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UST 28 : OCT/NOV 2019

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UK £15, USA $30, EUROPE €22

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Spread spectrum

Unmanned platforms are increasingly being used to explore the great unknown, whether it's in our oceans or out in space. This issue therefore looks at the latest system developments on the ocean surface (page 20), beneath it (page 24) and in orbit as well as further beyond (page 46).

These hazardous environments present some of the greatest engineering challenges, but as a result deliver some of the most innovative solutions.

The next generation of engineers are facing up to other engineering challenges, notably creating the fastest autonomous vehicle on the racetrack.

The student team behind AMZ Driverless (page 54) is pushing the boundaries of performance, and we look at the lessons learned about sensors and system architectures that are set to make their way into future mainstream designs, as well as the latest developments in engine control units (page 36).

Meanwhile, unmanned aircraft are being used more and more in mainstream applications as the technology matures. That is leading to more ways of refining the way the platforms are deployed and how they are integrated into teams of workers.

We also examine how one man's entrepreneurial spirit spurred him on to set up a company that uses airborne vehicles to install and inspect overhead power lines (page 76), while another has focused on a heavy-lift testbed for experimental comms payloads (page 92).

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UNMANNED systems TECHNOLOGY
Critical intelligence for land, sea and aerospace engineers

Volume Five | Issue Six
October/November 2019

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Whitfield House, Cheddar Road,
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BS28 4EJ, England
Tel: +44 (0)1934 713957
www.highpowermedia.com

ISSN 2056-9823
Printed in Great Britain

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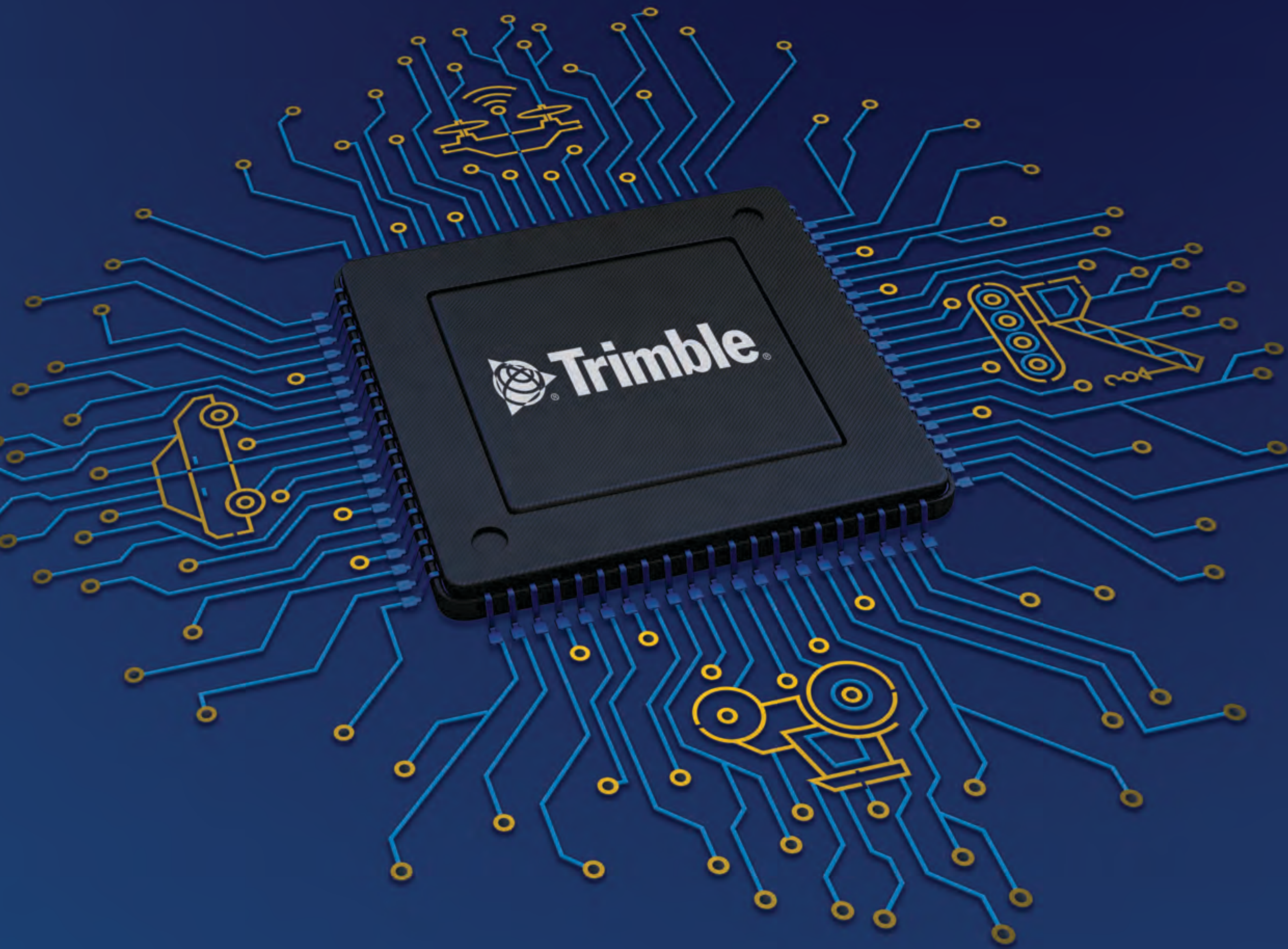
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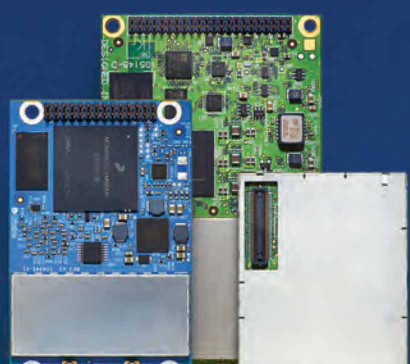


