performance, as well as causing far less backlash and other problems associated with gear motors.

Further into the future, improvements in the miniaturisation of axial flux ('pancake') BLDC motors will help integrate gimbals within much flatter spaces than has previously been possible.

Ongoing development of edge drive motors could also greatly reduce the packaging footprint of gimbals. These operate in a similar way to rim-driven UUV thruster motors, using a thin fixed stator forming the outer circle of a given gimbal and a ring of permanent magnets forming the inner rotor.

In addition to the space saved by their thin mechanical design, the wide diameters of such motors generally mean they naturally generate high torque, potentially reducing the power needed to control their gimbals. Their larger surface areas also help them cool faster than conventional motors, which improves their energy efficiency and lifetime.

CAN bus could also come to replace PWM in gimbal motors, to reduce the internal density of wires as well as increasing comms bandwidths for sending and receiving position sensor measurements and other data.

Structures

Gimbal manufacturers can access a variety of software to design and analyse new models before moving on to production. CAD programs such as SolidWorks and Siemens NX can enable the analysis of a gimbal's inertia, CoG, natural frequency and other parameters that the structure must account for.

All high-end gimbals are enclosed systems, to protect expensive camera equipment from dust and moisture, and to minimise atmospherically driven vibration and motion that would interfere with stabilisation.

A wide range of materials and manufacturing approaches are available for use in these protective housings, each of which provides different mechanical stiffnesses, tolerances and weights.

Additive manufacturing (AM) has proven useful for quickly producing, testing and iterating new gimbal designs. After a CAD model of it has been examined in simulations, additively manufacturing a physical model – which can now be done using metals and alloys, rather than just plastics – can enable its approximate tolerances, inertia and balance to be tested. Such tests can reveal fundamental structural flaws in the design of a new gimbal, before any investment in tooling or machine programming is made for full-scale production.

Furthermore, the ability to reduce manual input can be useful in some parts of gimbals. For example, the interface sections for mounting and connecting gimbals to their UAVs can contain a lot of tiny metal elements that have to be assembled manually in complex, time-consuming ways.

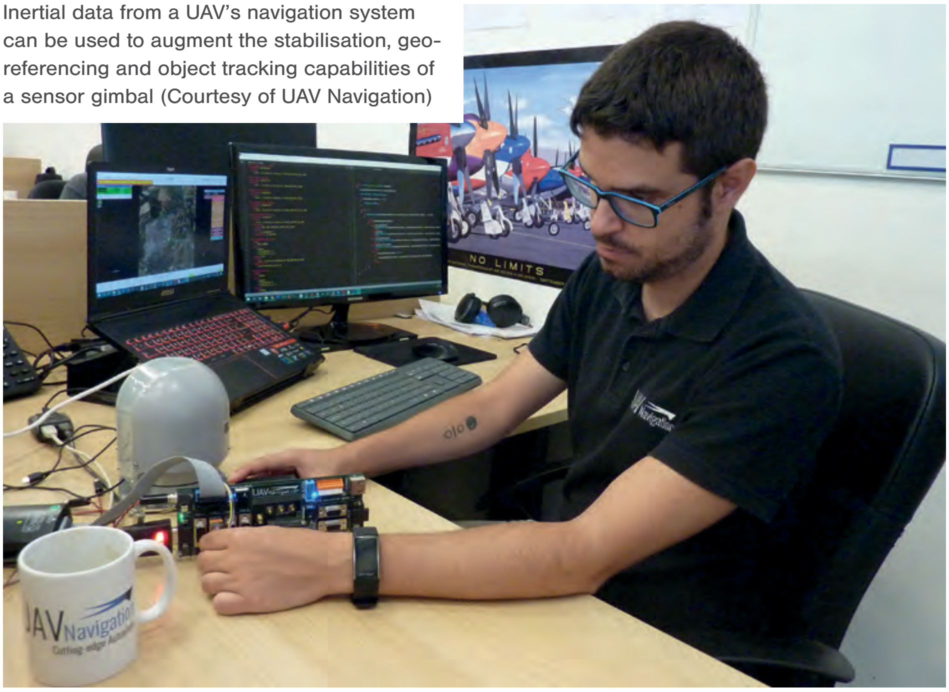
If metal AM is used to make complex sections such as monobloc parts, it could save gimbal manufacturers a lot of time and money, as well as being useful for identifying where material can be removed to save weight while maintaining balance and strength.

However, further improvements in the technology are needed for it to provide comparable tolerances and consistency to CNC-machined parts, as the latter still produces more structurally sound and consistent components, and more cost-effectively too.

Most high-end gimbals are made from CNC-machined aluminium alloys, to provide a high strength-to-weight ratio and a low thermal expansion coefficient. Also, they do not degrade over time from UV radiation, vibration or any of the other problems that adversely affect plastics. Their thermal conductivity helps draw heat from embedded processors too, conducting it to the outer hull to be dissipated by the surrounding airflow during flight.

Composite materials are also used for some structural parts in gimbals: fibre glass and carbon composite provide higher strength-to-weight ratios than aluminium. However, there are limitations to their usability in gimbals.

Producing composite material parts relies on using complex moulds and techniques, which are unsuited to the iterative processes typical of gimbal development and to the redesigns needed for accommodating new detectors, processors and other technologies. Also, gyro-stabilised gimbals can require hundreds of holes and threads: drilling those holes into composite parts breaks their fibres and encourages delamination.



Inertial data from a UAV's navigation system can be used to augment the stabilisation, geo-referencing and object tracking capabilities of a sensor gimbal (Courtesy of UAV Navigation)

Balancing

Advances in CAD software and the computer processors for handling them also help greatly in simulating the CoG and weight distribution across payload housings, which contributes to how well-balanced each sensor will be on its gimbal.

The more accurately the balance can be modelled, the less work will be needed later to get gimbal balance correct. It also means less current will be needed for the motors to control the pointing and movement of the cameras.

That is another important factor, because the actual process of measuring and improving gimbal balance is cumbersome. While the theory behind it is simple – you merely need to measure which side of each rotating assembly is heavier – putting it into practice involves repeatedly dismantling and reassembling a system's components, in order to measure the balance on each gimbal individually as well as how the overall system balances out when those parts are bolted together and interacting as they would during normal use.

As might be expected, a lot of trial and error is involved – adding and moving counterweights, or changing the position of components such as PCBs or encoders – to try to balance the weight across the gimbal system.

That often means placing each gimbal on a specialised weighing scale, with very fine bearings or needles installed to allow the scale to rotate freely. The heaviest part of the gimbal will then rotate to point downwards, so weight can be added on the opposite side.

However, there can be tiny but significant variations in how weight is distributed across and throughout the gimbal with each reassembly, with parts such as wires bending slightly differently each time, so extreme precision and care is needed. Many companies have developed their own proprietary methodologies for optimising the balance.

Additionally, the bearings on the gimbals and weighing scales can stick owing to the friction between them. If that happens, the balance measurements will be inaccurate, and the gimbal designer will have no real information on the improvements they have tried to make to the structure's balance.

More sophisticated, automated instruments are available for measuring the imbalance in each axis of a gimbal, but while they eliminate the need for dozens of rounds of disassembly and reassembly, they remain cost-prohibitive for gimbal manufacturers to acquire.

Geo-pointing and tracking

IMUs are critical not only for gyro stabilisation, but also to provide precise geo-pointing and tracking. Intelligent, dynamic tracking is of vital importance to defence, police and similar markets.

As a UAV flies, the payload gimbal will suffer vibrations and other forces that change its orientation. For highly dynamic flights involving the pursuit and tracking of moving targets, the MEMS IMUs integrated into small gimbals (for example, those weighing less than 3 kg) may not provide sufficiently precise information on the attitude of the aircraft to compensate for those forces.

To enable more accurate geo-pointing and tracking, a gimbal manufacturer and UAV developer can collaborate to use the inertial data being generated by the UAV's navigation system to provide an extra information feed to the gimbal.

Obviously, the more precise, reliable and frequently updated the UAV's inertial navigation system is, the greater the benefit of using its data to augment the gimbal's stability. That means the gimbal must at least be configured to take position and attitude information from the autopilot, or wherever the UAV's inertial navigation system is fitted.

> Gyro-stabilised gimbals can require hundreds of threads and holes; drilling them into composites breaks their fibres

Closer integration of the autopilot's software with that of the gimbal enables transmission of command and feedback data between the two systems, which offers scope for greater functionality. For example, geo-referencing can be carried out by programming the autopilot to aim the payload at a specific point on the ground, while also dynamically altering the flight pattern to provide the camera gimbal with the optimal vantage point for the target.

Alternatively, when flying along a series of waypoints for mapping or monitoring operations, the autopilot could command the gimbal to maintain or alter its heading and elevation angles based on previously defined parameters or triggers, without needing operator input. This can greatly help the accuracy of photogrammetry missions, as post-processing will

Cameras can be installed around the base of a gimbal to provide a 360° view for enhanced awareness and object detection (Courtesy of UAV Components)

Highly accelerated stress screening can be used to unearth a gimbal's likeliest eventual point of failure, and correct it, before repeating the process for further testing and optimisation (Courtesy of UAV Factory)

have no particular benefit if the camera is always slightly off.

With that in mind, this level of integration requires that the autopilot's interface control document, which contains the comms language and requirements of the device, be shared with the gimbal manufacturer. That enables pertinent data to be sent and received by both systems, but requires that the autopilot and gimbal developers collaborate to create a driver for powering that.

For more help with identifying and tracking targets, a new type of UAV gimbal design integrates a series of small cameras around its base, along with software-based 'stitching' of their video feeds, for a 360° panoramic view about the aircraft.

Advances in miniaturised smartphone cameras (and wide-angle lenses) can be exploited to prevent the panoramic cameras enlarging the gimbal base. When combined with the latest image processing systems, such a gimbal can be programmed to identify a range of different targets in all directions beneath the UAV, and prioritise them according to context-specific markers. The main EO/IR turret can then be pointed towards that prioritised target to zoom in on it and run further analytics to determine the next course of action.

Optics

Selecting the right gimbal window depends on the sensor, with the material being chosen to match the waveband in which the sensor performs best. The key is to be unable to notice any difference in the payload imagery whether the window is there or not.

Optical-grade glass is commonly used for RGB day cameras, with coatings optimised for minimal reflection and high durability.

Germanium is widely used for thermal cameras, as it provides very good transmission of MWIR and LWIR imagery. Silicon is also used in some gimbals with MWIR cameras (being relatively less costly than germanium), with further coating for 3-5 μm wavelengths.

Diamond-like carbon is particularly suitable as an IR coating for UAVs used for flying through sand, moisture or other sources of interference owing to its durability, although it tends to transmit 5-10% less IR light than other anti-reflective IR coatings.

For laser rangefinders, optical-grade glass with coatings specialised for wavelengths between 900 and 1550 nm are typical.

Different grades of optical sapphire are used for different wavelengths, from visible light through to SWIR and laser systems. Typical fabrication of sapphire windows involves ring polishing, a single-sided process that takes about 14-18 weeks to achieve minimal roughness, parallel surfaces on either side of the window, and high transmission of visible, IR or laser light. However, proprietary methods exist for double-sided polishing of sapphire windows, which can shorten lead times to between five and six weeks.

Sapphire provides far higher durability than most other optical materials, and with a coating it will last much longer than the other window materials without becoming scratched or cracked.

The optical quality comes from how well the crystals form, down to sub-grains that cannot be seen with the human eye but can certainly interfere with a laser rangefinder. The highest purity and quality of crystal structures are thus reserved for lasers.

Testing

Standards such as Mil-Std-461 and 810 often set the requirements for the operating tolerances of moisture, shock, vibration and temperature extremes of high-end gimbals, to name a few.

Some issues, such as misalignment or boresight errors are unavoidable during the manufacturing process, and must be addressed during testing so that they can be calibrated-out, either in software or mechanically. Given the complexity and number of integrated parts inside gimbal assemblies, however, it is impossible to test and calibrate (or redesign) everything that can go wrong over the system's lifetime.

One approach that can be very useful is Highly Accelerated Stress Screening (HASS). This requires a special chamber capable of subjecting the gimbal to significant shocks, including temperatures from -100 C to +150 C, and high vibration levels and shocks in random or pre-programmed directions.

These unearth latent defects in the assembly that could become apparent after several months of use, and encompass anything from loose wires to cold-soldered joints in the PCBs. The manufacturer can then go back through the production process to find where they occur, and replace the relevant manufacturing point with something more resilient.

HASS can then be conducted again, to find the next likeliest point of failure during the gimbal's lifetime, with tests and stresses on it being varied and randomised through a control interface to try different cumulative impacts on the system.

Conclusion

With gimbals being among the most mission-critical parts for a UAV's commercial and tactical viability, it is vital that manufacturers continue to adopt the latest technologies available for processing and stabilisation, while continuing to invest in their own core competencies in gimbal production.

Acknowledgements

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Examples of gimbal systems manufacturers and suppliers

AUSTRALIA
Ascent Vision Technologies
+61 265 811994 www.ascentvision.com

AUSTRIA
Dynamic Perspective
+43 1 28 100 28 www.dynamicperspective.com

BELGIUM
AltiGator (OnyxStar)
+32 (0) 497502349 www.altigator.com

CANADA
L3 WESCAM
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DJI
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ZHIYUN
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DENMARK
UAV Components
+45 20 63 11 98 www.uavcomp.com

ESTONIA
Threod Systems
+372 512 1154 www.threod.com

FRANCE
Merio UAV Payload Systems
+33 4 28 37 00 27 www.merio.fr

GERMANY
Kappa Optronics
+49 5508 974 0 www.kappa-optronics.com

HONG KONG
XDynamics
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INDIA
ZHIYUN
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Integrating a new type of solar cell and a new battery pack has extended the Silent Falcon EE's daytime endurance by about 60% (Courtesy of Silent Falcon UAS Technologies)

Cleared for take-off

Rory Jackson reports on the work by some developers to bring UAVs to an ever-widening range of applications

As end-users of UAVs become more proficient in their operations, and begin to request upgrades and reconfigurations that suit their specialist requirements, UAV manufacturers are trialling various new technologies and capabilities. These will provide critical benefits such as enhanced safety, reduced operator burden, and extended ranges and endurances, all of which are vital to ensuring the regulation and uptake of UAVs around the world.

Survey and monitoring

Silent Falcon UAS Technologies has unveiled the newest of its solar-powered aircraft, the Silent Falcon EE (for Extended Endurance). As its name indicates, it has been designed around providing longer flights, for applications such as border surveillance, wildfire monitoring and power asset inspections.

The Silent Falcon EE can remain in the air for up to 8 hours during the daytime and up to 4 hours at night (while carrying up to 3 kg of payload weight), which improves over the previous model's 5 hours of endurance during the

System upgrades included raising the power of the solar panels on the wings to 120 kW without increasing the solar panel area

day and 3 hours during the night.

"Realistically, we would only fly the older model for up to 3.5-4 hours in daylight and 2.5 hours at night," says John Brown, chairman and CEO of Silent Falcon UAS Technologies.

"The system upgrades included increasing the rated power of the solar panels on the wings from 80 to 210 W without increasing the solar panel area, which really extended our capabilities in daytime flight. We also changed the battery chemistry from lithium-polymer to lithium-ion, and in doing so increased the onboard energy storage from 732 Wh to 1.11 kWh."

The power converter responsible for making the solar power useable for charging the battery or powering onboard systems – the Multi Power Point Tracking device – has also been changed from a COTS system to one designed and built in-house to provide more energy efficiency and the ability to handle higher power loads.

Brown says, "Selecting new solar panels was key because we needed something with higher power density, improved power-to-weight ratio, and cost-effectiveness. It also needed a physical robustness that would enable it to withstand the parachute landings the Silent Falcon EE undergoes after flights, and to be worked into the structure of the wings during our carbon fibre lay-up processes."

The Silent Falcon EE uses a 'flexible silicon' material on its wings, which provides a 25.5% solar conversion efficiency. After testing a pair of flexible silicon test panels from the (undisclosed) manufacturer, the material was found to meet all the engineering team's desired parameters, albeit with a slight increase in weight and some minor manufacturing challenges that had to be overcome.

The new battery was designed and assembled by Justin Carr, the company's director of flight operations, who has gained experience in custom-building batteries for FPV racer drones that he operates in his spare time. After obtaining sufficient 21700-type cylindrical cells, he built the new battery according to a theoretical design he had been working on, and ended up with a system that increased the energy storage by 378 Wh while adding only 1 lb of weight.

On top of the power system upgrades, the Silent Falcon EE's GCS uses a new comms system called the SF TriAntenna configuration. This combines two directional antennas with one omnidirectional antenna (compared with the single-antenna system used previously), and test flights so far indicate large increases in bandwidth and far fewer drop-outs when the UAV nears the data link's maximum range.

"The system doesn't increase the comms range but it makes the data link much more reliable, which is critical for operator confidence when you're working at the long distances the Silent Falcon EE is to be used at, and in need of high bandwidths and throughput for transmitting data in real time," Brown says.

Also aiming for longer endurance times is Leonardo, which has unveiled the Falco Xplorer, its newest and largest long-endurance tactical UAV.

It joins the rest of the Falco unmanned aircraft series, which includes the Falco UAV (featured in *UST* 5, December 2015/January 2016). It has a 1.3 tonne MTOW with a payload capacity of 350 kg, a flight time of at least 24 hours and a BVLOS satellite comms capability.

The Xplorer is currently undergoing certification for flight in non-segregated airspace (with more flight trials scheduled throughout 2019), to enable it to be flown in civil operations such as emergency responses or coast guard patrols and interdictions, in addition to being designed for defence operators.

Research

In a new benchmark for alternative UAV power solutions, a collaboration between UK-based fuel cell manufacturer Intelligent Energy and South Korean liquid hydrogen developer MetaVista has led to the setting of a new world record for multi-rotor UAS flight.

The flight lasted 12 hours, 7 minutes and 22 seconds (compared with the previous record of 2 hours, 6 minutes and 7 seconds), and was accomplished with a quadcopter using a combination of an Intelligent Energy 800 W fuel cell power module and a MetaVista 6 litre liquid hydrogen storage vessel.

With the hydrogen tank and fuel cell installed, the test UAV had a gross weight of 7 kg, and largely hovered about the same spot outside the MetaVista offices for the duration of the flight.

"We had never worked with liquid hydrogen before teaming up with MetaVista; liquid hydrogen technology isn't entirely commercially viable yet, but MetaVista's research is focused on changing that," explained Andy Kelly, head of UAV product development at Intelligent Energy.

"It stands to provide a much, much higher energy density than the compressed hydrogen gas we're used to working with – perhaps three or four times higher. Making liquid hydrogen fuel viable is a matter of maintaining a temperature close to absolute zero inside the storage vessel, to keep the hydrogen in liquid form, but once you can do that, the pressure inside is so low that you don't need a very mechanically robust tank like you do to keep compressed hydrogen gas at 300 bar."

The MetaVista storage solution combines cryogenic insulation with lightweight materials. The boil-off hydrogen gas flows from the liquid storage tank across the anodes of the fuel cell to power it; Intelligent Energy did not have to make any modifications to its fuel cell module before the flight.

"We have a fairly loose set of specifications regarding input pressure, flow and temperature of the hydrogen gas, so once you can meet those, our fuel cell will run," Kelly says.

"For example, 0.5 bar is the required input pressure, and as the liquid hydrogen is stored at perhaps 3 bar, only a small regulator was required – much smaller than our standard regulator, which has to regulate 300 bar of compressed gas down to 0.5 bar. MetaVista had to modify the regulator and pressure transducer slightly in order to give accurate readings on the remaining fuel, but that was all."

A lightweight fuel cell has been combined with liquid hydrogen tank technology to achieve a new world record for multi-rotor endurance (Courtesy of MetaVista)

As Intelligent Energy and MetaVista have signed a memorandum of understanding for long-term partnership and collaboration (which happened after a previous test flight achieved more than 10 hours of flight with a 650 W fuel cell), further tests and development are expected in the months ahead.

Further afield, NASA is planning to send its Dragonfly multi-rotor aircraft to Saturn's moon Titan, where it will look for evidence of prebiotic chemical processes linked to the origins of life on Earth.

When it reaches Titan's surface, in 2034, it will use the density of the atmosphere (which is about 50% higher than that of Earth's) to 'leapfrog' up to 8 km at a time to different locations and environments, collecting samples and making measurements. The mission's total surface distance will reach 175 km, almost double that travelled by all the Mars rovers to date.

Safety

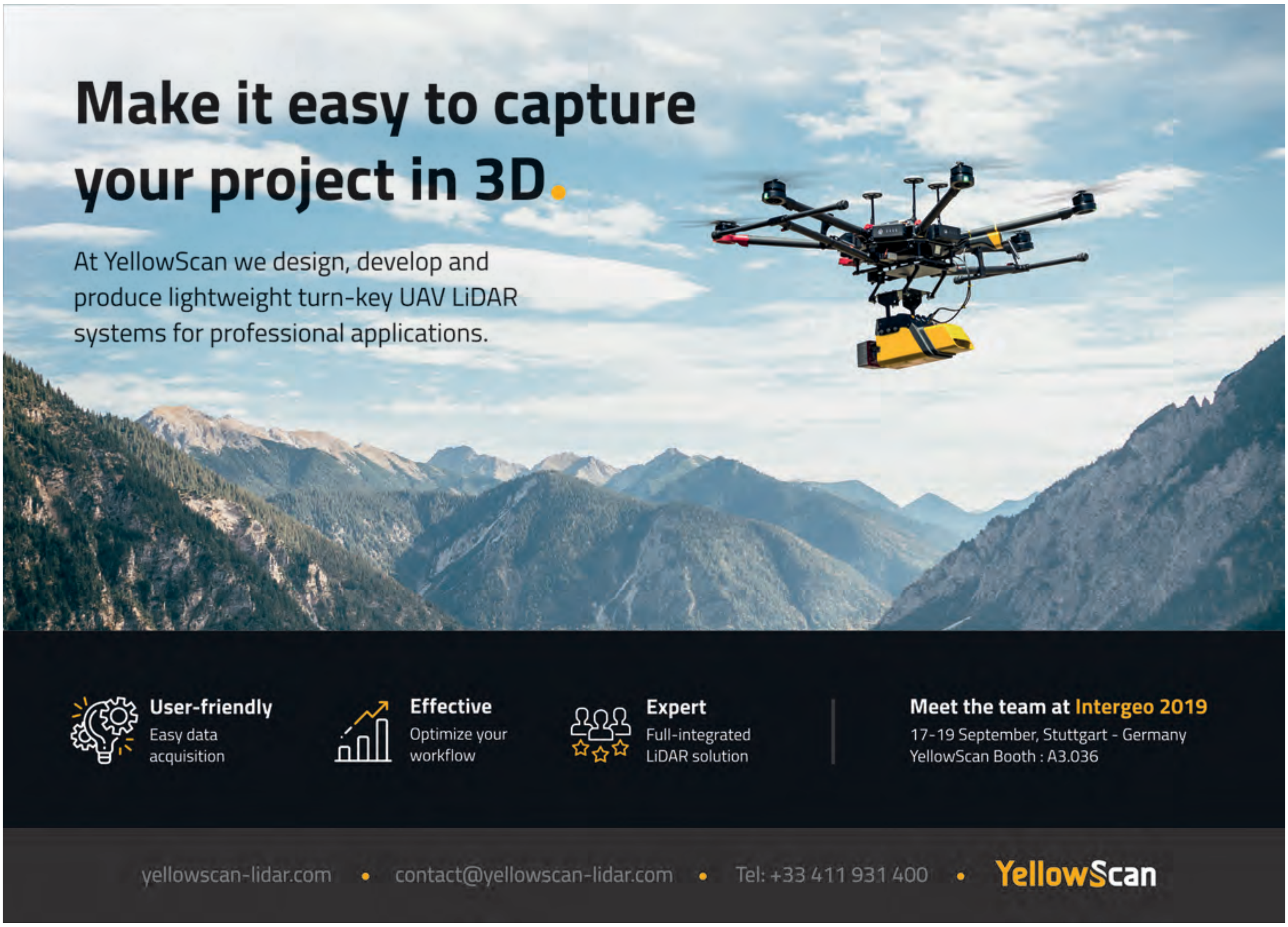
Alpha Unmanned Systems has updated its Alpha 800 helicopter UAS with a fully automatic autorotation capability, developed in collaboration with fellow Spanish company UAV Navigation using its Vector autopilot.

The autorotation enables emergency 'gliding' of the helicopter rotors if the engine, power transmission or tail mechanism fail during flight.

As Alvaro Escarpenter, COO of Alpha Unmanned Systems, explains, "In manned aviation, pilots have to train until they reach the point of muscle memorisation for the manoeuvre.

In UAVs, autopilots are generally not just programmed to perform autorotation: the rotor rpm is controlled by the engine, and the altitude or height is controlled by the collective pitch angle control or collective lever.

"Therefore, during engine failure, the revs are reduced, as is the lift,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Autonomous autorotation on helicopter UAVs will greatly reduce the dangers posed by an engine failure or transmission breakdown (Courtesy of Alpha Unmanned Systems)

causing the vehicle to lose altitude."

The autopilot typically responds by actuating the collective lever to increase the pitch angle, which only slows the main rotor more (since there is no power), until it stops entirely. Before this issue can be solved, the autopilot needs to be able to safely recognise and declare when an engine failure has occurred, in order to begin the autorotation manoeuvre.

Necessary mechanical changes to the Alpha 800 system included integrating a one-way bearing and clutch on the main rotor transmission, to ensure the main rotor can continue to be driven by the main transmission, but without the reverse happening. That prevents the tail rotor being pulled during autorotation, thus keeping all the energy on the main rotor and reducing the vertical and horizontal movement speed required for gliding.

Also, an rpm sensor has been directly coupled to the main rotor, to ensure a constant feed of rpm measurements to the autopilot. "Some UAV helicopters have their rpm sensors installed on the engine or some part of the transmission, which will not work during autorotation," Escarpenter says.

> Some helicopters have their rpm sensors installed on the engine or a part of the transmission, which won't work in autorotation

"The propeller blades must be designed with the capability to be set to a negative pitch as well, in order to increase the main rotor speed by pulling back on the collective lever when the UAV falls below the target revs."

The autopilot system from UAV Navigation has also been programmed with the necessary logical pathways to identify the conditions unique to an engine failure, and to control the mechanical aspects of autorotation that Alpha Unmanned had designed in.

After 18 months of working with UAV Navigation, Alpha Unmanned Systems conducted flight testing of the autorotation technology at its airfield, with the aim of consistently gliding and landing safely with the engine stopped. That also required developing the capability to simulate an engine failure without repeatedly (or ever) putting the UAV at risk of being destroyed.

The test programme consisted of more than 100 simulated autorotation manoeuvres with the engine at idle, with the flight team iteratively adding more complexity with each test as they collected and analysed the UAV's telemetry and flight data.

The Vector autopilot has also been gradually updated to improve its autorotation logics, and has had a number of protection features added to avoid saturating the engine or the collective lever (which reduced the possibility of a failure requiring autorotation in the first place).

Oil and gas

As the prospect of legal BVLOS commercial UAV flights becomes more and more likely, Robot Aviation has successfully conducted two BVLOS training flights with US company Skyskopes. The latter plans to use the former's FX20 aircraft in aerial oil and gas infrastructure inspections.

"Our training site allows us to fly BVLOS operations, which is important for us because in the US it's very complicated to do that, with strict constraints on flight corridors and similar obstacles of that nature," explains Niklas Nyroth, director at Robot Aviation.

"The flights took place in the first week of December 2018, and Skyskopes has bought an FX20 system specifically to provide an aerial inspection capability for the oil and gas industry in North

Dakota." Robot Aviation conducts its BVLOS tests in Norway.

With the FX20, Skyskopes aims to fly with a longer endurance and range than the multi-rotor systems that most aerial inspection companies offer, but BVLOS capability is key to that, in terms of legislation, enabling technologies and in-house training with those technologies.

The FX20 is electrically powered and capable of flying for up to 4 hours, depending on payload. The battery pack is made by a fellow Norwegian supplier.

To further enable BVLOS integration, a Mode-S transponder is installed on the UAV, as is a pilot-view camera to provide a live feed of what is ahead of the aircraft. The data and video comms link has a 40 km range, with an optional 200 kbit/s satellite link for BVLOS comms.

Testing BVLOS capabilities is problematic for US-based pilots, so European airfields such as that used by Robot Aviation are critical for development (Courtesy of Robot Aviation)

Defence

Sikorsky has successfully converted and flown one of its UH-60A Black Hawk helicopters as an OPV (optionally piloted vehicle), by applying an automation kit the company refers to as its Matrix technology.

The kit was developed and tested on a helicopter called the Sikorsky Autonomy Research Aircraft, with more than 300 hours of flight tests achieved so far.

"In a military space, you can still have missions such as bridge inspections, carrying loads and others that aren't as sophisticated as attack or reconnaissance missions," explains Igor Cherepinsky, the company's director of autonomy. "In such cases, it makes sense to have just one pilot and to offload work to an autopilot to reduce their burden, or perhaps fly with no pilot at all."

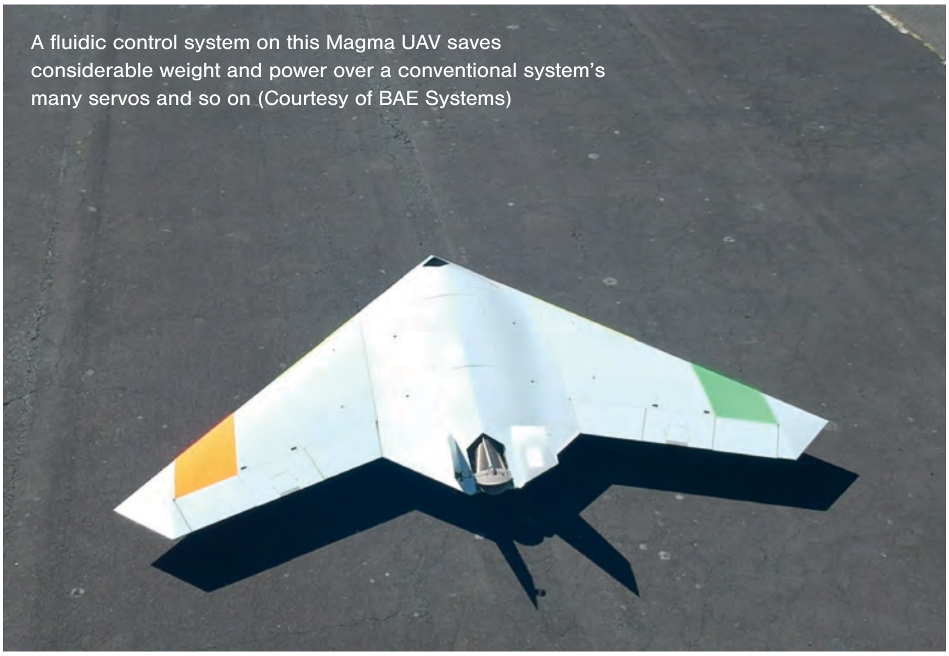
The Matrix technology consists of various software and hardware components that are selected and applied according to each vehicle's requirements, to accomplish these relatively simple operations without the need for data links or a 'man in the loop'.

To convert the manned helicopter to an optionally unmanned vehicle, the engineering team at Sikorsky first removed all the mechanical controls and replaced them with a fly-by-wire architecture, before adding more perception sensors for greater safety in navigation and obstacle avoidance. They included various optical cameras, Lidars and radar systems, with embedded sensor fusion algorithms to stitch the data together.

Although the aim has been to develop full autonomy, data links for line-of-sight and BVLOS operations are still maintained and operators can, where necessary, input commands of their own from the cockpit, rear cabin or a GCS.

"You can also have complex cargo logistics or other operations where you benefit from sharing information and control between the air and the ground, where logisticians direct the OPV from the ground, rather than having the pilot try to figure out where to put crates or pallets," Cherepinsky adds.

Varying degrees of autonomy could be employed by UH-60A Black Hawk OPV pilots, from partial automation to lessen the burden on the pilots to full autonomy for operations such as bridge inspections (Courtesy of Sikorsky)



A fluidic control system on this Magma UAV saves considerable weight and power over a conventional system's many servos and so on (Courtesy of BAE Systems)

"As the helicopter OPV approaches its destination, the pilots can hand over control to ground personnel for placing the cargo, before retaking the controls to return to base; there are lots of use cases for OPVs like that."

As well as improving safety and functionality, converting helicopters into OPVs could enhance their endurances or carrying capacities by removing the 100-200 kg weight of onboard personnel.

In another innovation towards greater endurance in defence aircraft, Boeing has awarded Harris a contract to supply the mission management processor for the former's MQ-25 refuelling tanker UAV.

The MQ-25 is being developed for the US Navy to extend the range of carrier air wings, in an $805 million contract to Boeing for four refuelling UAVs by August 2024. That programme might be extended to encompass 72 aircraft and $13 billion in funding.

The processor will handle sensor and comms functions on the UAV, while also providing onboard processing capacity for further advanced computational requirements. That and any further hardware or firmware provided by Harris will follow Boeing's open systems architecture solution, which is aimed at developing common standards across avionics systems. BAE Systems has also been granted a contract by Boeing to supply critical avionics components for the MQ-25 project.

The UK company will provide the UAV's vehicle management control system for operating all the flight control surfaces, as well as its IFF (identification friend or foe) system for discerning enemy vehicles from friendly ones.

Aerospace engineering

Meanwhile, BAE Systems is continuing with its r&d for flight control systems, using its own flying wing platform.

The Magma demonstrator UAV (featured in *UST* 26, June/July 2019), developed in collaboration with the University of Manchester, in England, has been used to trial 'wing circulation control' and 'fluidic thrust vectoring', techniques that use blown air from a compressor on the Magma's gas turbine engine to control pitch and roll, and which were tested in May this year.

The theory behind both techniques has existed for several decades, but testing was stopped long ago owing to the belief that they were fundamentally unachievable.

As Bill Crowther, leader of the Magma project at the University of Manchester, explains, "Previous attempts at wing circulation control have used large slots and large trailing edges, but our research has focused more on miniaturisation, high speeds and high pressures.

"Advances in CFD have helped, and additively manufacturing the required parts from titanium to very precise resolutions was critical to creating the 4-5 mm slots needed at the trailing edges of the Magma's 4 m wingspan."

The fluidic thrust vectoring assembly was also additively manufactured in titanium, with the overall system weighing about 3.3% of the weight of the aircraft (the team was targeting a maximum weight budget of 10% of the Magma's total weight).

"For example, the engine nozzle weighed 700 g. That delivered 200 N of thrust, with the whole system held in place by four M3 bolts," Crowther notes.

While conventional aircraft use numerous servos to actuate the flaps, ailerons, elevators and so on for flight control, these fluidic control techniques use only one or two servos each to actuate the required control valves. They are also much smaller, lighter and less power-hungry.

"If you compare the weight of the actuators used on the Magma with those on a similar but conventionally controlled aircraft, you use about 15% of the mass of the conventional control system, and they would probably consume less than 5% of the electrical power," adds Clyde Warsop, engineering fellow at BAE Systems.

"There is some cost in terms of the air bled from the engine, and the extra fuel burnt to do that, but our initial studies indicate a less than 0.5% increase in fuel consumption over a 1 hour flight."

Conclusion

Common among many of the new technologies being trialled on UAVs is transferability, and systems being developed for niche commercial, defence or research organisations will inevitably be reinvented and refined to provide even better performance and new use-cases as time goes on.

New product launches, partnership deals and applications abounded at the 2019 show

Second helping

Rory Jackson concludes his round-up in issue 26 with more product news from this year's exhibition

AUVSI Xponential is by far the largest unmanned systems trade show and conference in the world, with the 2019 iteration of the event having hosting more than 700 companies on the expo floor at Chicago's McCormick Place. With so many companies attending, countless new launches, partnerships and use cases for unmanned technology were to be found.

SBG Systems unveiled its new Quanta UAV series of navigation IMUs at the show.

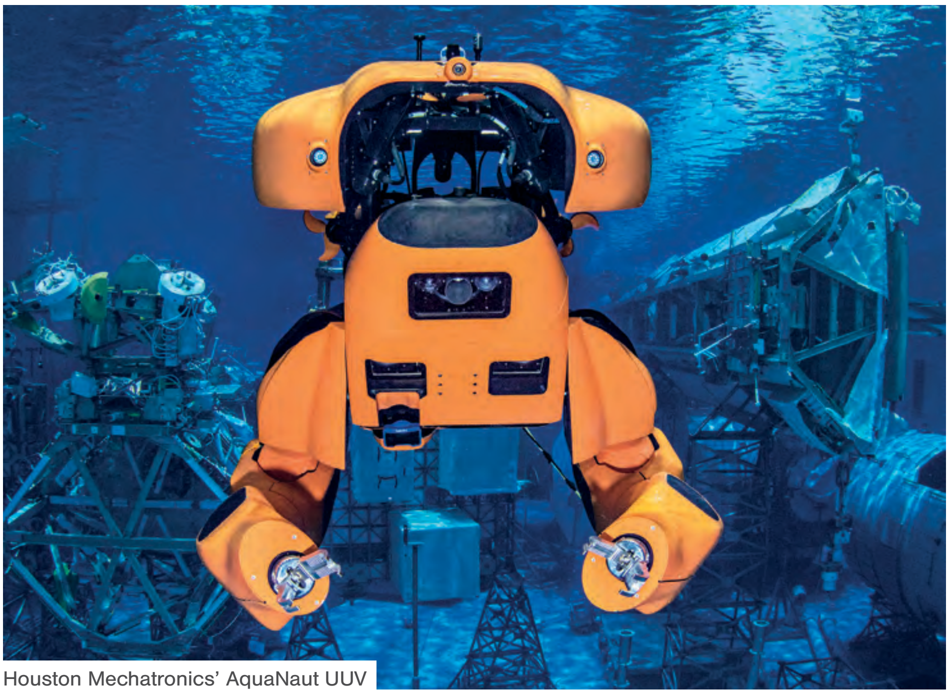
"Compared to our other IMU systems, Quanta is designed to specialise in survey applications such as Lidar mapping and other photogrammetry-type missions," said Alex Guinamard.

"It has an inbuilt data logger, to aid in post-processing operations, a web interface, and each Quanta board comes with a 12-month licence for our Qinertia post-processing software."

Qinertia's geo-referencing data comes from a network of more than 7000 base stations across 164 countries, in order to provide PPK centimetre-level accuracy. Alternatively, a user's own base station data can be used.

The Quanta UAV IMUs also come with RTK processing compatibility for further accuracy in geo-referencing images and point clouds during flight when supported by a GNSS. With RTK, roll and

A Quanta UAV series navigation IMU from SBG Systems



Houston Mechatronics' AquaNaut UUV

pitch are accurate to 0.03°, which with PPK processing improves to 0.025°.

The IMU weighs 76 g, measures 78.75 x 51.5 x 20 mm, and draws up to 3.5 W. The installed data logger can hold up to 8 Gbytes, with serial, Ethernet or CAN bus interfaces to the other onboard systems.

Houston Mechatronics is continuing development of its AquaNaut UUV, a hybrid ROV/AUV system developed for underwater construction, retrieval and other heavy subsea engineering tasks. "We now have a fully functional UUV, and we're testing that vehicle and its electrical manipulator arms with some runs recently completed at the NASA Neutral Buoyancy Lab in Houston," said Sandeep Yayathi.

"The arms have eight degrees of freedom, with a wide kinematic workspace, and five joints going down each arm with two more at the end for roll and grip."

The vehicle uses an onboard DVL-INS for navigation and station-keeping, with seven thrusters distributed around the hull for stationary hover, forward cruising, diving and various other manoeuvres for closely navigating subsea infrastructure.

Defence, oil and gas, and similar industries are anticipated as markets for the vehicle, particularly as the UUV's 200 km range can make the costly use of ROVs and manned surface vessels unnecessary.

RCV Engines has made the first customer delivery of its new (unnamed as yet) heavy-fuel engine for unmanned vehicle applications. It is an evolution of its well-proven 70 cc two-cylinder, four-stroke boxer engine profiled in *UST* 5 (Winter 2015).

"This new engine is a fuel-injected four-cylinder boxer engine that displaces 140 cc," said Eric Hill. "We've developed it with an ECU-controlled liquid cooling system for reliable thermal management in hybrid applications. The first customer engine has now been handed over for vehicle integration and functional testing."

Coupled to a suitable generator, the engine will typically operate at between 4000 and 8500 rpm. Its patented rotating valve technology accepts gasoline- or kerosene-based heavy fuels such as Jet A1, JP-8 and JP-5. Being a four-stroke, the engine has inherently low fuel consumption and exhaust emissions and, with a suitably designed airbox and exhaust muffler, can achieve a low acoustic signature without compromising performance.

Having installed CAN interfaces on its small, high-volume DA-15N servo actuator range last year, Volz Servos is continuing to make the CAN protocol available across its other systems, with the DA-26D and DA-30D redundant servos now incorporating CAN bus ports.

"Having CAN bus means simpler comms between servos and onboard processors such as ECUs or autopilots, as well as reducing the number of wires on the vehicle, and increasing the

The Volz DA-15N actuator, with CAN interface

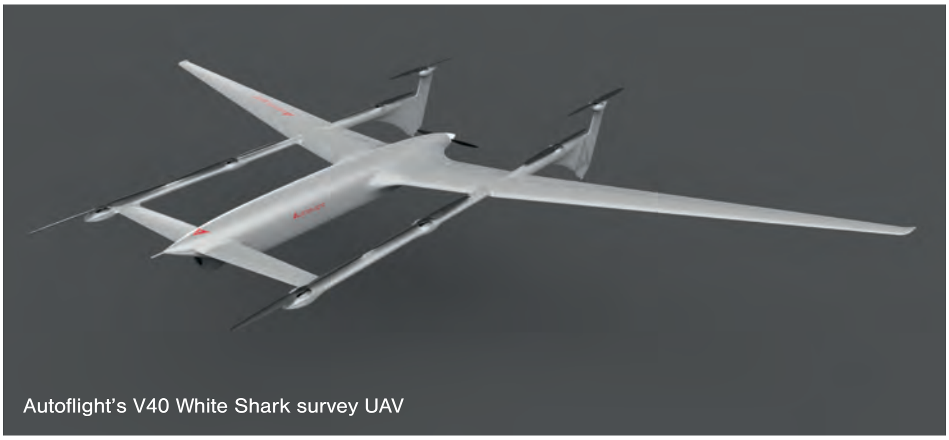
communication bandwidths," explained Mark Juhrig.

"CAN gives just the means to send and receive data, and takes care of all the lower levels of the protocol. Open standards such as UAVCAN are designed for communicating with servos, or we can design a custom standard with the customer to fit their specific architecture, for example to talk to their servos as well as their onboard sensors."

The company will next be installing the interface on its single-lane servos, such as the DA-26, DA-30 and DA-36, as well as its high-torque DA-30HT servo and its DA-22BLDC, largely by porting the same processes developed for the DA-15N.

Vertical Partners West has signed a partnership with Teledyne Energy Systems for the latter to provide the former with reverse engineering and domestic assembly services, towards developing future energy storage and battery management systems.

"In particular, the use-cases that will benefit from this partnership and the kinds of products that could come out of it will include applications with extreme pressures – such as UUVs – or situations where an unmanned vehicle is moving through extreme cold, and other challenging environmental conditions where you need to keep dust, sand and water out of the battery," said Keith Wallace.



Autoflight's V40 White Shark survey UAV

Vertical Partners West now has an energy storage deal with Teledyne Energy Systems

"The technologies our partnership is aiming to develop will also be useful for operations at high elevations – any situation where you have to precisely heat or cool the battery to keep it within its operational envelope," he added.

"Those are areas where Teledyne Energy Systems' experience in working with spacecraft and underwater vehicles over the past several decades will be useful. We already have multiple projects in place with some of our customers."

UAV developer Autoflight attended the show to unveil its new B15 UAV, which is designed for heavy-lift applications, particularly fast cargo delivery for logistics companies.

"We have designed it with a nose that opens to access the cargo bay at the centre of gravity, in which 5 kg can be stored, after which it can fly at up to 140 kph with a 100 km data link," said Thomas Hartzdorf. "That enables timely 'last-mile' deliveries of end-user products and components."