Scania's AXL autonomous and cab-less mining tipper truck has given it integrated styling

Truck is truly driverless

Autonomous trucks

Scania has designed out the operator cab in its next generation of driverless construction vehicle (writes Nick Flaherty).

The AXL uses a combination of radar, Lidar and camera sensors to detect obstructions, people and other vehicles around it, with a GPS receiver for navigation.

Radar sensors are reliable, but the resolution is insufficient to identify the likes of pedestrians and small objects at a distance. The camera offers enough detail and a good overview in two dimensions but requires a huge amount of software to convert 2D images of the surrounding environment to 3D, which is why the Lidar sensors were added.

"We need an overlap between the sensors, so that one can be a back-up," said Fredrich Claezon, system architect for autonomous vehicles at Scania. "What happens if the camera and radar suggest conflicting information? Which of them should we trust? With Lidar, we can obtain a better basis for decisions."

Scania sees software as a higher priority than hardware for its autonomous vehicle designs. However, the design is optimised for quarries and mines where the travel routes are simple and there are well-established obstacles, minimising the complexity of the software.

"The system isn't street-smart yet but it's certainly smart enough for use in mines," said Magnus Granstrom, development engineer in the autonomous systems team. "Driving in a mine is fairly simple and predictable. If you're driving in a more dynamic and less predictable environment though, more work is needed."

The challenge has been to balance the truck's proportions and blend the front module with the tipper unit. "Without a driver, half the cab is gone. A conventional mining truck has two distinct parts – the cab and the tipper unit. We've aimed for an integrated styling," said Granstrom.

Photonic direction for FOG

Navigation

KVH has started to roll out a photonic chip that dramatically simplifies the design of a fibre-optic gyroscope (FOG) and reduces its size (writes Nick Flaherty).

The chip combines all the photonic elements that are used to control the light used in a coil of fibre. It also detects the changes in the light that come from changes in the gyroscope's movement, allowing it to be used as an inertial measurement unit (IMU).