The craft is battery-powered, with up to 90 minutes of endurance. A hatch on the rear fuselage contains the UAV's electronics, and its twin-boom design integrates four downward-facing electric motors for VTOL, with one pusher propeller at the rear of the assembly. Ascent and descent speeds of up to 2 m/s (7.2 kph) are typical.

The B15 has two tailplanes, one at the rear of each boom, with only two servos across the entire airframe and one elevator on each boom to minimise the number of potential points of mechanical failure. Alternatively, the UAV can be designed with two ailerons instead of the two elevators if preferred by an end-user.

"Adding this tail assembly to what is otherwise a flying wing design makes the B15's flight much more stable, and easier to control," Hartzdorf said.

"Our software department worked to develop autopilot algorithms, hardware and even motors in-house to work with this UAV's specific airframe body design and flight profile."

Autoflight also displayed its V40 White Shark survey UAV, which was unveiled in early 2019 and features eight VTOL motors that run along the twin booms of the airframe from the canard to the main wing, with a wingspan of 5.1 m. The electric version of the craft has an MTOW of 45 kg (22 kg empty weight) and a payload capacity of 8 kg. It can typically fly at up to 130 kph, or 95 kph in standard cruise.

The V40's powertrain can also have some of its batteries swapped for a hybrid range extender, to boost the flight range from 450 km (the maximum on battery power alone) to 1300 km (or more, pending further flight tests). The hybrid propulsion system also enables a 140 kph maximum speed and a 100 kph cruise, although the flight ceiling is reduced from 4500 m to 3500 m.

"It is designed for missions such as maritime surveillance, border control, traffic monitoring and similar, and we use only CAN bus comms inside the aircraft to maintain fast and stable data transmissions between all the subsystems," Hartzdorf noted.

UAV Components displayed two new sensor gimbals for unmanned aircraft for the first time at the show.

"The first one we're unveiling is the Øi Lite, which comes with a 10x optical zoom and weighs 290 g, although we're hoping to do a little more redesigning to get that down to 250 g," said Frank Severinsen.

"The second is the Øi 360, which is designed with six smaller cameras fixed in the upper rim above the main sensor ball, arranged radially in a 360º FOV, with a built-in Tegra TX2 media processor chip from Nvidia, a 30x optical zoom and two FLIR thermal cameras. This arrangement can be used for additional situational awareness so that pilot teams don't collide with anything while focused on the view from the main gimballed camera."

The Øi 360 can also be programmed to turn and focus autonomously on moving objects or targets of interest picked up by the 360° cameras, to gain a closer view and gather intelligence using the thermal cameras or the 30x zoom.

"The Nvidia processor we've chosen can run all the necessary neural networks and other AI algorithms for running intelligent recognition or detection algorithms through the 4K cameras, so that UAVs being used to monitor specific targets such as in border survey, maritime surveillance or industrial inspections can do so more easily," Severinsen added.

The company also unveiled its new C2Nav GCS for UAV operators, which is based on the Panasonic Toughbook CF20 and Toughpad FZ-A2 ruggedised tablets, and comes with versions for Windows, Linux and Android operating systems. Specifications of the C2Nav will be released later this year.

Lastly, UAV Components launched its G2Nav, the company's first large ruggedised GCS which comes in a Pelican case. It integrates two 21.5 in

A Tallysman HC Iridium antenna

180 cc engine from Avanti Unmanned Systems

Septentrio's 'mosaic' GNSS module

touchscreen monitors and a range of control interface options including standard keyboard, multiple joysticks and dials.

The larger size of the G2Nav (compared with the company's usual smaller, tablet-sized GCSs) allows higher levels of processing power and more powerful data links to be integrated into the system, for users looking to conduct missions at high altitudes with long endurances and live HD video outputs.

Tallysman showcased a major extension of its lightweight GNSS and Iridium antenna portfolio, debuting the first three models of a high-performance line of housed helical antennas; they are the lightest line of antennas to be released by the company.

They are the HC600, an 18 g passive Iridium antenna; the HC871, a 25 g dual-band active GNSS antenna supporting GPS/QZSS L1/L2, GLONASS G1/G2, Galileo E1, and BeiDou B1; and the HC872, a 36 g dual-band active GNSS antenna, supporting the same frequency coverage as the HC871, as well as L-band correction services.

"We've designed our helical line of antennas to achieve an axial ratio of below 1 dB, and in many cases below 0.5 dB," said Mohamed Emara. "Furthermore, with our pre-filtering features, we mitigate interfering signals such as wi-fi on 2.4 GHz, 4G LTE at 700 MHz, and other near-frequency signals that can cause problems for UAV operations in busy, urban areas."

Avanti Unmanned Systems has developed a range of reciprocating UAV engines, from 32 to 180 cc, and at the show it displayed its 180 cc two-stroke, two-cylinder product.

"The 180 cc engine has been developed to fulfil a range of UAV propulsion envelopes and needs," said Chris Goodman. "It produces up to 18.5 hp, and we have built an alternator/starter into it that can generate 400-600 W of spare power.

"We're seeing a lot of interest in hybridisation as well, so we offer an option for a larger alternator that can generate power in the 3-4 kW range."

The standard alternator/starter weighs about 870.5 g, and the starter is powered by an internal lithium-polymer battery (typically a 24-45 V, 6S or 7S system).

The crankcase is machined from an aluminium 6061-T6 billet, rather than cast, which makes the crankcase stronger and much less prone to cracking, according to the company.

While displacing 180 cc (with a bore and stroke of 53 and 41 mm respectively), the engine's cylinders also have a compression ratio of 8:1. The engine idles at 1300 rpm and runs up to 7200 rpm. It takes 93 octane fuel, with a 1:40-1:50 ratio of two-stroke oil and gasoline in the fuel mixture, and weighs a total of 4.752 kg.

Septentrio showcased its 'mosaic' GNSS module, which is designed as the company's smallest form factor satellite navigation solution.

"It measures 31 x 31 mm, and integrates the same capabilities as the rest of our GNSS receivers, including RTK processing and our AIM+ interference mitigation algorithm," said Francesca Clemente. "Such small size and light weight is critical for UAVs, and is also useful for automotive systems as they are equipped with more and more sensors for autonomy and redundant navigation."

The Mosaic receiver weighs 7 g and updates at rates of up to 100 Hz. It also integrates Septentrio's IONO+ algorithms to correct for ionospheric disturbances of received satellite data, as well as its LOCK+ algorithm that enables tracking to be maintained amid rapid signal changes, for example those caused by mechanical vibrations or shocks, earthquakes or ionospheric scintillations. That enables prolonged operations in a range of harsh environments.

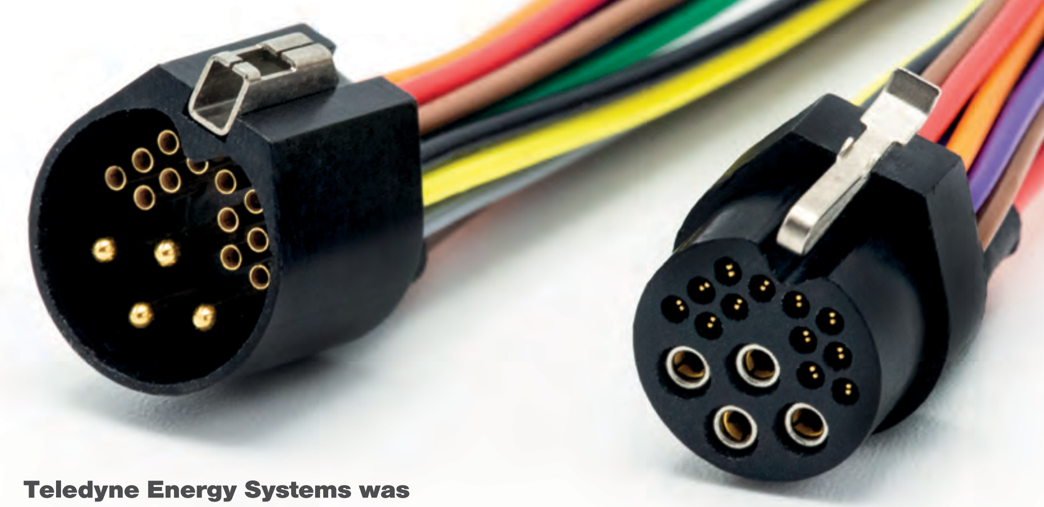
Most of the development work on the module went into determining the number of components and functions that could be minimised, and identifying ways to minimise the distance between the components that remained.

Omnetics showcased its newest plastic hybrid circular connector for UAVs that need lightweight interfacing components.

"Reduced weight is driving more and more of the decision-making in UAV designs, and we've been aiming to reduce our size and weight accordingly," said Scott Unzen. "Making our latest hybrid connector from plastic rather than metal was key to that, and it combines 12, 3 A micro-contacts with four 7.5 A size-20 power contacts in order to provide several power and comms interfaces in a single housing."

The connector also uses a 'click' latch to add to the security and integrity of the interface. The housing is made from glass-filled liquid crystal polymer or polyphenylene sulphide, and the connector's exact weight will vary depending on the insulation material and gauge selected by the end-user.

Omnetics hybrid circular connector, with latch



Teledyne Energy Systems was walking the aisles of the expo floor to discuss the newest version of its subsea charging station for UUVs, an update to the Subsea Power Node (as reported in *UST* 22, October/November 2018) called the Teledyne Subsea Supercharger.

"This new iteration has the same capabilities as the Subsea Power Node, but it's been redesigned with a pressure vessel housing that'll enable it to go down to 1000 m below sea level," said Thomas Valdez. "The old pressure vessels were plastic, mostly so we could quickly produce and test the prototypes, but now they're made of steel to provide that extra strength for deeper operations."

The base Subsea Supercharger provides 100 kWh of energy storage, an 8 kW operating power output and voltages up to 400 V. So far, it has been tested in the dockside waters of Rhode Island in the US, but the company also plans to test it underwater in Aberdeen, Scotland, in September.

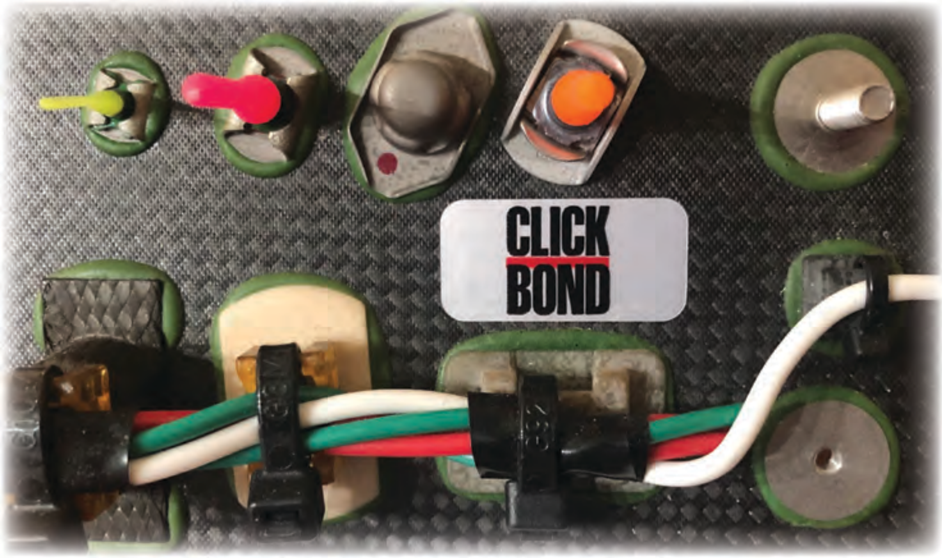
The Subsea Supercharger from Teledyne Energy Systems

MKS Servos attended the show to unveil its newest actuators for unmanned aircraft, including the HB135WP-12, which is among the company's larger models and has been developed for high power and torque applications.

"It's a 12 V servo, which runs up to 14.8 V and puts out up to 135 kg-cm of torque," said Thomas Cooke. "It's currently a PWM configuration, but it also has an analogue feedback loop with a magnetic encoder for position feedback. It uses a 10 mm output shaft as well, although we'll have a number of different hubs and arms as options for it."

The servo measures about 73.4 x 64 x 33 mm and weighs 389 g, and is housed in an IP67-rated, CNC-machined 6061 aluminium enclosure.

MKS also launched its P1000 servo, which is EMC-certified as per its (undisclosed) end-customer's requests. The P1000 is also the company's first CAN bus-compatible servo, and produces 381 kg-cm of torque at 24 V, while weighing 1.2 kg and measuring 144.65 x 96 x 38.1 mm.



Click Bond adhesive-bonding fasteners for unmanned vehicles

Roto Motor's 85 FS AL UAV engine

Roto Motor, a developer of reciprocating engines, showcased its newest UAV engine, the 85 FS AL.

"It uses electronic fuel injection, and as standard it has a 300 W starter/generator," said Petr Cita.

"It was designed principally for UAVs with wingspans of around 4 m and weighing up to 35 kg. The entire engine weighs around 4 kg, and typically has a 500-hour interval between overhauls."

For end-users wanting more electrical power, the system can be fitted with a 600, 1000 or 2000 W generator.

The engine is a four-stroke, two-cylinder boxer displacing 80 cc and producing up to 4.1 hp (3.06 kW). It is air-cooled, and runs on 95 octane fuel (with 2% oil); fuel consumption is between 600 and 920 g/h, and it has a maximum speed of 6500 rpm.

Click Bond showcased its latest solutions for adhesive-bonding fasteners in place on unmanned vehicle structures. The company offers a line of adhesives designed for use in temperatures from -55 to 177 C. These fast-curing adhesives enable assembly and installation in less than an hour.

"Instead of riveting, you bond our fasteners in place," said Amy Arnold. "Riveting nut plates requires making three holes for every hole you actually need – one for the bolt and nut, then two more for the rivets on either side.

"Bonding therefore eliminates at least two-thirds of the holes from vehicle hulls and bulkheads, which preserves structural integrity, minimises leak paths and helps prevent galvanic corrosion by reducing contact between metals. It also reduces manufacturing time and repair work compared with riveting.

"Drilling fewer holes also helps preserve structural integrity in composite materials, as there is less opportunity for fractures to propagate."

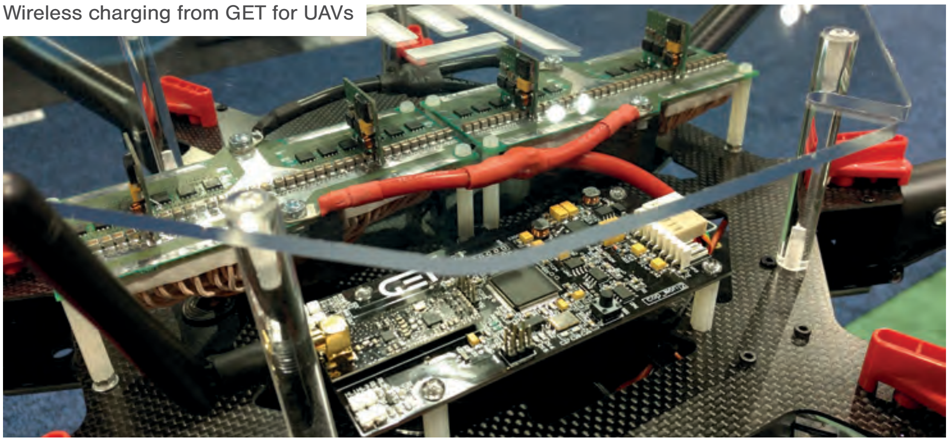
In addition to nut plates, studs and stand-offs, the company has developed installation fixtures for providing continuous clamp-up during the adhesive cure to ensure optimum bond strength. They also offer high re-use nut elements (up to 50 times) for applications that experience high wear, such as on access panels or over battery packs.

Aerospace company Spaitech showcased its range of UAV systems, including the Sparrow UAS, which is designed for operations with special forces-type groups.

"Having designed and certified the electronics and programming to military standards, it's now in use with special forces in different regions of the world, with groups such as marines, paratroopers and high-mobility reconnaissance teams," said Igor Bogomolov.

"To keep it invisible to radar, the hull is built from a radio-transparent composite,

Spaitech' Sparrow UAV, for special forces-type operations



Wireless charging from GET for UAVs

and we've kept the weight to 3 kg. Its speed ranges from 70 to 140 kph for additional stealth in flight."

The Sparrow has a comms range of 20 km, and endurance is between 45 and 85 minutes depending on flight speed.

Spaitech also exhibited its Sparrow LE (Long Endurance) UAV, which can fly for up to 3.5 h, and at speeds between 60 and 150 kph, up to a maximum altitude of 5000 m. The hand-launched system has a wingspan of 3 m, an MTOW of 9.5 kg, and a range of up to 40 km. The airframe body is made from the same proprietary radio-transparent composite as the Sparrow's, to enhance stealth applications in special forces operations.

All Spaitech UASs are equipped with digital communication-encrypted channels. Anti-jamming and anti-spoofing algorithms are implemented to resist the electronic countermeasures systems used in warfare. The company has also developed software packages for post-mission analysis and online analytics of gathered data.

"All the main electronic boards in the UAVs are developed by our engineers, so we can amend or add any additional features to the system our customers need," Bogomolov added.

Sullivan UV attended the show to exhibit some new solutions for supporting the trend towards hybridising fuel-powered UAV powertrains.

"We've developed a 2000 W generator that has an electronics unit to provide voltage regulation, with a high-efficiency active rectifier to rectify the power coming from the alternator, as well as electronics for starting the engine," said James Hudson.

"It controls engine rpm and provides serial data output as well as a secondary output for running avionics or servos. The electronics include basically everything you need outside of the alternator itself to regulate power from your engine."

The generator's design incorporates 14 permanent magnets and 12 poles (which are wound to suit the targets for power, engine revs and system voltage), as well as a sensorless, brushless motor controller for turning the alternator to crank and start the engine. The company can program the performance of the software for controlling the starter function depending on the model and parameters of the engine being used.

"We can also modify the data output to use a CAN protocol if an end-user prefers that over RS-232," Hudson added. "And we've added EMI filtering to the device to prevent it from generating 'noise' that could affect nearby electronics on the aircraft.

"Lastly if your load varies significantly, we can modulate the engine throttle – speed it up or slow it down as needed to maintain the output voltage."

Global Energy Transmission (GET) showcased its technology for inductive (non-contact) wireless charging of UAVs, which was originally developed as a solution for extending the short flight times of battery-powered UAVs.

"Unlike other automated charging solutions, our GET Wireless Charging Station doesn't require the UAV to land or have its battery swapped," said Leonid Plekhanov. "Even in snow, dust or humidity, there's no change in the charging rate, and one station can charge multiple UAVs at a time.

"The system can send out up to 12 kW over a distance of up to 8 m, and for a UAV carrying a 6 kg payload we can generally charge that level of battery fully in six minutes."

It uses resonant magnetic phase synchronous coupling to send power wirelessly to the receiving antenna on the UAV, with a normal operating transmission efficiency of 80%. Much of that efficiency comes from a proprietary tuning system for the data channel between the ground station and onboard receiver, which autonomously measures and matches the resonant frequencies between the two.

"We chose components to ensure a high quality of resonant magnetic coupling systems," Plekhanov added. "For example, our receiver antennas are made with a special kind of aluminium copper-clad litz wire, to avoid the proximity and skin effects often associated with solid wire that can lead to current losses, and to decrease the weight of the antennas."

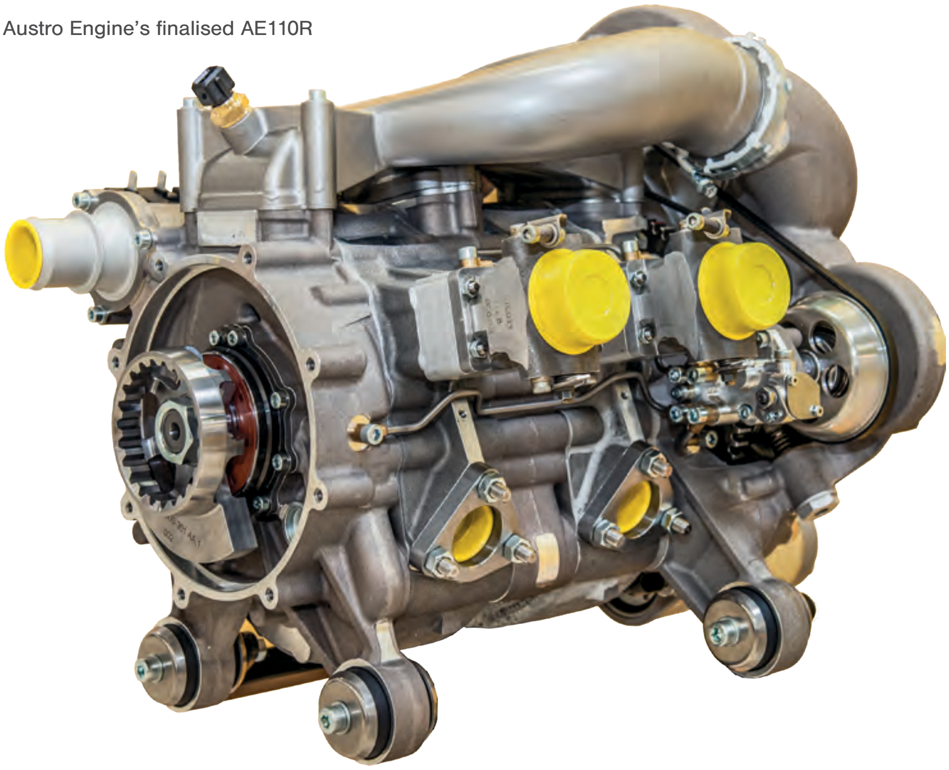
As well as enabling smoother, more seamless charging for UAVs, the company sees the charging stations as allowing persistent survey and inspection capabilities for companies needing constant surveillance of critical industrial assets such as petrochemical pipelines or power stations. A UAV can fly along lengths of infrastructure with charging stations installed wherever the UAV needs to remain in one place to fully charge its battery while conducting a spot-inspection.

Austro Engine has finalised the design of its AE110R twin rotary engine, following the first public unveiling of the engine concept at AUVSI 2018.

"We've shipped the first prototype engines to customers for initial testing, and in parallel we're just finishing a few tasks on the ECU and related hardware components, but the engine is essentially ready for use," said Mario Spiegel.