The chip combines the photonic elements that previously required complex alignment, such as the beam splitter, couplers and an interferometer, in a chip made using a standard CMOS silicon process.

These integrated components connect to KVH's D-shaped fibre that has an elliptical core to get a high accuracy in the FOG and support multiple branches of light.

This gives designers extra options for more accurate algorithms, as it avoids the losses incurred when optical components are connected together.

This chip is linked to an ASIC for the electrical processing, feedback and control circuits. This combination reduces the size of the FOG by a factor of five with the same power consumption.

"This is technology that we expect will transform our FOGs and IMUs," said Martin Kits van Heyningen, co-founder and chief executive officer of KVH.

"We're now accelerating investment in our core photonic chip technology, which we see as the most significant development in FOGs in decades."

The prototype unit had a higher performance than the existing FOG-based IMUs in angle random walk (ARW) and bias instability, two of the most important performance parameters that contribute to the safety of an autonomous vehicle.

KVH's photonic chip reduces the size of a fibre-optic gyro to the one at the front of this display

> We expect this technology to transform our FOGs and IMUs; we see it as the most significant development in FOGs in decades

The ARW, or noise, of the prototype has been calculated at less than 0.0097°/√h. The bias instability, or drift, is 0.02°/h.

Having all the photonic components integrated into one chip also improves the reliability of the FOG as well as allowing it to operate across a wider temperature and humidity range than previous discrete FOG systems.

As a result, 30 makers of systems for autonomous vehicles operating at Levels 4 and 5 autonomy are working with the prototype, said Kits van Heyningen, who expects the technology to be qualified in a military aircraft next year.

The next step is to combine the light source, photonic chip and electrical chip on a piece of silicon in a package to make the FOG even smaller, as well as reducing the size of the electrical portion of the design.

"We're starting development of a simplified electronics design that can then be reduced to a single custom-integrated chip. That will dramatically reduce the size and cost of the electronics to match the similar gains of the photonic chip," van Heyningen said.

First MASS trial ends

Surface vessels

NYK in Japan has conducted the world's first Maritime Autonomous Surface Ships (MASS) trial, addressing technical as well as regulatory challenges for autonomous shipping (writes Nick Flaherty).

The test of the *Iris Leader* was carried out under the Interim Guidelines for MASS trials by the International Maritime Organisation. The guidelines were published in June, ahead of changes planned for next year, for testing autonomous ships.

The 70,000 t car carrier was fitted with a navigation system called Sherpa System for Real (SSR), which was developed by Japan Marine Systems, a subsidiary of NYK.

In a journey of 1007 nautical miles from Xinsha, China, to the port of Nagoya, Japan, and then from Nagoya to the port of Yokohama, also in Japan, the ship was automatically controlled while being monitored and maintained by its crew.

The SSR collected information on environmental conditions around the ship from existing navigational devices, calculated collision risks, automatically determined optimal routes and speeds that were safe and economical, then automatically navigated the ship using data from a GPS satellite receiver.

A radar-based system detected craft in the water that could have been an obstruction, and steered around them.

The 'Iris Leader' completed a trip of more than 1000 nautical miles under automatic control

By using data and experience gained through the trial that had not shown up in onshore simulation, NYK was able to demonstrate the feasibility of the SSR.

The system used in the trial will also be applied to other coastal ships as a core technology for remote and unmanned navigation.

The trial data will be used to update the SSR by optimising the difference between the optimal course derived by the program and that determined by professional human judgment.

This will be used with a patented system for berthing large ships. When a ship is berthing, the SSR calculates the exact reduction in ship speed as the distance to the wharf nears. It takes wind and tidal information into account, along with the position of tugs, and controls the rudder and engine to provide the correct speed.

Glider goes the last mile

Aerial vehicles

FlareBright has developed an autonomous glider called ADDER (Autonomous Delivery Drone Emergency Resupply) for last-mile resupply to a pinpoint location (writes Nick Flaherty).