"ECU software is different from airframe to airframe, so we need to know the specific requirements from a customer. In this case it has to be fine-tuned to the customer's mission profile, especially when it comes to such areas as injection quantities and timing, and idle speed revs."

Austro Engine's finalised AE110R



The 47 kg engine produces up to 110 hp and has an integrated 2 kW alternator. The company has also designed the engine with an expected TBO of 500 hours.

Spiegel said achieving this high TBO came largely from the company's experiences with the AE50R rotary engine (featured in *UST* 03, Summer 2015), which naturally shares several mechanical and operational principles with the AE110R.

"The AE110R can also be used as an auxiliary power unit (APU) to maintain the operation of basic systems in armoured vehicles such as air conditioning or mission-critical systems. If used as an APU, the TBO of the AE110R will be much higher than 500 hours, owing to the differing constant load characteristics in this application.

"We have also conducted bench testing in harsh environments and high-load profiles, to better guarantee that the expected 500-hour TBO translates through into practical field-work."

"In addition we've worked to develop a CAN interface for the ECU to simplify integration down to a single point of electronic comms between the flight controller and the engine, with a throttle servo installed on the engine that is actuated by the ECU, so there's no mechanical control input required from the engine."

Moog displayed some of its newest servo actuators, which are designed for 28 V DC power applications needing

The Moog 863 rotary actuator

integrated electronics and gearboxes, for applications in the unmanned and electric VTOL markets.

"Our Model 220 Rotary servo actuator will deliver between 50 and 100 lb-in of torque, while our Model 863 Rotary servo actuator will provide 150 lb-in," said Richard O'Donnell.

"Meanwhile, our Model 863 is IP67-rated and completely sealed using a connector seal, a shaft seal and another gasket to seal between the gearbox and the electronics," he said. "It is often recovered from water, as it is widely used on target drones and UAVs, and can withstand depths of 3 m for 48 hours without damage or water ingress."

The gaskets typically use Teflon or similar materials to seal the connector and the output shaft.

The Model 220 weighs about 270 g and measures 10.4 x 7.4 x 2.3 cm, while the 863 weighs about 910 g while measuring 11.3 x 10.4 x 4 cm.

Delta Digital Video's 7805R

Delta Digital Video showcased its new, small-form-factor H.265 video encoder, the Model 7805R.

"It's our smallest video encoder using the new H.265 compression algorithm. It measures about 97 x 92 x 30 mm, while weighing 227 g," said George Nelson.

"The size challenge comes from H.265 being computationally intensive, so you need more processing power, which translates into more heat generation. That typically results in the need for a bigger fan to get the heat out of the box, or some form of conduction cooling."

As well as being SWaP-optimised for UAS integration, the 7805R is designed to be a drop-in replacement for its H.264-compliant predecessor, the 6805R.

The 7805R consumes 10 W in normal operation, and can output video at resolutions of 1080p29/30, 720p59/60, 1080i59/60, 480i29/30 and 576i25. The encoder has a rated latency of about 50 ms and can operate at altitudes of up to 35,000 ft.

The NorEaster uses two concentric output shafts to drive counter-rotating propellers, negating the need for a tail rotor (All images courtesy of Peter Casey, O'Neill Power Systems)

A question of timing

Rory Jackson examines the development of this radial engine for helicopter-type UAVs that uses a cam-based mechanism for its drive transmission

O'Neill Power Systems is a start-up company based in Fall River, Massachusetts, which has developed and patented a unique propulsion solution with great potential for helicopter-type UAVs. Its NorEaster engine was originally conceived by company CEO Jim O'Neill, and has been further developed by Bob Norton, an engineering professor from the Worcester Polytechnic Institute (WPI) in Massachusetts, who has since become O'Neill's chief engineer.

It is a four-stroke, 80 hp radially arranged eight-cylinder reciprocating unit. It has two output shafts, integrated coaxially, to drive two counter-rotating propellers. Opening the engine housing reveals a drive transmission system that relies not on a crankshaft or turbine but on a cam-based mechanism that is unlike anything seen elsewhere.

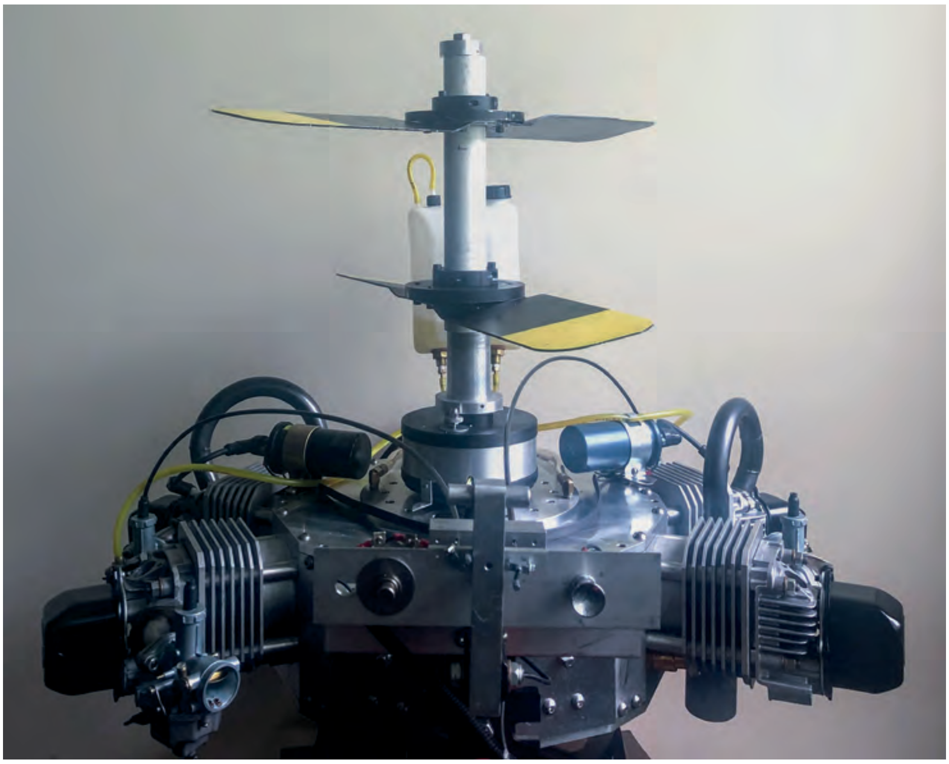
Rather than being developed to target one or two specific engineering problems or requests from UAV operators, the NorEaster is designed to replace existing helicopter drive systems entirely, thus resolving the myriad issues associated with them.

The NorEaster's history

The CEO's inspiration for the engine came to him in 1969, when he was stationed in South Korea on military service.

"Although I wasn't a helicopter pilot, I spent a lot of time on helicopters, just as a lot of my associates were doing in Vietnam," O'Neill explains. "What I noticed back then about conventional helicopter designs is that the tail rotor is incredibly vulnerable. Even if you're well-clear of enemy combatants, it's so easy for the rotor to get knocked and disrupted by the branch of a tree or some other obstacle."

The tail rotor is also a significant source



The engine Is currently in its fifth prototype, which initially entered dynamometer testing about a year ago, starting with a version featuring four cylinders

of the considerable work that goes into helicopter drivetrain maintenance, and the cause of a great number of crashes. These flaws drove much of the motivation behind the NorEaster's development.

Related to the tail rotor are several other issues that the conventional helicopter powertrain is subject to, which O'Neill wanted to address. "On almost all helicopters, you start with an engine, typically a turbine engine for larger helicopters, the output for which has to go through a highly complex transmission system with a reduction in two directions – one for the lifting rotor, one for the tail rotor," he says.

Helicopters typically require rotor lifting speeds of between 500 and 1500 rpm, compared with the typical turbine speeds of 10,000-20,000 rpm.

Norton says, "Those transmission reductions are one of the most problematic technologies in aviation, purely in terms of maintenance requirements. They require persistent care, they often fail, and when they do it's often catastrophic, because you then have a helicopter in the air with no lift. Without a pilot well-versed in autorotation, that helicopter is going to hit the ground extremely hard."

The NorEaster effectively eliminates that transmission, because the cam-drive system gives an automatic, internalised reduction ratio, equal to the number of lobes on each cam.

And since it has been designed with two counter-rotating output shafts, there is no need for a tail rotor to counter torque – each propeller cancels the other's torque reaction, as well as almost the entirety of each other's vibration.

A conventional helicopter powertrain also takes up a significant proportion of aircraft weight. As indicated, it requires a number of dedicated structures and gearboxes, as well as gearing systems to keep the engine's centre of gravity stable.

"So we wanted something that was more like an outboard motor for helicopters," O'Neill says. "It's a single, fully integrated turnkey unit, with no need for a complex transmission system. You just bolt it on to whatever you want to fly, and it uses a fraction of the parts and weight of a conventional helicopter transmission, which is critical for the viability of UAVs in particular."

It was around 1999 that O'Neill first conceived the idea of a cam-driven engine. "I made a couple of crude prototypes," he recalls. "Soon after, through a stroke of luck, I met Bob Norton, who had written several books, including one on cam design and had taught at WPI for more than 30 years. He examined the cams I had designed and tested, and became a key partner in the design and development of the NorEaster engine."

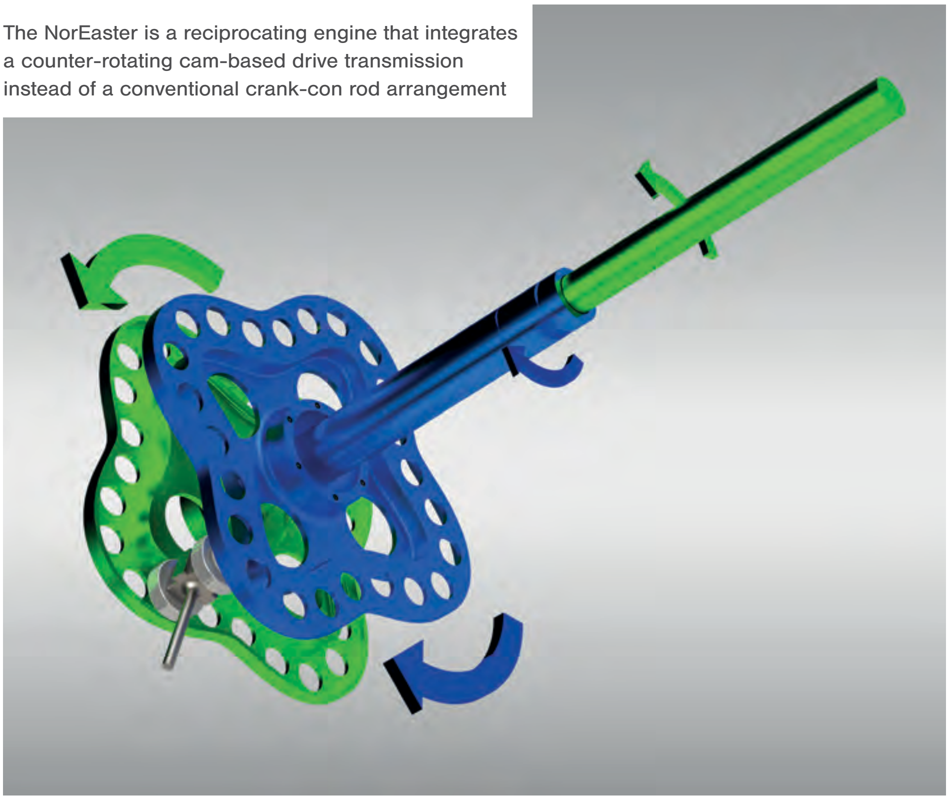
Their collaboration quickly led to a third prototype, which used a four-stroke power cycle and featured two counter-rotating output shafts, one extending from the top of the engine and the other from the bottom.

After testing and demonstrating that model, development of the engine was moved to WPI. With the help of two teams of mechanical engineering students, a fourth prototype was designed. That two-stroke version had an improved cam drive design to provide the revs and reduction ratio that O'Neill and Norton were looking for.

"Further improvements on that led us to the version we have right now – our fifth prototype, a four-stroke 80 hp engine, with some dyno testing done to validate that the design performs exactly as we've been aiming for," O'Neill says. "The next step would be to do a lift test, and that will be the last step, pending further development with partners and end-users."

Development of the current version began two years ago, with the first dyno test following a year later. Significant input into it has also come from Bob Anderson, founder of OceanServer Technology, an AUV manufacturer also based in Massachusetts.

The decision to revert to a four-stroke cycle came partially from O'Neill and Norton's automotive engineering backgrounds, which made them more familiar with such technology, and



The NorEaster is a reciprocating engine that integrates a counter-rotating cam-based drive transmission instead of a conventional crank-con rod arrangement

from not being able to get the speed and horsepower they wanted (although the engine ran with vibrations as low as they hoped for).

"In my opinion, the stroke cycle is irrelevant," Norton says. "If you can make a two-stroke cycle work on this engine, you'll get as much power as you would from a crank engine."

Many of the components and much of the ancillary engine systems surrounding the drive and transmission are COTS products, having been selected principally for cost-effectiveness. The main aim of development has been to iterate and optimise that patented transmission across each prototype, rather than develop costly bespoke subsystems to maximise the performance specifications.

With the minimal vibration, secure reduction ratio and low maintenance requirements of the drive transmission system – especially when compared with helicopter powertrains – as core selling points, O'Neill Power Systems has made it clear that the various supporting systems are bound to improve in the future.

As the company is actively seeking partnerships for the NorEaster's further development, its engineering team is open to input on what the exact nature and form of those improvements will be. Their own future objectives include an aviation-grade ECU with electronic fuel injection and an improved ignition system.

At the moment, O'Neill Power Systems is located at the University of Massachusetts Dartmouth Center of Innovation and Entrepreneurship, where professors and students contribute to the engineering and business development as well as other aspects of the company. Much of the ongoing work on the engine is overseen (and aided) by Edward Spring, laboratory manager and mentor at UoM Dartmouth.

Cam drive and transmission

The NorEaster weighs 91 kg, with dyno tests thus far indicating a peak power output of 100 hp (75 kW). The system measures 92 x 92 x 30.5 cm, not including the output shafts, which will vary in length depending on the end-user's vehicle and the flexibility of the rotor material they have selected.

Its speed is in the 1000-2000 rpm range. Maximum torque output is 950 Nm, with 760 Nm produced during normal operations and is dependent on the design of the combustion cycle and its components.

O'Neill estimates that this degree of power and torque could enable a helicopter UAV incorporating the NorEaster could carry up to 450 kg of payload, making it particularly applicable for aerial logistics, urban air taxis and other heavy-lift missions.

The inside of the engine contains two chambers which are symmetrical in the horizontal axis. Each chamber contains one drive cam – a four-lobed arrangement resembling a four-pointed star, designed to be push-actuated by the NorEaster's pistons.

Both output shafts extend upwards through the engine, with the lower chamber's drive cam's narrower shaft threading up through the wider shaft mounted on the upper chamber's cam. Each drive cam is also oriented to rotate in the opposite direction to the other, to provide the counter-rotation of the propellers.

The eight cylinders and pistons are oriented radially and co-planarly around the eight external surfaces of the 'cam case'.

Rather than comprising a conventional head and pin to attach a con rod's small end, the NorEaster's piston heads have a fixed 5 cm rod extending from underneath them, into the cam case. At the bottom of the central shaft comprising most of the piston rod is a perpendicular cross-member.

As the pistons move up and down, their linear motion in the cylinders (and the absence of transverse forces in the cylinder from con rod oscillation) is maintained by keeping the rod cross-members slotted within a guide plate.

The cam case contains two of these guide plates – one for the pistons' upper cross-member halves, another for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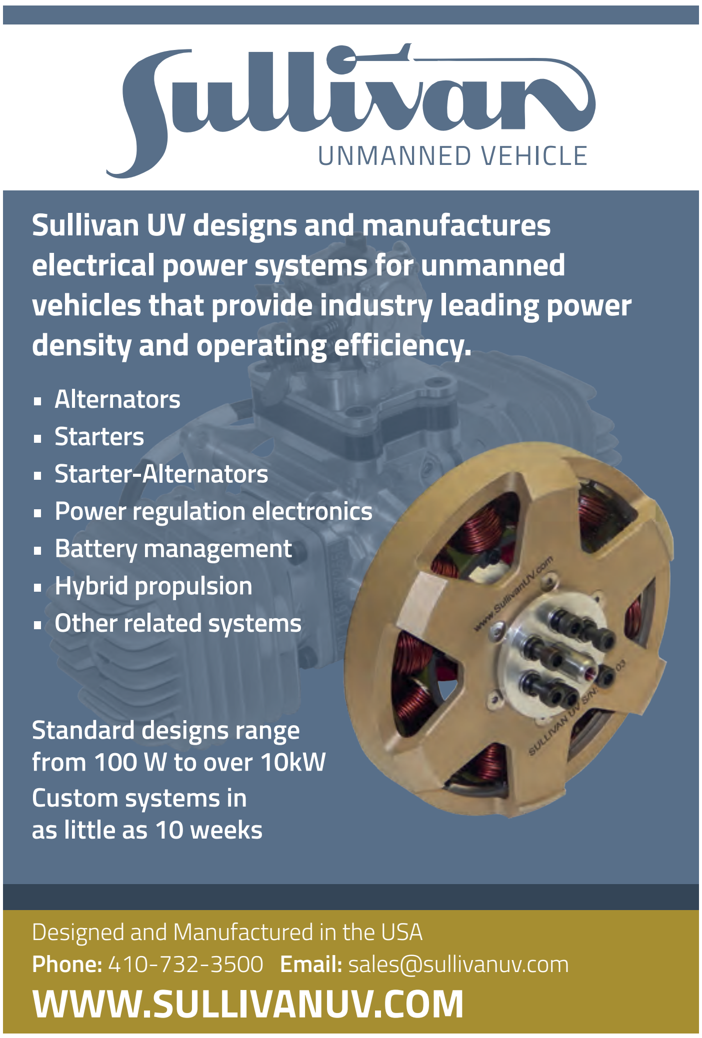
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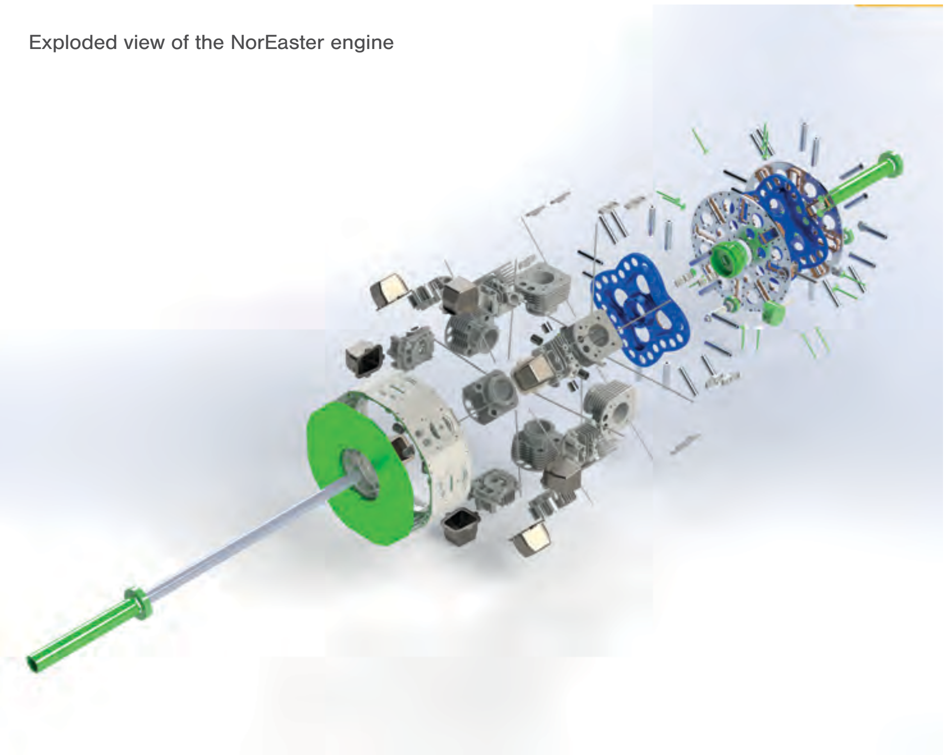
Exploded view of the NorEaster engine



the lower halves – with straight-line slots running between the centre and outer parts of the case for the cross-members to run in. Mounted on each cross-member are four ball bearings, with the outermost being around half the diameter of the inner bearings.

The drive cams and pistons are oriented so that when the piston head fires downwards (towards the centre of the engine), the larger ball bearings on the cross-members push down against the two separate cams in their respective engine chambers. Each bearing rolls against its cam's downward-sloping surface, to push them apart.

From above, this effect looks rather like scissor blades being opened by a round metal object pushing into them and forcing them apart. By this method, rotational momentum is given to the drive cams, the linear motion of the pistons being converted into rotational motion for the output shafts and propellers.

After pushing apart the downward-sloping cam surfaces and reaching the cams' bottom dead centres (BDCs), the piston is then driven back up into its cylinder for the exhaust stroke, by the immediately following upward slopes of the cams, which carry forward their rotational momentum and push up against the large bearings.

To ensure the piston is carried up steadily, an additional, downward-facing cam surface is designed along the opposite inner rim of each driving cam. This effectively creates a raceway between the cam lobes and the rim, and helps the overall efficiency of the system by ensuring that no kinetic energy is 'lost' as the pistons and cams push each other up and down.

The smaller bearings fixed to the outer part of the piston rods' cross-members run along and against this upper rim. The reason for that is to prevent the need for the larger bearings to run within this raceway – doing so would mean the upper and lower tracks of the raceway acting on the bearing in opposite directions. That could cause the large bearing to spin in both directions and generate unnecessary friction, meaning more oil would be needed and negating the reason for having rolling bearings in the first place.

Once the cross-member bearings reach the top dead centre (TDC) of the next lobe (for the cylinder's next intake stroke), the next cylinder along fires and pushes the cams, with the upper track of the cam raceway then pulling the first cylinder's piston down to draw in the fuel-air mixture.

Typically, in the NorEaster (with the four-lobe drive cam), four of the eight pistons stroke downwards at once. One opposing pair of cylinders will be firing, while the other pair will be taking in fuel and air. As this happens, the other four pistons are being pushed upwards for compression and exhaust.