It is delivered by a larger aircraft and is said to glide in for the last few hundred metres to its target location on the ground in all weathers and atmospheric conditions, even when there is no radio or GPS availability. The key is the navigation software, based around image recognition, to steer the glider to its destination.

The prototype will deliver a payload weighing up to 200 g over a 200 m distance and to better than 2 m accuracy. A larger version for heavier payloads, with a longer reach and better accuracy, will be developed in the future.

The ADDER uses camera and machine learning technology from an observation gliding UAV called SnapShot. This can take high-quality aerial images from a height of 100 m in most weather and atmospheric conditions.

GNSS for problem areas

Communications

U-blox has unveiled its newest GNSS receiver, the M9, which has been designed with autonomous aerial and automotive applications in challenging locations in mind (writes Rory Jackson).

The applications include heavy-lift and transportation through urban canyons that are prone to large multi-path errors, or near telecoms infrastructure or other structures that produce strong EM emissions. It has security configurations aimed at protecting against spoofing and jamming, along with new features for mitigating RF interference.

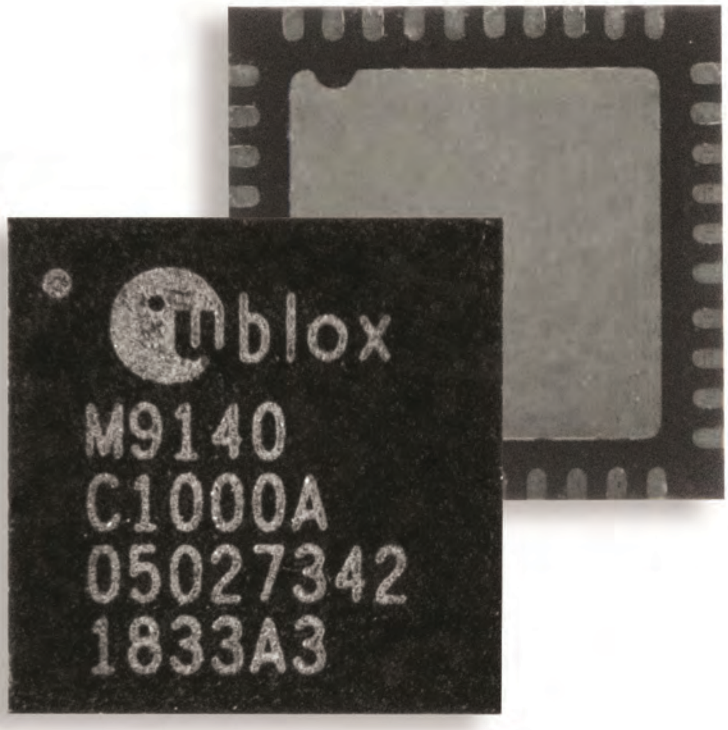
The M9 is configured to track L1 signals from GPS, GLONASS, BeiDou and Galileo concurrently, to provide a wider range of satellites and ensure that enough of them are visible to the host vehicle's GNSS antenna amid skyscrapers and other potential obstacles. It improves on its predecessor, the three-constellation M8.

"Having more satellites visible enables the receiver to use the positioning data from the 'best' signals," said Bernd Heidtmann, product manager at U-blox. "For example, that can mean the one with the strongest signal in terms of received power output, but an algorithm weighs many other parameters as well to determine which is best."

The new system has a static accuracy of up to 2 m (or up to 1.5 m with SBAS correction), compared with static accuracies of up to 2.5 m or to 2 m with SBAS on the M8.

To further aid positioning accuracy for UAVs, the M9 has a position update rate of 25 Hz (a 7 Hz improvement over the M8), a capability that is attributed to the bigger RAM on the new UBX-M9140 GNSS chip powering the M9 (compared with the M8's chip).

The UBX-M9140 is in a quad flat no-leads package measuring 5 x 5 mm, mounted on U-blox's NEO-M9N board module, which measures 12.2 x 16 mm. It uses the same pin-out configuration as the company's previous NEO modules.



The UBX-M9140 is configured to receive signals from the four main GNSS constellations, and give three levels of RF filtering to mitigate interference

The M9 has three RF filters integrated into its hardware and firmware to lessen the likelihood of performance degradation through RF interference, whether that be from jamming, nearby transmissions or emissions from other components next to (or on) the GNSS circuit board.

For reducing out-of-band RF interference, a surface acoustic wave filter is installed between the GNSS antenna input and a low-noise amplifier on the NEO-M9N.

Inside the UBX-M9140, two more filters are installed, one of which is a static notch filter for blocking in-band interference from signals registering at a specific frequency. This and the SAW are carryovers from U-blox's previous GNSS receivers.

The other filter is an 'adaptive notch' type, a new feature being introduced with the M9. It has been developed to lock on to and reject in-band signals that are varying in their exact frequency. LTE signals for example can behave in this manner, and will become a more widespread source of interference over time.

"We've been receiving increasing requests for new security features from end-users, who are particularly concerned about attacks on their positioning and correction solutions via the internet," Heidtmann said. "Spoofing is what people are most concerned about – a consumer tablet or laptop is enough to trick a GNSS into reporting the wrong time or position to an autopilot.

"We've therefore developed some proprietary algorithms for detecting spoofing with our firmware, and we've also put in protections for the firmware transfer process to prevent hostile actors from modifying the firmware as its updates are installed onto the M9.

Further specifications and data on the M9 and its components will be released by U-blox at the end of this October.

Wing bends to the mode

Aerial vehicles

A team of engineers at NASA and the Massachusetts Institute of Technology have developed a deformable wing that can be passively configured for different modes of flight (writes Nick Flaherty).

The wing is made from hundreds of tiny identical pieces of polymer that are bolted together to form an open, lightweight lattice framework and then covered with a thin layer of the same polymer.

Instead of needing separate moveable surfaces such as ailerons to control a plane's roll and pitch, the new assembly system makes it possible to deform all or part of the wing by incorporating stiff as well as flexible components in its structure.

The resulting wing is much lighter and therefore more energy-efficient than metal or composite designs. The lattice has a density of only 5.6 kg/m^3, compared with rubber for example, which has a density of about 1500 kg/m^3.

Each phase of a flight has its own set of optimal wing parameters, so a deformable wing could provide a much better approximation of the best configuration for each stage.

Instead of using motors and cables to produce the forces needed to deform the wings, the team designed a system that automatically responds to changes in its aerodynamic loading conditions by shifting its shape in a self-adjusting, passive wing-reconfiguration process.