Once the first four pistons' cross-members reach the BDC of their respective cam lobes, and the second four have reached TDC, they alternate their movement, with the first four now stroking upwards as the second four stroke down.

By having two horizontally opposing cylinders firing on each stroke, the directional force of each cylinder's combustion is cancelled out, reducing engine vibration. The firing order of the cylinders follows clockwise around the engine when viewed from above, with an even firing time between them. This means that, initially, the first and fifth cylinders will fire, followed by the second and sixth cylinders, and so on.

It follows from this that each horizontally opposed pair of lobes corresponds to similar halves of the power cycle. Going around the cam, the first and third lobes' surfaces contact the piston bearings during their exhaust and intake strokes, while the second and fourth lobes correspond to the compression and combustion phases.

All these contacting surfaces and bearings mean oiling is crucial. "In its current design iteration the oil pump is external, but we hope for the production model to integrate the pump inside the cam case," O'Neill comments.

"Right now, the cam case itself is also the oil pan, so oil is pumped up at the top of the driving cams, with gravity and centrifugal motion providing for the

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Pitch & Roll	0.2°	0.1°	0.1°	0.03°	0.01°	0.01°
Positioning	-	20 mm (RTK)	8 mm (RTK)	-	8 mm (RTK)	8 mm (RTK)

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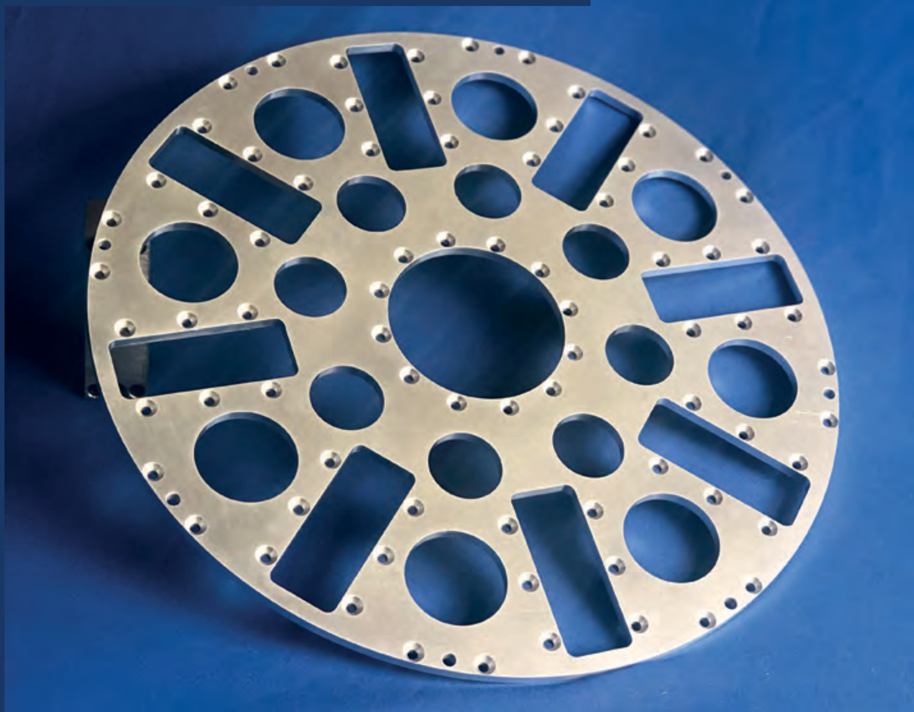
Anatomy

NorEaster helicopter engine
Radial eight-cylinder, four-stroke
Naturally aspirated
Carburetted
Weight: 91 kg
Size: 92 x 92 x 30.5 cm
Maximum power output: 100 hp
Operating power output: 80 hp
Maximum torque: 950 Nm (700 lb-ft)
Operating torque: 760 Nm (560 lb-ft)
Bore: 6.826 cm
Stroke: 5.588 cm
Displacement (per cylinder): 205 cc
Total displacement: 1640 cc
Compression ratio, 8.5 to 1
Compatible fuel types: petrol
Operating speed: 750 rpm

Many of the NorEaster's key components, including the guide plates, were CNC-machined from aluminium



The NorEaster's cam case comprises seven main components. An eight-sided cam housing forms the main structural block, with the inner side being cylindrical and featuring a rim running around the middle.

The cam housing is CNC-machined from an aluminium billet. While no coatings are currently used, future versions might be anodised for corrosion resistance. Piston rod apertures are then drilled radially inward at the centre of each of its eight faces.

Next, two circular guide plates are installed inside the cam housing. These are also CNC-machined aluminium with potential for anodising, and each plate is fastened to one side of the cam housing's inner rim, with 32 M25 fasteners.

Eight slots are cut axially into the guide plate to the same length as the piston stroke, with a central aperture for the output shafts and main bearings. Sixteen additional holes are cut into the guide plate for cooling and reduced weight.

The engine has a pair of four-lobe (38 cm at maximum diameter) drive cams machined from plates of hardened steel and coated using a proprietary method and material, with one over each guide plate. The concentrically arranged output shafts are machined separately from hardened steel and welded on afterwards.

It also has four main ball bearings, two on each shaft – two in the space between the output shafts, and two between the shafts and housing covers to hold the drive cams in place.

A tool steel valve cam for driving the intake and exhaust valves is bolted using six fasteners atop the upper drive cam, around the wider output shaft.

After the cam case's sides are ground to accept the pistons and cylinders, eight COTS aluminium cylinders with Nikasil inner coatings (cylinder heads machined in-house, also from aluminium) are fastened to each of the eight sides, using four M10 fasteners each.

The pistons are also machined from aluminium, with three rings about the piston head. The top two are compression rings, with an oiling ring underneath. A piston rod 5 cm long extends from under the head, with a cross-member extending from either side and mounting two pairs of ball bearings for contacting with the drive cams.

The cam case is closed on either side by a pair of housing covers. These octagonal aluminium plates might also be anodised for added corrosion resistance in future versions of the engine. Each housing cover is bolted to an opposite opening of eight-sided cam housing using 32 M8 fasteners and 18 M32s.

distribution of the oil across the cams, all around the cam case, and to the bearings, piston rods and oil rings. The oil eventually settles at the bottom of the cam case, where it is then recirculated, with no losses as the system is fully closed."

In the NorEaster's current iteration, cooling is provided by the downward thrust of air from the propellers, which flows over the outer surface of the cam case and across the cylinders.

The number of lobes on the driving cams may be subject to change. The primary aim of the engine's design is that the output shafts move at between 750 and 1250 rpm, as befitting a helicopter rotor system.

As the cylinders and pistons were originally designed for four-stroke operations at 4000 rpm, the cam currently has four lobes to provide a four-to-one reduction ratio. Accomplishing this reduction without belts or gears means the engine avoids all the inherent maintenance issues and points of mechanical failure that helicopter transmission systems are prone to.

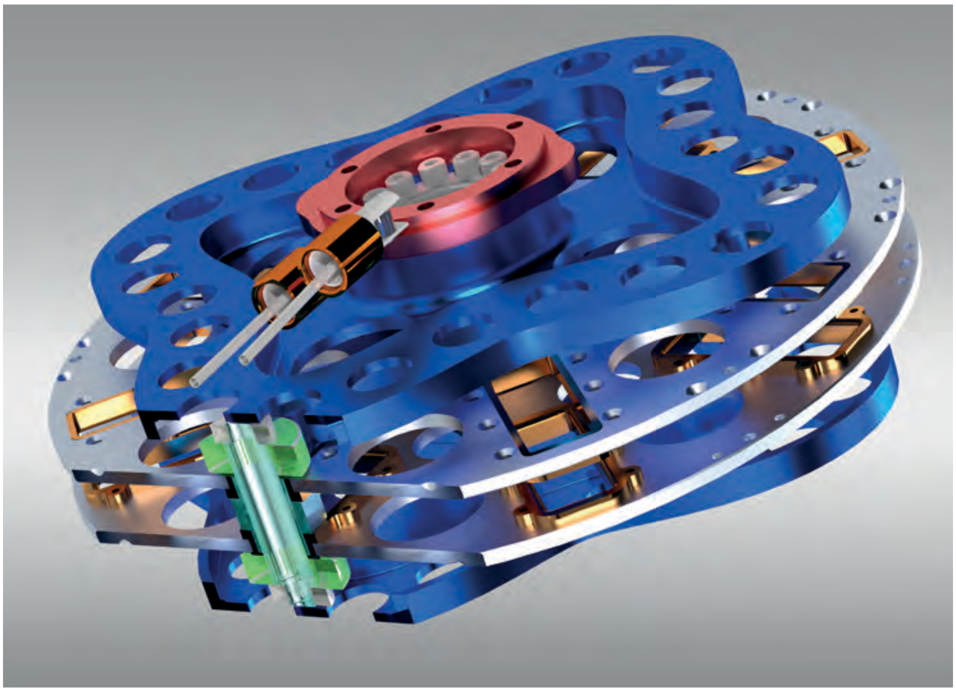
"I designed all the cams using my own cam design program, Dynacam," Norton explains. "The cam profile data from Dynacam was then imported into CAD programs to generate the cam surfaces."

Valve control

As the current configuration of NorEaster uses a four-stroke power cycle, the cam-driven engine has been designed with a series of components to form a secondary cam system, which acts as the power system's valvetrain.

"The valve drive system is so simple on this engine, compared with what you'd usually find on an automotive or UAV four-stroke," Norton comments.

The heart of the valve control and timing is a valve cam. That is the effective 'camshaft' of the NorEaster, although it is much wider than it is long (and therefore more closely resembles a pair of coupled rings than a shaft), and does not need any timing belt or chain to operate the valves or keep accurate timing.



Within the (blue) drive cam's raceway, the large bearings (green) on the piston rod's cross-member push down on the cam's inner lobes, while the smaller bearings (grey) on the outer part of the cross-member are pushed up to run against the outer lobes

That has allowed the overall valvetrain to be designed in line with O'Neill's philosophy of avoiding belt-oriented transmissions. Its design features two cams, set on two tiers with two lobes each, each cam's lobes being set opposite to each other.

In this arrangement, one cam actuates the cylinders' intake valves while the other is fixed to operate the exhaust valves. As each valve cam has two lobes, compared with the four on the drive cams, each valve is opened and closed in order as well as once per power cycle, with timing fixed by the fact that the upper drive cam is directly driving the valve cam.

Put more simply, just as two power cycles (or eight strokes) are completed for every rotation of the drive cam, so each valve will be opened and closed twice for every revolution of the output shaft.

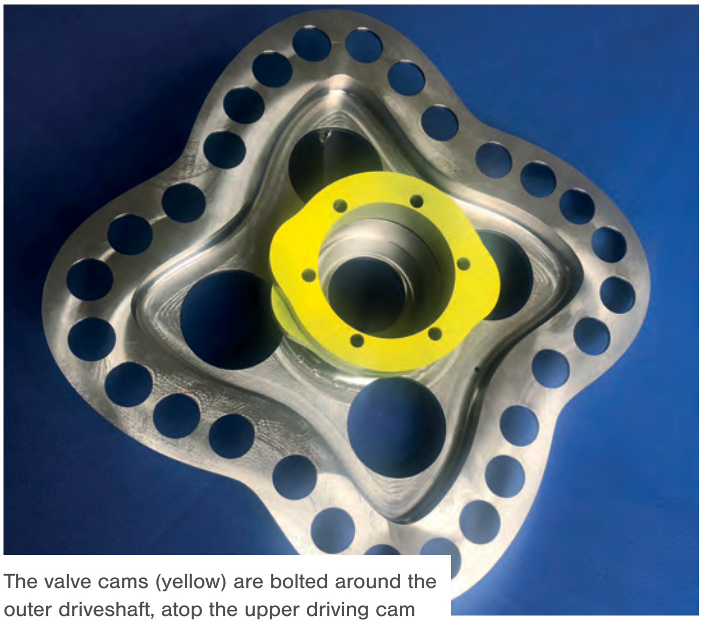
To actuate an intake valve, the valve cam's first upper lobe comes into contact with a roller lifter, eight of which are arranged about the path of each lobe (for a total of 16). The lobe pushes the roller lifter upwards, which lifts a 22 cm pushrod up against the input end of a rocker arm.

The output end of the rocker arm thus rotates downwards, pushing down against the spring-loaded intake valve and opening the port to the carburettor's fuel-air mixture. As the zenith of the valve cam lobe passes, the roller lifter and pushrod are lowered down again, and the valve lifts upwards to seal the intake port with the valve seat.

After the combustion phase, the second valve cam comes around to set in motion a largely identical procedure to open and shut the exhaust valve. While each valve cam's lobes are set 180º apart, the exhaust valve cam is offset slightly so that each intake lobe's corresponding exhaust lobe follows slightly faster, at about 144º.

The intake valve seat (and by extension, the intake port) is 2.6975 cm in diameter, while the exhaust valve is 2.22 cm across. Both ports are placed atop each cylinder, equidistant from the centre of the bore, with a flat valve angle (0º) between them.

Each valve cam (pink) pushes up against the lifters (gold) to actuate either the eight intake valves or eight exhaust valves, via a linkage made up of pushrods, rocker arms and spring-stems



The valve cams (yellow) are bolted around the outer driveshaft, atop the upper driving cam

A round steel tube extends upwards from the exhaust chambers atop the cylinder heads, before turning 180º to funnel the exhaust fumes down between the cylinders. "We've also equipped it with mufflers from Briggs & Stratton, to reduce the noise generated by that eight-cylinder system," O'Neill points out.

"Originally the cylinder heads had the exhaust directed to the top, but we didn't want that flowing near the rotors, so we redesigned it to direct the fumes below where they'd be less harmful."

On the current prototype, fuel is stored in a gravity-set fuel tank, with separate hoses extending from it to the carburettors on each cylinder head. Each carburettor has its own throttle body for air intake control.

Cam engine versus crank/con rod engine

As well as improving over helicopter turbine-and-belt arrangements, the NorEaster's cam-based drive system is designed to provide certain advantages over the more conventional reciprocating engine's crankshaft-based drive.

In a crank engine, each con rod's big end rotates with the motion of its crank pin, while the small end of the con rod, being fitted to the piston pin, generates a secondary 'side-to-side' harmonic.

That can create friction and wear between the piston and its cylinder wall, by pulling to one side during its downward stroke and to the other during the upward stroke.

The NorEaster's pistons are not pulled side to side in this way, as the drive cams exert balanced forces on either side, and the guide plates hold the cross-members in place to prevent the pistons being 'twirled' in either direction.

Also, as mentioned, the radial operation of the NorEaster with the cylinders firing in opposing pairs means all the harmonics of the inertial force generated by combustion cancel each other out.

"The co-planarity of the cylinder distribution about the cam case also means there is no inertial shaking moment," Norton says. "And again, the counter-rotation of the output shafts and propellers cancels the reaction torque, making for a minimally vibrating power output."

The future

In addition to welcoming engineering input from future partners and end-users, O'Neill Power Systems envisages several other configurations of the NorEaster.

One, designed for UUV propulsion, uses an electric motor as the main power source driving the lower cam, with the cylinders removed and the piston rods held in their slots to actuate the upper cam and its output shaft.

This alternative use case for O'Neill's drive transmission system is titled the VorTaq. "UUVs are mostly electrically powered, with one propeller, so they need control fins which are constantly adjusting to compensate for the dynamic roll the prop induces, to stay level and flat to generate quality sonar imagery," says Anderson of OceanServer Technology.

"The counter-rotating propellers would induce no roll, so you could reduce those control fins significantly, meaning fewer potential points of mechanical failure and much less drag on the vehicle."

A future version might also integrate a tertiary output drive shaft, driven by a timed gear intermeshing with teeth formed on one of the drive cams. That would extend perpendicularly from the NorEaster, to drive a pusher propeller.

Whatever form the next engine takes though, it is undeniable that the technology at the heart of the NorEaster system has the potential to revolutionise the next wave of UAVs and their markets.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Life in the slow lane

Rory Jackson explains the workings of this autonomous impact protection vehicle for road repair and maintenance crews

US-based Kratos Defense is a contractor involved in developing vehicle automation systems for military users, primarily as a way of reducing the number of personnel needed in dangerous operations such as route clearance or convoy missions. While demonstrating a Humvee-type military vehicle with autonomous capabilities, an observer commented to Maynard Factor, director of business development at Kratos, that the demonstrator's technologies could be applied to a crash attenuator vehicle.

These are essentially human-driven mobile crash barriers that drive behind highway work zones to protect against motorists accidentally driving into the workspace. They typically comprise a truck towing an impact attenuator – a wheeled device designed to absorb the damage from vehicle collisions.

However, the person in the towing vehicle is exposed to a high risk of permanent injury, and even death in some cases, despite the protection afforded by the impact attenuator. Factor and his team therefore saw an ideal opportunity to adapt the technology they had developed for the military into a commercial application.

That led to the development of the company's first major commercial autonomous venture, the Autonomous Truck Mounted Attenuator (ATMA) – or autonomous impact protection vehicle, as it might be called in the UK and some other countries owing to differing naming conventions.

The two truck chassis were not developed by Kratos but come from Royal Truck & Equipment, the largest manufacturer of truck-mounted attenuator vehicles and specialised vehicle

The ATMA system uses two trucks in a leader-follower arrangement, with the rear truck providing an autonomous crash barrier for what is typically a moving highway work zone (Photos courtesy of Kratos Defense)

technology in the US. The first prototype was developed in 2014.

Kratos has integrated a 'bolt-on' kit into what is otherwise a standard vehicle from Royal Truck & Equipment that includes computers, actuators, navigation sensors, additional sensors for obstacle detection, and RF equipment. The kit has an optionally manned capability, allowing it to be driven by a human, or at the flip of a switch it can be turned into an unmanned system.

As Factor explains, "When we deployed it and did some demonstrations, the people who have to drive these truck-mounted attenuators recognised it as a solution to what is one of the most dangerous jobs in the work zone." Soon after that, Kratos received its first contract, with a British highway maintenance company called Colas.

Panasonic's FZG1 ruggedised notebook provides the ATMA's user interface, which typically displays a number of indicator lights showing the status of crucial systems

> The people who have to drive these attenuators recognised it as a solution to one of the most dangerous jobs in the work zone

The ATMA automation kit

The ATMA's automation kit is typically integrated into two trucks, which are operated in a leader-follower configuration. The lead vehicle is manned, with navigation sensors and computers mounted under the driver's seat to collect data on speed, position and heading, before transmitting it to the follower vehicle.

The exact work being conducted will be determined by the nature of the lead vehicle and the team operating it. It could be traffic cone deployment or line painting, for example.

An operator control panel for the ATMA system is installed on the dashboard of the lead vehicle; typically it's a Panasonic FZG1 ruggedised notebook PC, which is used by Kratos across a number of its solutions. "Either the driver or a dedicated ATMA operator in the right-hand passenger seat will be looking at this, and can see a number of mission-critical variables on it," Factor explains.

Chief among these is the GPS status, which shows green when the follower vehicle is receiving the leader's position, and red when GPS data is not being transmitted. A similar system is used for the vehicle-to-vehicle inertial

A number of emergency stop switches are located around the follower truck, which are designed to shut off engine power and activate the brakes

navigation information, to ensure speed and heading are constantly being received by the follower truck over the ATMA's data link.

From the user interface, the operator can also drag a bar to select the commanded gap – the distance the follower vehicle should maintain between itself and the leader.

The radio transmission components are installed behind the driver's cockpit, and the main computer beneath the seat (referred to as the system control unit, or SCU) is an FPGA processor board designed in-house by Kratos. An SD card is typically installed in the SCU to log navigation and performance data.

"The system is designed in such a way that it doesn't interfere with the normal operation or ergonomics of the vehicle – we don't want anything in the way, and we may adapt it differently for different vehicles," Factor notes.

"This system works for Royal Truck & Equipment, but we may design our retrofit kit and integrate our computers, sensors and notebook PCs slightly differently, or very differently, based on a different company's trucks and attenuators."

In line with this objective, the retrofit kit is powered by the truck's onboard battery. Overall, the kit requires less energy than the hazard lights and the various other items typically installed on highway construction vehicles, as Factor and his team wanted to avoid installing an extra battery on either vehicle.

Outside the cockpit, both the leader and follower vehicles have a primary GPS antenna installed, normally mounted atop the frame on the front of the trucks to ensure the clearest possible line of sight between the antennas and positioning satellites.

A secondary GPS antenna is typically installed for redundancy, and another antenna is installed to transmit emergency stops (switches for which are installed around the two vehicles and in the lead truck cockpit). Both GNSS antennas are AG25s from Trimble.

"Often these trucks will be used in a stationary or slow-moving construction zone – maybe with the two vehicles moving at between 8 and 24 kph – and sometimes there are people walking around or between them," Factor says. "So in the event that some safety-critical concern arises, we have installed emergency stop or e-stop switches around the follower vehicle for any worker to jog over and hit one, which will shut it down immediately."

Additionally, in the lead vehicle cockpit, the driver and operator have access to an independent back-up e-stop. That will stop the follower vehicle, shut down the engine and all the other systems, and fully engage the brakes; it is on its own dedicated wireless interface.

That separate data link is encrypted and untied from the vehicle computer and the SCU in case the other e-stops are affected by a failure in another onboard system.

Pre-mission checklist

Before any highway work is carried out, additional safety is provided by a set of pre-mission checks. These are typically carried out at wherever the day's work is to start, having manually driven both trucks from their depot or from a staging area in the vicinity of the highway.

"The prototype system was sort of a baseline when we first deployed it – we were trying to figure out which parts we needed and if there was anything important the system lacked," says Factor. "For example, we had the leader-follower system, but we didn't have a user interface."

That interface was developed in response to initial feedback from Colas and the Colorado Department of Transportation, which was trialling the system towards making it certifiable for US operations.

Similarly, a standard checklist for drivers and operators to run through was developed in response to user requests. As Factor notes, "A checklist and training with an easy-to-follow structure enables users to smoothly incorporate the ATMA into their work routines."

First, the driver starts the leader vehicle's engine, releases its parking brake, then switches its battery breaker to 'on'. That connects the ATMA SCU to the vehicle's battery, and must be done in order to have power supplied to the operator's control panel, data


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links and other systems later on in the checklist.

The driver then boots up the ATMA control system from the user interface. Although the interface software is switched on, the operation of the autonomy system will remain locked until the operators confirm the checklist has been completed.

From the user interface, the driver must switch the control unit from ‘off’ to ‘idle’; this triggers power delivery to the ATMA subsystems. After that, the rest of the ATMA system in the leader vehicle initialises, and that vehicle is ready to move.

An engineer should be present in the follower vehicle at this time. The driver in the lead vehicle radios that engineer and tells them to start the follower’s engine. Then, much like on the lead vehicle, the engineer is instructed to pull the parking brake for the rear truck before activating the battery breaker.

Once all these steps are carried out, the GPS and navigation data signals on the user interface switch from red to green, indicating that the rear vehicle is receiving the necessary data to follow the path laid out by the lead truck.

Leader-follower operation

The driver then switches the control panel from ‘idle’ to ‘go’, and the engineer can leave the follower vehicle’s cockpit and move to the lead truck to operate the ATMA user interface while the driver focuses on the road. The follower truck begins moving along a series of GNSS waypoints that are copied from the leader truck’s path (or ‘e-crumbs’ as Factor describes them), ensuring that the approximate dimensions of the road workspace are maintained.

For autonomous control of the steering, Kratos has designed a ‘steering ring’ which the operator locks onto the follower vehicle’s steering wheel before moving to the lead vehicle. This device has a gear that interfaces with an actuator connected to the main computer, which then turns the truck left or right as required.

The operator can opt to check the video camera in the front of the follower vehicle’s cockpit for a close view of the gap between the two trucks. “From there, you can pause the Follow function,” Factor notes. “For example, if you drive through a traffic light and see in the video that it turns yellow as the lead truck passes through, it’s often safest to stop the follower vehicle there momentarily.

“The lead vehicle can carry on, still generating and transmitting e-crumbs and inertial navigation data to the follower. Once the operator sees the light turn green, they can reactivate the Follow mode, and the impact protection vehicle will catch up to whatever the set distance gap is.”

The gap to be maintained between the truck will vary from 7 to 450 m, and depend greatly on the operations and how each customer typically carries them out. For example, a highway construction team working in the UK will often prefer to have the vehicles closer together than those in the US would keep them, as an habitual approach to preventing motorists from driving into the work zone.

“UK users are also far more inclined than those in the US to conduct the pre-operation checklist at the depot or staging area, and then consider driving it to the work zone in autonomous leader-follower mode, potentially at speeds of about 60 kph,” Factor explains.

“It’s dangerous for workers to exit the truck, so in some cases they prefer to make sure the follower vehicle’s cockpit is empty from the outset. And even at that high speed, they generally keep the vehicle-to-vehicle distance tight to discourage drivers from entering the gap.”

During early development, the vehicle-to-vehicle distance was difficult to change without going into the software and changing code parameters. However, user feedback indicated the gap would need to be altered dynamically during highway operations, so a slider bar for selecting that distance was added to the user interface.

While the driver takes the lead truck along its route, the operator can continually check the control interface to ensure that all the vital systems are working as required. As mentioned, this includes a system of green and red lights on the notebook to show if the GPS data and inertial navigation feeds have been dropped at any point.

Also, operating status indicators are

Cameras in the windshield of the follower vehicle and at the rear of the lead vehicle provide multiple vantage points of the work zone and the surrounding highway area given for the SCU, for the transmission quality of the vehicle-to-vehicle data links and to show if the follower vehicle is in gear as commanded.

"The ATMA also has a range of redundancies that were added as a result of customer feedback, such as in the comms, the satellite and inertial navigation systems, and the e-stops. Even the encryptions to protect against malicious hacking, and frequency-hopping to reduce RF interference around busy highways or toll booths, were all designed in during development to ensure safety."

The vehicle-to-vehicle radio links use FIPS 140 encryption, an industry-standard AES encryption method used by military operators and other groups. For additional protection to the onboard processing, the operator's control notebook uses Windows 10 as its operating system for the ongoing cybersecurity that the software platform receives.

The primary link typically operates at 2.4 GHz, while the redundant link works on 915 MHz, with both capable of frequency-hopping to circumvent jamming or interference. This is important, as working on congested roads or passing through toll booths can mean dangerous levels of near-frequency 'noise' from vehicles and buildings, which could disrupt the connection between the ATMA trucks.

And although the two data links are defined as 'primary' and 'redundant', in normal operations they work simultaneously. This ensures that if one drops or is blocked completely, the other is already initialised and available, keeping a constant flow of critical data between the leader and follower vehicles.

Operational safety and impact protection

As indicated above, an additional layer of safety on top of these system redundancies is given by the ATMA's sensor architecture, which provides the follower truck with a multi-modal, 360° obstacle detection capability.

A Delphi electronically scanning radar is integrated at the front of the follower truck to provide the primary long-range obstacle detection

The engineering team at Kratos has aimed to develop an obstacle detect-and-avoid system for the front of the follower vehicle, and detect-and-warn at the sides, to account for the unpredictable nature of mobile highway construction and maintenance.

At the front of the follower truck, a radar and eight-channel Lidar are mounted to provide obstacle detection up to a range of about 80 m. "It's not 64-channel Lidar, because we only need it for obstacle detection, and we want to keep costs down where we can," Factor notes.

"Also, 64-channel Lidar is navigation-grade – we don't need any other navigation systems. We have the lead vehicle, and the follower vehicle is getting its satellite and inertial navigation data from that.

"And we have a human in the loop, as well as obstacle detection and awareness sensors as needed."

Should an obstacle be detected ahead of the follower vehicle, it will slow to a halt. Different levels of stopping can be triggered depending on the speed of approach, the level of alarm, concurrent problems such as loss of navigation or comms, and other factors that might depend on end-user requests.

These range from a controlled gradual slowdown to an immediate hard brake. Two linear actuators are integrated beneath the driver seat, and have control linkages running beneath the floorboards to actuate the brakes. One of the actuators is controlled from the follower vehicle's computer, while the other is connected to the independent e-stop controller to provide a hard brake (while also shutting off the engine) in the event of a control failure with the main computer.

As mentioned, a video camera is installed in the windshield, with another at the rear of the leader vehicle, pointing towards the follower truck. The operator can switch between these to scrutinise different angles of the intra-vehicle gap and check for motorists, pedestrians or anything else approaching the sides of either vehicle.

Also, ultrasonic sensors are placed at the four corners and either side of the follower truck to provide standard automotive proximity warnings if vehicles or people get too close.

Kratos has written the sensor


Ultrasonic sensors provide close-range collision warnings, as is standard for automotive sensors

Some key suppliers

Vehicle chassis: Royal Truck & Equipment
Main computer: in-house
Operating system: Windows 10
Servo actuators: Moog
GNSS-INS: Trimble
GNSS antennas: Trimble
Cameras: SV3C
Radars: Delphi
Lidars: LeddarTech
Main and redundant data links: Microhard
Independent emergency stop data link: FreeWave Technologies
Operator control system: Panasonic

fusion algorithms in-house, combining the driver software from different ATMA component manufacturers with ROS (robotic operating system). "ROS has a lot of open-source modular components that we've integrated into the software," Factor says.

"That keeps things standardised and eliminates anyone's special coding techniques, which is important for evaluation and keeping the system safe."

Perhaps most important, the ATMA will not react to fast incoming vehicles from the rear. The impact protection payload being pulled by the follower truck must remain in place to protect the work zone.

If a crash should occur, it will be detected either by an impact sensor in the crash attenuator or by the SCU detecting a jolt in the follower vehicle's GNSS coordinates that is characteristic of a collision. In response, the follower immediately activates its brakes to avoid rolling forwards into the workspace.

As Factor explains, "In many real-world cases of highway maintenance work accidents, the human driver has had the instinct to get out of the way when they see an incoming large vehicle in the rearview mirror, and the impact will clip the side and send the vehicle flying down it. Our automation system eliminates that altogether – you don't have to worry about that, because automated systems don't get scared."

Follow-up analysis and future research

When the highway work team has finished a job, the ATMA operator can switch off the Follow function and move into the follower vehicle. They then switch it back into manual mode before driving it (typically with the lead vehicle) to wherever it is needed next.

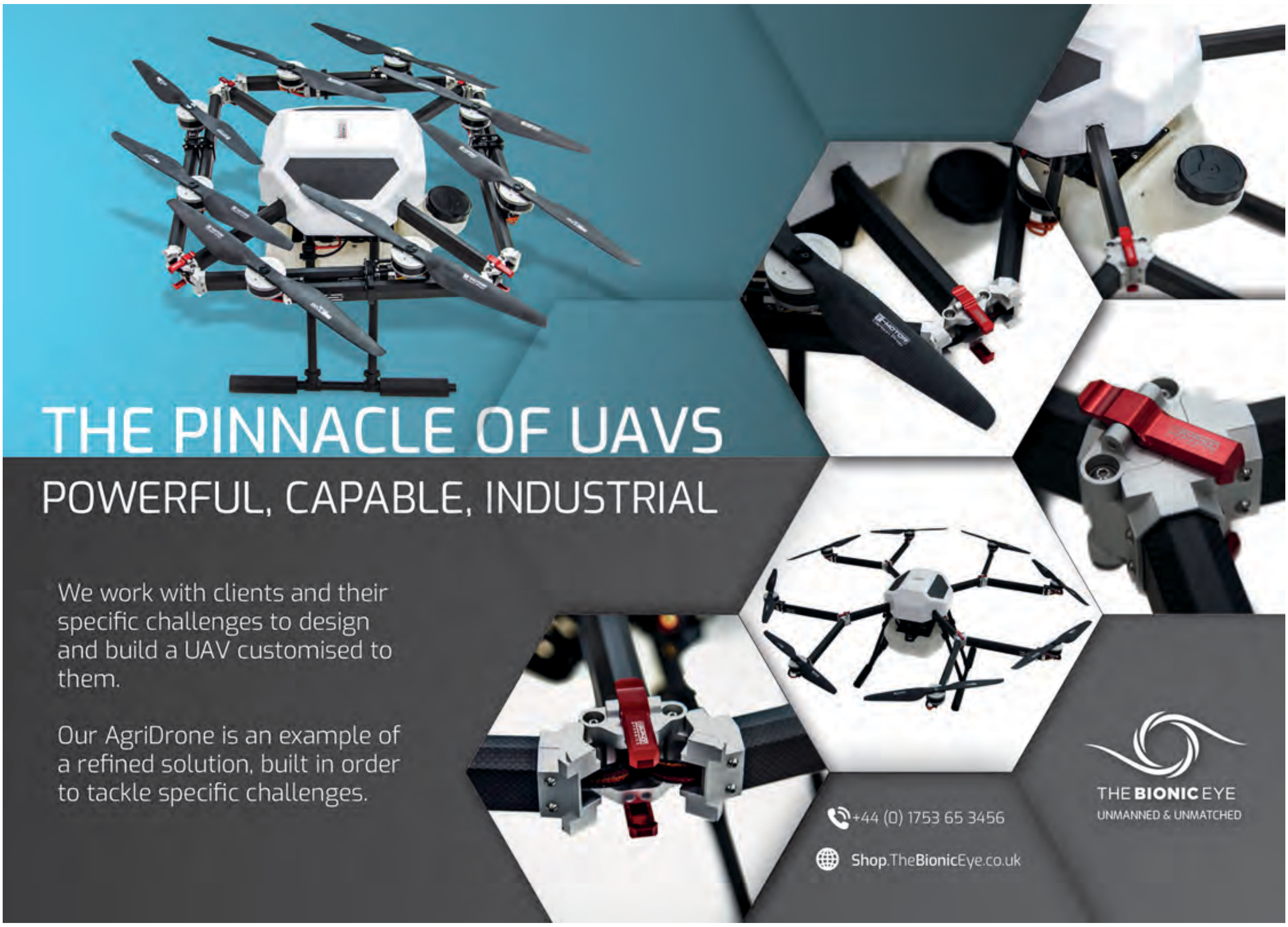
"Our SCU's SD card is capable of storing up to 24 hours of data, which can then be analysed afterwards to improve future operations," says Factor. That means the operating team can judge the overall safety of the ATMA system, for example by seeing how closely the vehicles were aligned during operation.

With post-processed kinematic GPS, the exact paths taken by the leader and follower trucks can be plotted with centimetre-level accuracy, and analysed for inconsistencies as small as a few centimetres. While that could be time-consuming and potentially unnecessary for most operations, it may be that an accident or a problem with the system occurred during a day's work, so an end-user might run such an analysis to assess why it happened.

In some locations, Kratos is also supporting a research-oriented pilot programme. As Factor explains, "That's necessary for legislators and authoritative bodies to approve this system, to let us use it on state roads. They want to be able to see how accurate it really is, or if there were any kind of obstacles disrupting the operation, and similar sorts of variables. They'll use that data for research purposes, but in normal operation, users have no major need for the data."

Conclusion

As more approvals and customer feedback are gained, the ATMA system is being continually redesigned and improved to suit different trucks and transport regulations, enabling more and more lives to be saved on highways around the world. ◻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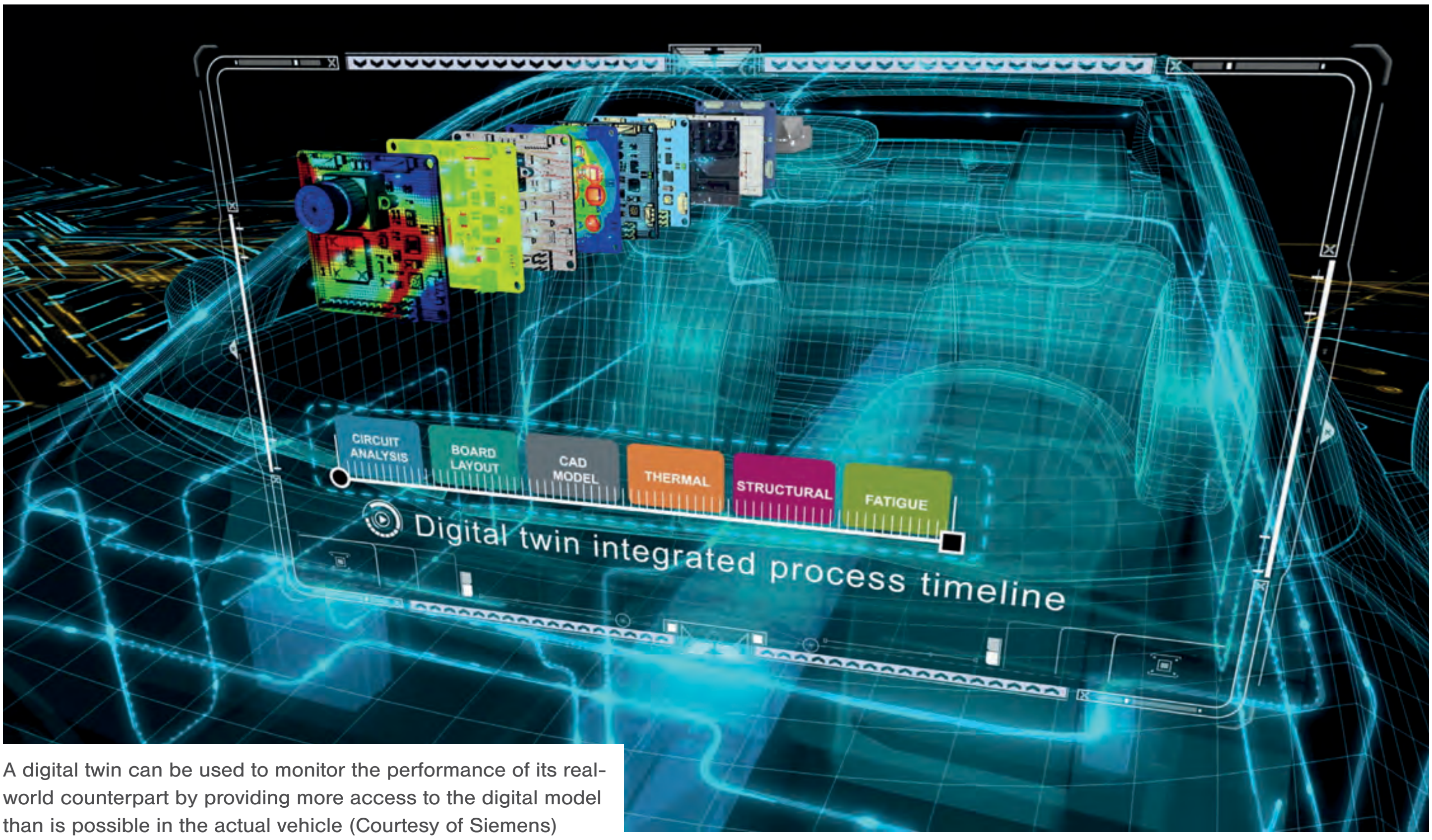


A digital twin can be used to monitor the performance of its real-world counterpart by providing more access to the digital model than is possible in the actual vehicle (Courtesy of Siemens)

How's it going?

Nick Flaherty explains the impact autonomy is having on monitoring the performance of unmanned systems

The ability to monitor the performance of an unmanned system becomes a key design criterion when autonomy is added to it. Taking its remote operator out of the control loop means the system has to make its own decisions about the integrity and performance of its subsystems.

The design and implementation of the performance monitoring in such platforms is undergoing a significant shift that is influencing changes in system architectures. Basic telemetry from a system in operation is no longer adequate for diagnosing problems or highlighting potential problems. Built-in self-test and onboard diagnostics (OBD) are used alongside fault-tolerant designs to ensure that component failures are detected early.

Machine learning (ML), often using neural networks, is increasingly being used to monitor the performance of components, to monitor the signals from sensors, the vibrations in the airframe or chassis, or the current from the battery pack. While some ML techniques have included sophisticated software such as the Kalman algorithm running on microprocessors, microcontrollers are now adding neural network hardware ML accelerators to support neural networks directly.

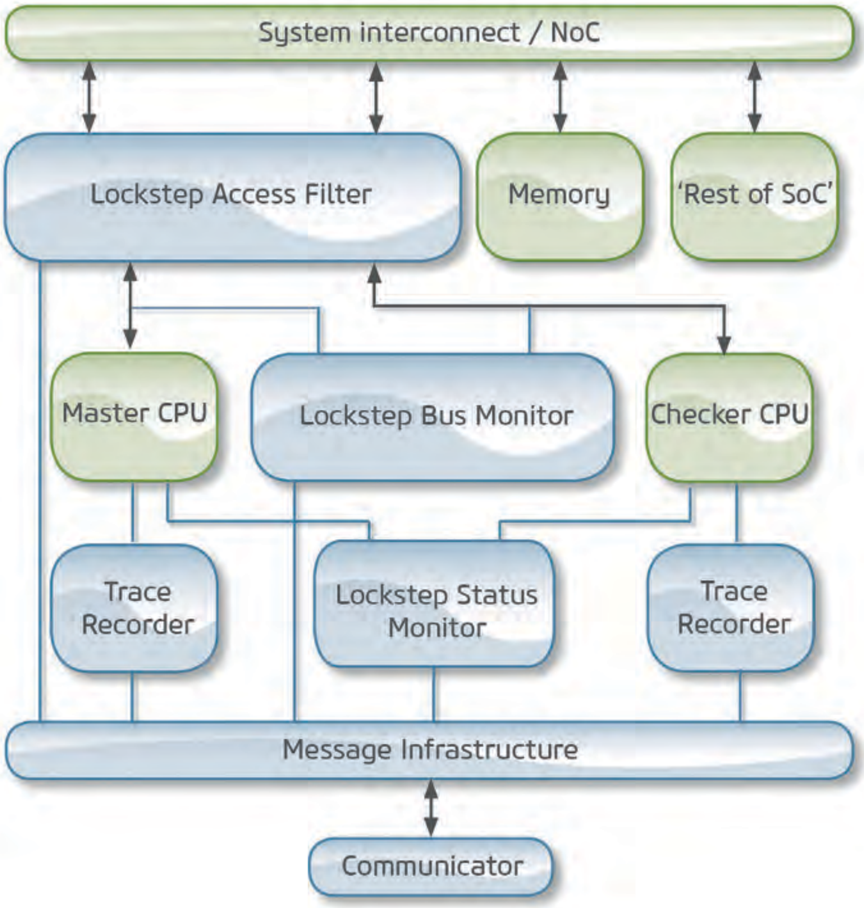
That is driving a split between centralised monitoring, for example in a domain controller that consolidates the functions of multiple electronic control units, or to have the ML monitoring taking place in smaller microcontrollers local to sensors.

A third option is to include the monitoring within the fabric of a system-on-chip (SoC), tapping into the infrastructure used for debugging the performance of the chip during system development. The data can be processed locally in the fabric using a lightweight processing engine, or shipped to the cloud for analysis.

This use of the cloud has become increasingly important for monitoring battery packs. There is a growing trend for data from the packs to be monitored remotely, with autonomous vehicles sending the data to the cloud for analysis by sophisticated machine network algorithms. These monitor individual packs, but collating data from all the vehicles in a fleet – or even across an entire range of vehicles – allows more subtle trends to be identified.

That raises the question of reliability, however, as cloud connections are vulnerable if a comms link fails.

Monitoring hardware added to a system-on-chip can be used to assess the condition of the chip (Courtesy of UltraSoC)



Chip-level monitoring

Tapping into chip-level diagnostics is a recent development for performance monitoring. Here, small monitors are added to key functional blocks and have their own comms network. This adds up to 1% of the die area of the SoC, and so far has been used for debugging the chip.

Once the blocks are designed into the chip they gather lots of fine-grained data to understand what's going on in the chip. As the blocks are still present in production it makes sense to use them to provide details of the chip's performance.

This data can be sent out via the comms links to the chip, whether it be Ethernet, USB3 or PCI Express. It can then be delivered to the vehicle operator or even the operator's customer. That is opening up new ways of managing data.

There is also the option of an on-chip analytics subsystem. This is a ring-fenced ML capability that could be pre-programmed to monitor specific parameters, such as throughput and latency, which will vary from application to application such as the length of the queue of data and response times. This means the embedded modules can watch for a specific event or spot any trends, and raise an alarm if necessary.

Another advantage is that all the debug data is also available, by using a small memory buffer on the chip and a larger data store off it. The debugging and monitoring hardware for this on-chip monitoring could take up 1-1.5% of the chip die area.

Having the monitoring on-chip improves the response time, allowing any issues to be detected more quickly. In tests on an SoC controlling a camera sensor, on-chip monitoring identified non-responsive pixels in a few microseconds. Taking the data off-chip for post-processing in software took up to 100 ms.

The technology is being used in a driver assistance ADAS chip that will be available later this year. Other automotive controllers using the technology are due to be launched next year.

On-chip neural networks

Using on-chip ML starts with capturing enough representative data about the phenomenon being modelled. This usually involves placing sensors on or near the object being monitored in order to record its state and any changes over the time, for example the temperature or vibration.

Chip makers now provide software and hardware development tools that help to capture and label the data. An example here would be a sensor subsystem that includes motion and environmental sensors, a microcontroller, an SD card connector and Bluetooth connectivity.

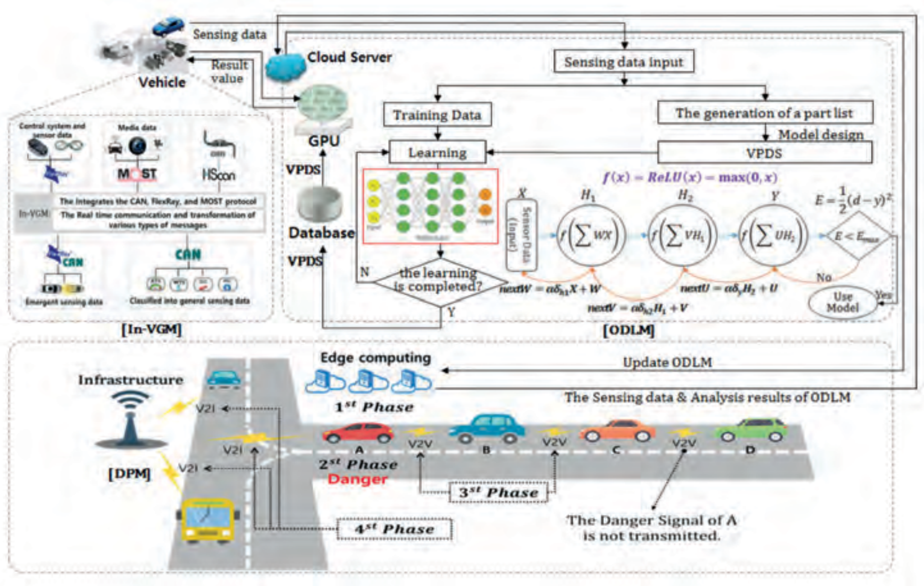
This subsystem labels the data for 'supervised learning', where the data sets have to be characterised so that the different outputs can be classified correctly. These classified data sets are called the 'ground truth' and will be used to train and then validate the neural network.

The system developer must decide on the type of topology the artificial neural network (ANN) should have in order to be able to best learn from the data and provide useful output for the target application. The developer will typically use popular off-the-shelf deep-learning frameworks to design and train ANN topologies.

Training an ANN involves passing the data sets through the neural network in an iterative manner so that the network's outputs can minimise any error on the output. This is usually done on a computer with virtually unlimited memory and computational power, to allow many iterations in a short period of time. The result is a pre-trained ANN.

The next step is to embed the trained ANN into a microcontroller. The software tools allow fast, automatic conversion of trained ANNs into optimised code that can run on a microcontroller.

This can be integrated with low-level drivers, middleware libraries and



The structure of an integrated self-diagnosis system for an autonomous vehicle. It includes an in-vehicle gateway module that collects data to feed to an optimised deep-learning module, which is then fed to a data processing module that sends the data to the cloud (Courtesy of YiNa Jeong et al, Catholic Kwandong University)

sample applications assembled into a single software package using software development tools.

Another example of using a neural network for performance monitoring is an acoustic-based fault diagnosis technique for three-phase induction motors driving the wheels of a driverless car. Four states of the motor were analysed – a healthy motor, a motor with a broken rotor bar, a motor with two broken rotor bars, and a motor with the faulty squirrel-cage ring.

A multi-layered neural network can analyse the output of a microphone and compare that to the different failure mechanisms. The neural network can then identify potential failures before they occur.

Software monitoring

Another way of monitoring the performance of a system is to monitor the data bus, which these days is often a Controller Area Network (CAN).

Besides CAN, autonomous vehicles are usually equipped with Ethernet. The decision and control modules are connected to the CAN bus, while the sensors are connected to the Ethernet, although sensors such as IMUs now have CAN interfaces as well. CAN and Ethernet use different frame structures, so combining the data effectively to compress and send to the cloud is a major challenge.

A data recorder for doing just that has been tested on an autonomous vehicle, and the tests show that the data can be reduced by a factor of seven. Data on the in-vehicle network (IVN) is compressed and transmitted to a remote centre for vehicle monitoring and data analysis.

The input interface is either CAN bus or Ethernet. The data comes from sources including the perception module, decision module, control module, Lidar, radar, cameras, RTK GPS, IMU and the odometer. The data parser can tell if the message is for real-time monitoring or historical data recording.

The real-time monitoring covers the vehicle's location, speed, heading, mileage, diagnostic trouble codes and so on, and is sent to the remote centre every second. Meanwhile the historical data, including all the data on the IVN, is compressed into files every 10 minutes and sent when there is available bandwidth.

Upon the arrival of a CAN message, the new data is mapped onto a 2D space associated with the specific CAN ID.

The data recorder collects vehicle information and sends the data to a central server over the 4G cellular network. The real-time data receiver decodes some selected parameters for vehicle monitoring, while the historical data file receiver aggregates all the commands to the vehicle through the remote command transmitter.

The modules on the test vehicle (an electric golf cart) generated more than 50 kinds of CAN messages with different periods. During each 10 minutes, 150,565 records were collected.

Each CAN record consisted of arrival time, CAN ID, data length code and data bytes, producing over 2 Mbytes in the 10-minute sampling period. This was then compressed to 305 kbytes using techniques such as data grouping and differential sampling, easing the pressure on the comms link.

Self-diagnosis

Another approach is an integrated self-diagnosis system (ISS) using a multi-layered neural network. This collects information from the vehicle sensors, diagnoses itself and sends the results to a central server. One example uses an ISS with three modules.

An in-vehicle gateway module collects the data from the in-vehicle sensors and transfers the data collected through various protocols in the vehicle. These include CAN, FlexRay and Media Oriented Systems Transport (MOST) protocols that are used to link to the OBD.

The data collected from the in-vehicle sensors is transferred to the CAN or FlexRay protocol, and the media data is collected while driving is transferred to the MOST protocol. The various types of messages transferred are transformed into a destination protocol message type.

A second module, the optimised deep-learning module, creates the dataset used for training a multi-layered neural network, taking the data collected from the in-vehicle sensors and assessing the risk of vehicle components failing, as well as the risk to other parts that might be affected by a defective component, thus

Performance monitoring is integrated into autopilot software to allow UAV operators to replay a flight with visibility of all the parameters (Courtesy of UAV Navigation)

A QR code allows the condition of an individual battery pack to be uploaded to the cloud and combined with data from other packs in a fleet. This can also allow an individual pack to have a customised charging algorithm (Courtesy of Bosch)

diagnosing the vehicle's overall condition.

A third module, the data processing module, sends the data to the cloud and links to a V2X-based accident notification service that informs adjacent vehicles and infrastructures of the self-diagnosis result analysed by the OBD.

A link to the cloud has a shorter transmission delay and ensures a higher transmission success rate. The timing impact introduced by various CAN/Ethernet multiplexing strategies at the gateway is used to derive upper bounds on end-to-end latencies for complex multiplexing strategies, which is the key for the design of safety-critical real-time systems.

The various actual arriving orders of gateway messages are examined in detail. An explorative worst-case response time (WCRT) computation method reduced the WCRT by 24%, dramatically improving the responsiveness of the system.

Autopilot monitoring

Performance monitoring is increasingly integrated into the autopilot in a UAV, as it gathers all the sensor data. That means the performance monitoring can be handled through the autopilot via different basic alarms, such as failure in a comms port, the GNSS signal or an IMU failure.

That can be taken further though. Telemetry analytics allow a UAV operator to load the log file from previous flights and analyse the data to graphically represent all the variables received through the telemetry, to see all the parameters and even make multiple comparisons of different data points.

That allows performance monitoring services where users who have a problem or incident, or are unsure about the behaviour of certain parameters, to send the log file for analysis.

The data also provides a graphical representation of the variables in real time, so that users can be performing the flight while seeing the telemetry from the autopilot. A replay mode uses the data to look back through the details of the flight to monitor the performance.

That requires careful consideration of the data management. The configuration of the general-purpose I/O lines and flight paths are stored in non-volatile memory, where wear-levelling is an important factor in maintaining reliability.

Diagnostic data is often recorded in the same page of a memory chip, then overwritten by the next set of data. That can mean certain pages are used more regularly, leading to a reduction in the reliability of storing the data as each read-write cycle wears down the memory cell, leading to the loss of data, one of the most common long-term failures in an electronic system. Wear-levelling algorithms move the data around a memory chip to record the data in different areas of it, ensuring even wear across the memory chip.

The software also provides back-ups of data, so if the system detects an error it can automatically recover a copy from a redundant module of the memory and replace it. This is stored in a separate page on the same device to guarantee reliable operation, However, it means the data has to be stored with different ID tags and with tight controls on its location.

Digital twins

Another non-invasive way to monitor the performance of an autonomous system is to use a digital twin. This is a simulation of a complete vehicle or aircraft that is used for development and testing.

A behavioural model of each component can be used to develop the overall system performance, then components can be replaced with detailed models of individual subsystems and chips. These models are used to develop the ML algorithms of platforms, driving or flying millions of virtual miles to enhance the algorithms.

The models can also be used for monitoring the performance of the system after it has been developed. They can run 24 hours a day, seven days a week, in an accelerated environment, highlighting any problems as the platform ages. That can potentially give early warning of the failure of a particular component or subsystem that can then be checked in the real world.

Having a digital model allows for detailed instrumentation, giving visibility of many elements such as processor or sensor cores in a platform that may not be accessible in the real-world version.

Another key advantage of a digital twin is that a simulation model can be used to develop the training data for the multi-layered neural networks used in the performance monitoring subsystems. This training can be difficult in real-world systems as it could take many months of real-world testing to generate the models, and then many more to verify them. This process can be shortened markedly by using a digital twin to generate the training data.

Battery monitoring

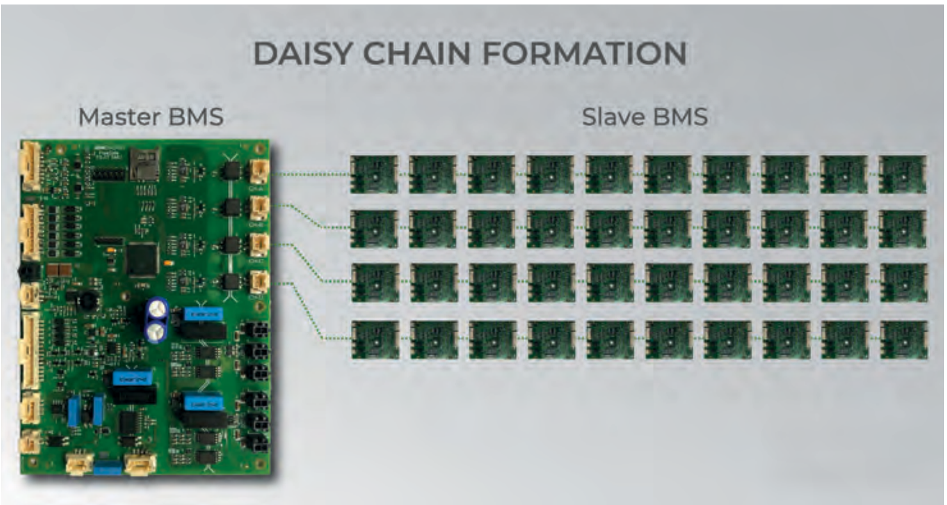
A key area of autonomous vehicle monitoring is the battery system. This has traditionally been done via the battery management system (BMS), using a range of algorithms including Kalman to flag up changes in the pack's performance.

The average service life of modern lithium-ion batteries is eight to 10 years, or between 500 and 1000 charge cycles, and battery makers usually guarantee mileages of between 100,000 and 160,000 km.

The use of faster and more powerful charging, up from 50 to 320 kW, and with higher numbers of charge cycles for an autonomous system, puts more pressure on battery packs.

Stress, either from temperature or high current draw, makes cells age faster. The older the batteries get, the lower their performance and capacity, and the shorter the vehicle's range.

New cloud-based services are being developed that supplement individual vehicles' BMSs. Algorithms in the cloud continually analyse the status of a battery and take appropriate action to prevent or slow down cell ageing.



A battery management system with a master and slave has been designed with a cloud connection to collect data from thousands of battery cells in vehicles to monitor their performance (Courtesy of Ion Energy)

These measures can reduce the wear and tear on a battery by as much as 20%. Real-time data gathering is essential here, as the cloud service uses the data to optimise every recharging process and modify how the vehicle drives.

This 'battery in the cloud' is being used by a Chinese autonomous vehicle provider. All the battery-relevant data, including ambient temperature and charging habits, is first transmitted in real time to the cloud, where ML algorithms evaluate the data. That provides visibility of the battery's current status at all times, and can also give a reliable forecast of its remaining service life and performance.

It also uses data from fleets of vehicles. This 'swarm intelligence' identifies more of the stress factors for vehicle batteries and identifies them more quickly.

For example, fully charged batteries age more quickly at particularly high or low ambient temperatures, so the cloud service makes sure the batteries are not charged to 100% when conditions are too hot or too cold. Reducing battery charge by only a few percentage points protects against inadvertent wear and tear.

As soon as a battery fault or defect is identified, the operator can be notified. This increases the chances that a battery can be repaired before it becomes damaged or stops working.

The cloud service also optimises the recharging process itself. The algorithms in the cloud can calculate an individual charge curve for each recharging process, regardless of whether it takes place at home or elsewhere.

That means the battery is recharged to the optimum level, helping to conserve the cells. Apps with charge timers monitor the recharging process so that it is carried out when demand for electricity is low. Optimising both fast and slow charging, and controlling the current and voltage levels during the charging process, helps to extend battery life.

It also allows the cloud service provider to offer its own charging strategies, rather than those in the charger or BMS. That in turn can allow fast charging without damaging the battery, or a more leisurely standard charging process over several hours, enhancing the battery's capacity and service life.

Another driver for using a cloud service for performance monitoring is a lack of detailed technical knowledge about neural networks, especially in emerging markets. Sending the data to a service in the cloud for analysis means operators don't need these specific skills but can still gain advantage from the latest performance monitoring technologies.

A 23 Ah 48 V cell from LG Chem for example is being used in a portable battery that is compatible with common

Examples of performance monitoring technology suppliers

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autonomous systems. The BMS collects deep analytic information such as state of charge, state of health (SoH) and warranty information, along with vehicle tracking.

This monitoring requirement means the BMS is split in two: the battery management unit (BMU) and the system management unit (SMU). Each BMU can manage six to 18 cells in series, so the SMU coupled with the BMU can be scaled up to handle 720 cells.

This allows the depth of charging to be fine-tuned at a cell level. The data system with the SMU and LG Chem cell takes 124 data points every 500 ms on the cell voltage, state of charge and SoH, shipping 1.8 million data points to the cloud.

This is useful for error identification and battery diagnostics, and also creates a giant repository of battery data in the cloud. There can be the issue though of who owns this data – the BMS supplier, the battery supplier, the seller of the systems or the users?

However, there is a potential conflict between the results of the model and the incoming diagnostic data that needs to be resolved. Using the data as part of the model leads to predictions about the system's ongoing health.

Conclusion

There is a clear engineering trade-off in monitoring the performance of autonomous systems.

Local processing of the data using embedded debugging traces and dedicated on-chip neural networks can provide a much faster response time to flag up any problems. On the other hand, sending data back to the cloud requires more sophisticated onboard systems for capturing and compressing the data, and transmitting it to central servers.

Acknowledgements

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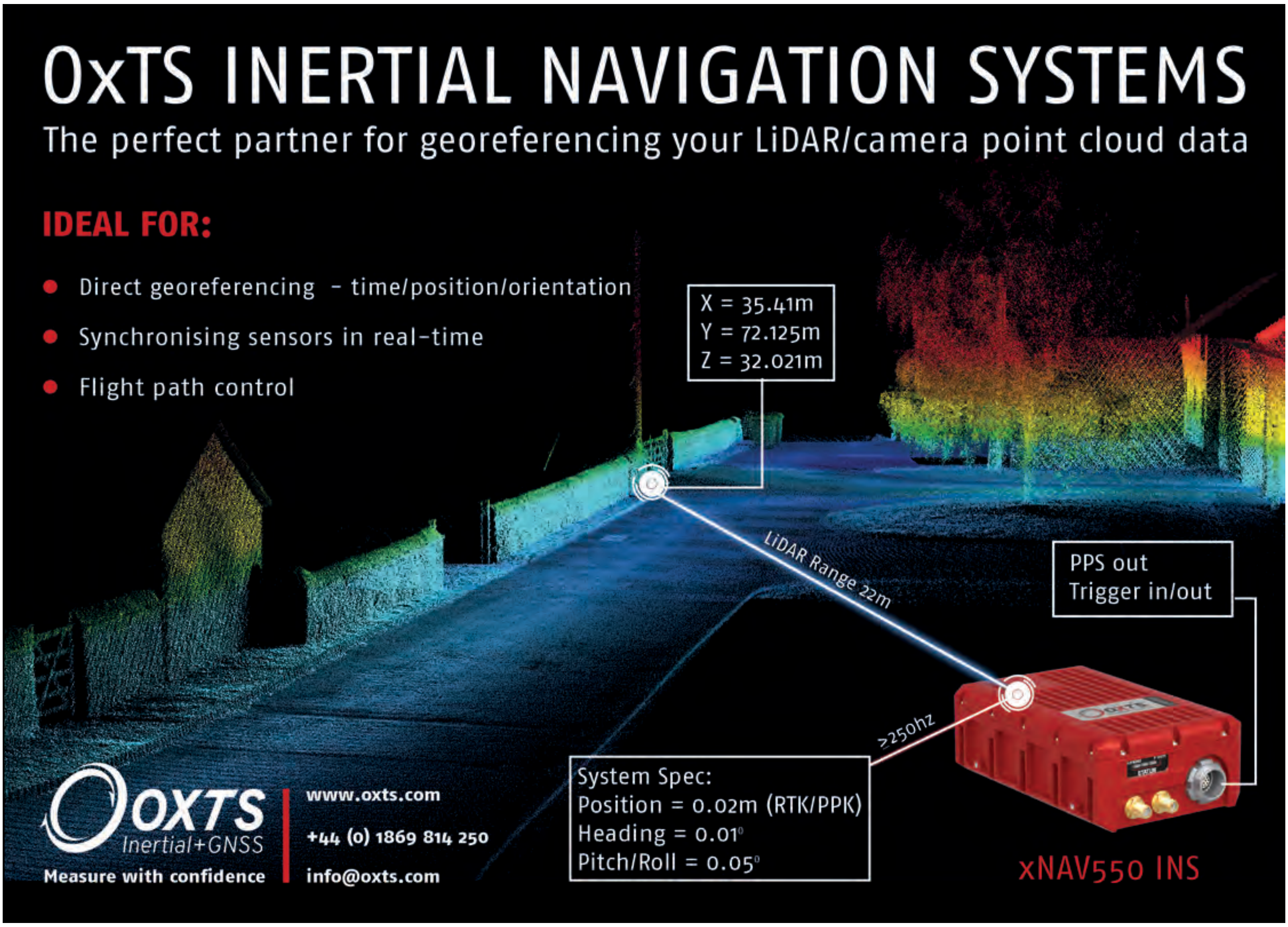
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Acoustic composition

Rory Jackson explains how this all-new USV was developed to provide long-endurance hydrographic surveys

The marine autonomy capabilities of Kongsberg Maritime are well-founded. Long-running projects such as the Hugin AUV, and newer ones such as the Sea-Kit and Yara Birkeland, have demonstrated the company's ability to develop hardware and software for a range of sea systems.

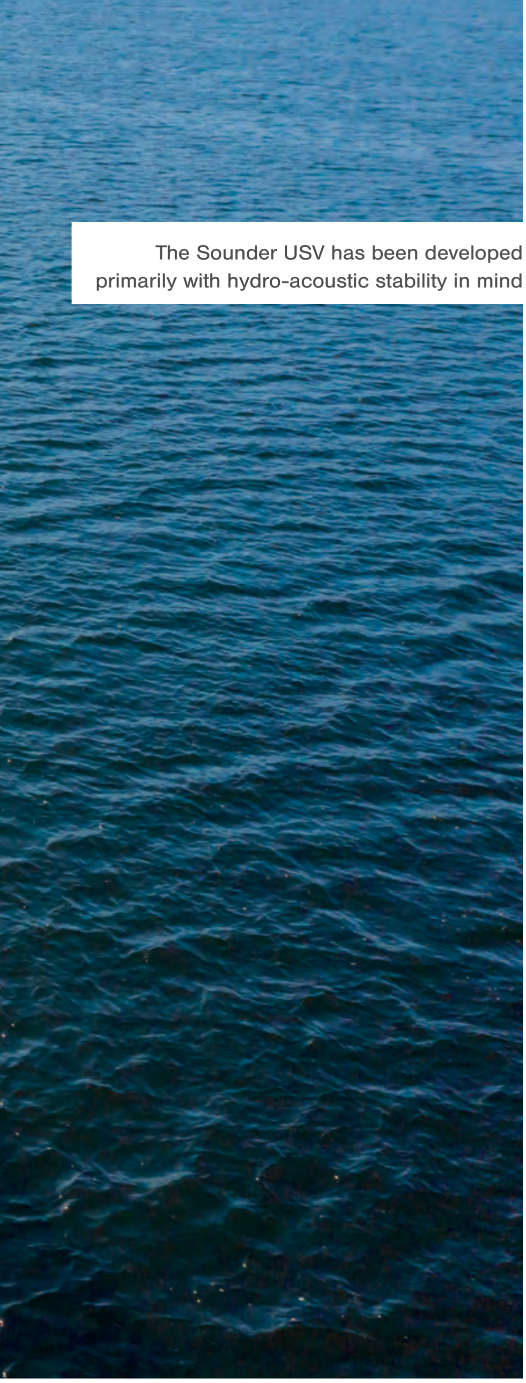
In examining the large (and fast-growing) market for survey-grade USVs, many members of the Norwegian company noticed that there was widespread conversion of work boats into unmanned craft. That was depriving the market of surface vehicles that had been designed from the outset around optimised hydro-acoustic performance.

Development of the Sounder, Kongsberg Maritime's first all-new USV platform, began in earnest around early 2018. In the pursuit for a long-endurance hydrographic survey vessel, it worked with the Norwegian Defence Research Establishment, or FFI, its long-standing partner on various technologies including the K-Mate maritime autonomous control system, and boat manufacturer Viking Norsafe, which was responsible for designing and building the hull.

The hull

Input and expertise from Viking Norsafe was critical to achieving the seakeeping performance the Sounder would need.

"If we have both water and air going underneath the hull around the acoustic transducers, that introduces an element of noise into any data we're trying to gather, potentially creating gaps or losses of resolution in the sonar imagery," explains Richard Mills, director of marine robotics at Kongsberg Maritime. "So we needed a hull shape that would minimise that aeration of the sonars; it's sometimes difficult to get rid of it altogether."



The Sounder USV has been developed primarily with hydro-acoustic stability in mind

That would need to be balanced against the need to avoid adversely affecting the Sounder's roll and directional stability, while keeping it lightweight and manoeuvrable.

As Stian Michael Kristoffersen, product manager of USV solutions, notes, "The hull was gradually designed around cutting through the water without disturbing it too much. It needed a narrow bow, which would push away the water in front but also allow the water at the sides to glide along the hull as smoothly as possible.

"Any imperfections or inconsistencies along the hull would generate microbubbles, leading to aeration in the water, causing noise and attenuation

> The hull needed a narrow bow, which would push away the water in front yet allow the water at the sides to glide along the hull

for the echo sounders or other hydro-acoustic sensors. So finding that optimal hull shape was crucial from the outset, and we spent a lot of time with Viking Norsafe to get it right."

However, developing the hull to give good hydrodynamic performance with respect to sensor aeration could have come at the expense of directional stability, since reducing hydrodynamic 'disturbances' along the hull might mean eliminating control surfaces.

To that end the underside of the hull has two fixed fins, one at either end towards the rear, to provide directional stability far away from the payloads near the centre of the Sounder.

Much of Viking Norsafe's design analysis was based on CFD simulations, which were produced by fellow Norwegian company CFD Marine. "They have considerable experience and computer facilities geared towards modelling and analysing hydrodynamics," Kristoffersen notes. "Now that the Sounder has been thoroughly tested in water, we've found it to perform very closely and accurately to CFD Marine's software simulations."

In addition to hydrodynamic performance, the hull needed to be lightweight enough to enable manoeuvrability and easy handling, while remaining strong enough to support 20 days' endurance at sea.

"Viking Norsafe come from a background of building lifeboats, rescue boats and military RHIBs, which have very high demands for strength and reliability," Kristoffersen explains. "That part of their experience went a long way towards informing the material composition and mechanical structure of the hull."

The hull consists of a two-layered 'sandwich' structure, with an outer hull, an inner liner hull and foam filling the space between them. The outer and inner hulls are made from fibreglass for a smooth and lightweight hydrodynamic finish, and the foam is polyurethane.

"The foam adds buoyancy throughout the craft, and also helps with strength – the three layers are very stiff when combined together," Kristoffersen notes. "The outer hull is just over a centimetre thick, and even if something penetrates that it would still have to go through the foam and inner liner for there to be any water ingress inside the USV."

The inner liner is also designed with extra foam in the bow, to provide extra protection in the Sounder's forward direction, with a 40-50 cm foam-filled gap between the outer and inner hull about the tip of the bow. For the rest of the hull, the foam is roughly 1.1 cm thick.

Overall, the hull's dimensions come to 8 m in length and 2.1 m in width, with a draft of 0.7 m. In operation, the overall height of the Sounder is about 4.4 m.

However, the mast near the back of the USV rests on a pair of hydraulic dampers that allow it to be pulled back and laid down on the aft deck, and that takes the vehicle's height down to 2.3 m.

This ability to make the Sounder more 'compact' allows it to be fitted in a standard shipping container for ease of transport to harbours or other bodies of water. After unpacking it, the mast

The hatch design lets users change payloads and subsystems between different missions, perhaps several times in one day

The bow of the Sounder USV contains polyurethane foam about 40 to 50 cm thick, compared with about 1.1 cm thickness throughout the rest of the craft

The largest hatch atop the USV's deck covers the moonpool payload bay, and has additional hatches for mission electronics, mooring equipment and so on

is pulled back up and fixed into place with a quick-lock system before a new mission begins.

Payload integration

"Across our previous unmanned marine vehicles we've always seen that every customer has slight differences in the payloads and associated electronics they want to install," Kristoffersen says. "We've therefore tried to keep the Sounder as flexible and agnostic as possible with regard to which payloads can be integrated, while keeping it as easy as possible to change them."

The Sounder therefore comes with a series of four hatches on top of the deck. To enable integration of multiple different payloads between missions – specifically echo sounder-type payloads or others that also need to be submerged in order to produce their imagery – a moonpool is designed from the rear into the second hatch.

The moonpool hatch is typically marked with 'Sounder' to make it quickly recognisable. It allows remote lowering and raising of payloads into and out of the water, and the moonpool can carry up to 1000 kg of payload.

Directly in front of the moonpool payload hatch is a compartment designated for the installation of processors and other critical ancillary equipment for handling payload and other mission data.

To that end, a standardised 19 in server rack in the compartment can be lifted in and out to swap electronics modules as needed.

"This design aspect is intended to let users change multiple payloads and their important subsystems between missions, perhaps several times in one day if needed, with minimal time spent reconfiguring the system," Kristoffersen explains.

The Sounder's propulsion uses a Steyr six-cylinder diesel engine to drive a single fixed-pitch propeller. Steering is provided by three rudders

The forwardmost and rearmost hatches are simple storage compartments, where ropes and other mooring equipment can be stowed if desired.

As well as providing the moonpool, the design and manufacturing teams at Kongsberg can mould sensor payloads directly into the fibreglass of the hull if requested. Also, inside the bow area, a steel backing plate is fixed onto the inner fibreglass layer.

The plate can be used to mount additional payloads if a user wants to collect data at the front of the craft, without having to lower a particular sensor into the water. These would then be connected through to the Sounder's power system, or they might use their own separate battery if enough space had been left on the plate.

As well as being compatible with such systems as Kongsberg's various multi-beam echo sounders (and other sonar-based imaging sensors), the Sounder can also use the Simrad SX90 low-frequency omni-directional fishery sonar.

This cylindrical transducer transmits sound waves 360° horizontally around the boat, and is programmed to generate radar-like imagery of the direction, distance and size of schools of fish.

The first Sounder with an SX90 has been sold to TASA, the largest fishing company in Peru. It will be used to look for large groups of fish up to 2 km away from the USV, and can be combined with a downward-facing echo sounder.

After navigating to above a given school of fish, that will enable the Sounder to take acoustic measurements inside and around the school to determine the school's size distribution.

Based on the general size of the fish, the crews operating the Sounder will then be able to determine whether the school should be tracked down and hauled in by a trawler, or whether it should be left to mature in favour of another catch.

Propulsion

The Sounder has a maximum speed of 12 knots, while the recommended operating speed is from 4 to 8 knots. Up to 20 days of endurance can be achieved if operations are typically run at 4 knots.

Propulsion is delivered by a single fixed-pitch propeller, powered by a Steyr SE 126E25 diesel engine. Selecting this particular engine rested on a number of considerations by both Norsafe and Kongsberg.

"We wanted to keep the propulsion as simple as possible in how it operates, using a marine engine that would be familiar to operators and technicians in hydrographics, mine countermeasures, fishery surveys and other applications for which the Sounder is intended," Kristoffersen explains.

The Steyr SE 126E25 is a four-stroke, turbocharged six-cylinder engine. Each cylinder has a bore of 85 mm and a 94 mm stroke, for a total displacement of 3.2 litres. It uses direct injection, has a top operating speed of 2500 rpm, produces a maximum torque of 390 Nm at 1800 rpm, and a dry weight of 340 kg.

While the design team's targets for speed and endurance could have been satisfied by a smaller, four-cylinder engine, they went with the straight-six Steyr as it produces less vibration than the four-cylinder models that matched the mission envelope. Less vibration naturally means fewer blurs in the survey imagery.

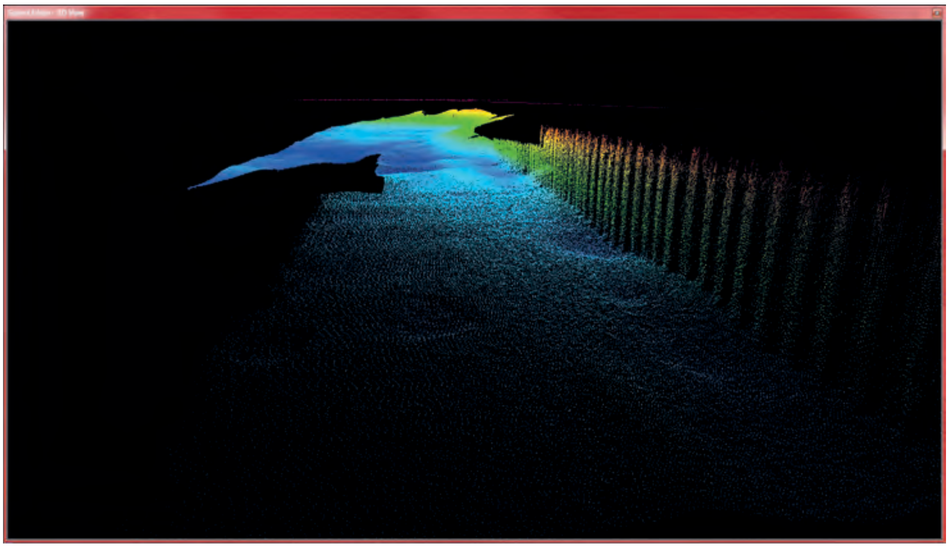
The engine also has a lower specific fuel consumption between 4 and 8 knots than the four-cylinder marine engines that were investigated, so the relatively larger engine was selected to aid endurance and fuel efficiency.

As the propeller is fixed pitch, no gearing is used to rotate the angles of the prop blades; instead the speed is linked to engine rpm. The drivetrain comes with a separate marine gearbox to provide the transmission for running the propeller at operating speeds and maximum speed.

"We experimented a bit with different propeller sizes, iterating with different versions to achieve the optimum endurance with that engine set-up," Kristoffersen says.

Norsafe's emphasis on choosing the Steyr six-cylinder also came from it being a SOLAS engine: this is a standard for maritime use that enables automatic shutdown (therefore helping platform stability) among other things if the Sounder should accidentally flip to 90º. Once it rights itself, the oil settles and the engine can be restarted.

A generator has been mounted on the engine's flywheel to power the various onboard computers, sensors and other systems. It produces up to 4 kW, although that can be increased if requested.



The Sounder is to be equipped with various echo sounders (depending on the user), so designing the hull to prevent disruption of sensor data has been critical for the vehicle's development

The engineering team achieves this increase by adding one or two belt-driven dynamos, which can boost the maximum output to 6 kW.

That can be useful if a mission requires a heavy hoisting mechanism or winch for handling towfish or other sensors that are too large for the moonpool payload bay. For most operations, however, Kongsberg anticipates that the 4 kW generator will be enough.

The Sounder's manoeuvrability is provided by three rudders. One is placed behind the propeller, while the other two are fixed on each of the aforementioned side fins. A single steering pump is used to actuate the central rudder, and the other two rudders are mechanically linked to the middle one.

That gives the Sounder a turning radius of just under 15 m when travelling at its 12 knot speed limit.

Autonomy

Kongsberg Maritime's work on the K-Mate autonomy engine has continued gradually over the past four years, and development was conducted with FFI on specific software for BVLOS surface autonomy, which is now being used on the Sounder.

"The vast majority of the capabilities that we see out there at the moment have some level of waypoint alignment autonomy or rudimentary survey autonomy," Mills comments.

"But we wanted to make sure we could combine survey autonomy with intelligent scene analysis and situational awareness, to put some more complex autonomous decision-making capability into USVs and so make them safe to operate over the horizon."

This surface autonomy r&d began about eight years ago, the main goal of which was autonomous decision-making aimed at compensating for gaps in the information being sent back to the operator's control station (owing to bandwidth limitations or other issues).

The K-Mate autonomy engine is intended as a flexible, modular system to come as close as possible to a 'one-size-fits-all' marine autopilot, and continues to be developed on other platforms.

For example, the Odin USV (co-developed between Kongsberg Maritime and FFI) was used in August 2017 to demonstrate a version of K-Mate with a COLREG-compliant level of autonomous obstacle avoidance. That enabled it to navigate around stationary objects as well as crossing objects in danger of collision.

The Sounder's own collision-avoidance capability is powered by a range of sensors, the most important of which is the Simrad HALO24 radar. This provides the first layer of obstacle detection, between ranges of 20 and 40 nautical miles from the Sounder, although the resolution will degrade at the longer ranges.

If the radar detects and tracks an object, several other sensors can serve to identify it. A pan-tilt-zoom camera from FLIR is integrated to provide a visual feed of anything within 3 km of the Sounder. AIS is also available for applying transponder signals to radar information, so that ships' identifications, positions, courses and speeds can be quickly accessed.

And for anything short range that passes identification by the radar, AIS and camera, a VLP-32C Lidar from Velodyne provides distance and 3D imagery of targets within a 200 m radius around the vessel.

The Lidar can also be used to map or track land, with 600,000 measurements generated per second for point clouds at typical operation, and a rotation rate of between 5 and 20 Hz.

"In the future we want to develop our autonomy software to handle that automatically. Ideally the radar would detect something, such as a vessel, and the camera would zoom in and identify it using machine learning if AIS doesn't sufficiently label it first," says Kristoffersen.

"The camera and Lidar can then be used to autonomously track the direction it's moving in, whether it's a fishing boat or something else."

In the course of autonomously avoiding potential obstructions, however, a hydrographic survey USV could be thrown off of its course for whatever mapping or similar operation it has been tasked with. That can cause lapses in the total area covered in each survey, so Kongsberg is working to account for that in the Sounder's autonomy.

"In the future, this USV will adjust and re-attempt its survey patterns on the fly, based on how well the sonars are producing imagery at each waypoint," Mills explains.

"We've gone over a vast amount of data from AIS, radar, cameras and

The mast atop the Sounder acts as a mount for Kongsberg's Maritime Broadband Radio, an Iridium satellite system, a Simrad radar and a FLIR camera

Lidar to create a threat-priority list. That determines the degree of avoidance taken by the USV around different types of boats and other objects, and the behaviour it takes in looping back around to cover any potential gaps momentarily left in the pre-planned survey route."

Kongsberg's SeaNav 300 GNSS provides the main position and heading data for the craft (while also logging velocity accurate to 0.25 kph), with inertial measurement data coming from a Kongsberg MGC-R3 IMU. This unit is integrated into the Kongsberg Sunstone inertial navigation system.

A range of correction or processing options are available. For example, with DGNSS or SBAS correction, the USV's position is accurate to 1.2 m.

Comms systems

The standard comms set-up on the Sounder uses Kongsberg's Maritime Broadband Radio, which has a range of about 50 km, a bandwidth of 16.5 Mbit/s and operating at about 5.5 GHz.

If that link happens to drop, an Iridium satellite link is installed as a back-up. The Iridium bandwidth will not be enough for transmitting the live camera feed (unlike the 5.5 GHz link) or any other key mission data, but still enables simple commands and updates on the Sounder's status and its subsystems. For example, the operators could use it to bring the Sounder back within radio range.

That satellite comms system has its own battery pack so that, if the Sounder's engine or generator fails, it can continue to transmit commands and its GNSS position for at least 72 hours, or more if the operator reduces the Iridium's update frequency. The end-user can then find the craft and pilot it back or arrange to have it retrieved, depending on whether just the generator or the whole engine system has gone down.

The radio and satellite data link systems are mounted on the aforementioned mast, and the company is looking at adding 4G, VSAT and Inmarsat links, to expand the Sounder's comms capabilities and redundancies.

"The latter two would also give greater bandwidth than Iridium, and VSAT in particular would open the door to live HD BVLOS video feeds," Kristoffersen adds.

The future

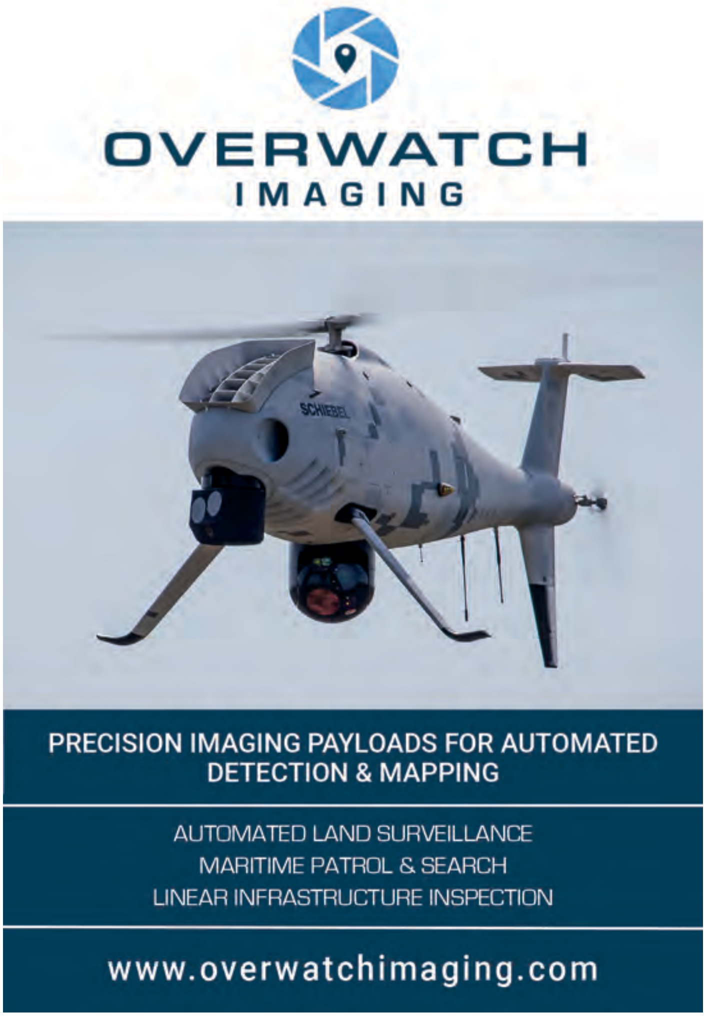
In addition to future updates in the vehicle's comms, Kongsberg Maritime will be examining how COLREGs evolve in response to the advances made in vessel autonomy.

With several nations and marine autonomy companies developing maritime collision avoidance, marine autopilots might eventually need to conform to standards that many different authorities can agree on. ◻

Specifications

Length: 8 m
Beam: 2.2 m
Height: 2.3/4.4 m (mast down/up)
Draft: 0.7 m
Weight: 4200 kg
Propulsion: 93.2 kW (125 hp)
Top speed: 12 knots
Maximum endurance:
20 days (at 4 knots)
Payload power: 4 kW (at 4 knots)

Some key suppliers
Hull design and manufacturing:
Viking Norsafe
CFD services: CFD Marine
GNSS and INS: in-house
Autopilot: Simrad
Autonomous control: in-house
Engine: Steyr
Lidar: Velodyne
Radar: Simrad
Camera: FLIR
Sonars: in-house
Data link: in-house
Additional technological research and consultation: FFI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"Now, here's a thing"

Inspired by artists who create works from objects they find lying around, a team of engineers from Japan has built robots using irregularly shaped tree branches connected by hinge-like servo motors, and employed deep reinforcement learning to teach them to walk (writes Peter Donaldson).

For now, the idea seems to be more about exploring the art of the possible than about practical applications, but it raises the prospect of creating useful robots or vehicles at short notice from a few servos, a computer, a power source and either carefully selected found objects or very basic kits of structural parts. One example consists of three branches of different lengths and diameters, the longest and thickest in the middle joined by a pair of servos to one Y-shaped fork and one short, curved stick.

In their paper, "Improvised Robotic Design with Found Objects", the team says, "When the robot is trained towards the goal of efficient locomotion, these parts adopt new meaning – hopping legs, dragging arms, spinning hips or as yet unnamed creative mechanisms of propulsion. These learned strategies, and thus the meanings we might assign to such found object parts, are a product of optimisation and not known prior to learning."

Initially, the robots were created virtually and learned to move in a simulated environment. Once the team had selected the tree branches, they laser-scanned and weighed them to create 3D computer models, then simplified the geometries to make simulation easier. The servos also had to be modelled, as did the friction between the branches and the ground.

> The study raises the prospect of creating useful vehicles at short notice from a few servos and so on, and basic kits of parts

The simulation allowed the model to explore a wide range of movements, while the reinforcement learning applied 'rewards' to those deemed helpful to effective locomotion. In the simulator, multiple software agents were able to learn, each taking a few hours to finish the process.

Greater rewards were given for movements that took the robot long distances from its starting point, while low rewards were given for any that produced undesirable behaviours such as spinning on the spot, wiggling, flipping, drifting, sliding or anything that might result in stress or wear in a real robot.

An agent that developed a propulsive motion with Y-shaped branches was the most successful, so its joint values, such as angles and rates of motion, were copied from the simulation to the physical robot's servo motors.

Several iterations were made between the simulation and the real world to minimise the differences between them in the robot's behaviour, with the friction coefficient of the floor and the scale of the rewards having to be revised several times. This and other issues could be solved by running the learning process in the real world; the team did try that but the learning took too long.

If they were to do it again, they conclude, they would make the robot bigger so they could fit cameras to it to observe its motion more closely and so that it could carry its own controller and power source to free it from its tangle-prone cable. However, they proved that a few core hardware components, machine learning software and a handful of sticks can become a functioning robot. ◻

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