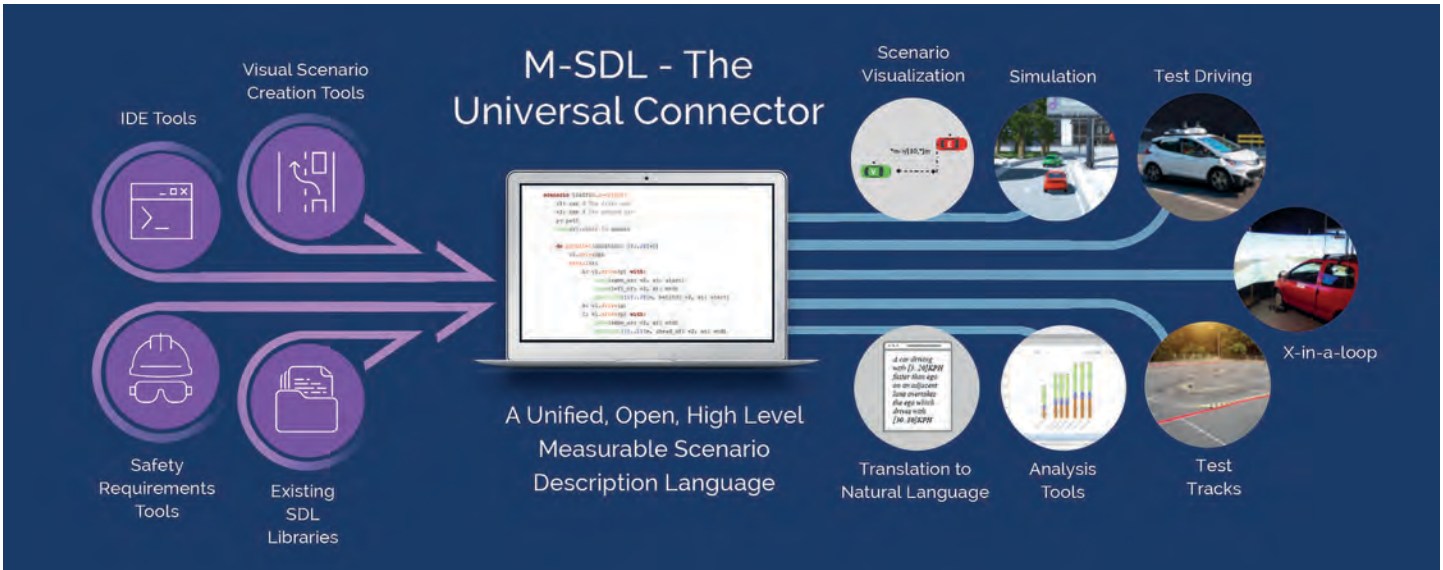
"We're able to gain efficiency by matching the shape to the loads at different angles of attack," said Nicholas Cramer, a research engineer at NASA's Ames Research Center. "We're able to produce exactly the same behaviour as you would have actively, but we've done it passively."

This is achieved by careful design of the relative positions of struts with different amounts of flexibility or stiffness so that the wing, or sections of it, bend in specific ways in response to particular kinds of stresses.

This follows on from a prototype wing about 1 m long for a typical remote-controlled model aircraft. This new version measure 5 m, a limit set only by the size of NASA's high-speed wind tunnel at its Langley Research Centre.

The elements are built using injection moulding with polyethylene resin in a 3D mould. Each part is produced in just 17 s, bringing it much closer to scalable production levels. Structures could be easily constructed using a swarm of small, simple autonomous assembly robots.

The design and testing of the robotic assembly system is the subject of an upcoming paper.



Schematic of the human-readable M-SDL ecosystem

Simpler system safety tests

Software testing

A start-up in Israel has developed a common and standard Scenario Description Language for verifying and validating systems in autonomous vehicles (writes Nick Flaherty).

The Measurable Scenario Description Language (M-SDL) developed by Foretellix, provides a common, human-readable, high-level language to simplify the capture, reuse and sharing of scenarios. It can easily specify any mix of scenarios and operating conditions to identify previously unknown hazardous edge-cases.

This allows developers to monitor and measure the coverage of the autonomous functionality that is critical to proving the safety of an autonomous vehicle design, independent of tests and testing platforms.

It is similar to high-level description languages such as VHDL and Verilog, which are used to design and verify complex silicon chips.

Foretellix has also made M-SDL open so that software development tool vendors, suppliers and developers can use it. It is working with the Association for Standardization of Automation and Measuring Systems (ASAM) standards committee on the next generation of the OpenScenario standard.

> M-SDL can easily specify any mix of scenarios and operating conditions to identify previously unknown hazardous cases

This is necessary because developers of autonomous systems cannot be sure the tests on the systems are actually orchestrating desired scenarios or evaluating test coverage as intended.

Safety methods and metrics are currently based on the number of miles driven in simulation and road testing, as well as the number of disengagements from autonomous operation to a human operator.

The coverage of these tests though is insufficient, non-scalable, and not easily shared or reused. They also don't provide mechanisms for identifying previously unknown hazardous edge-case scenarios or aggregate coverage metrics across all virtual and physical testing platforms.

"The ability to achieve measurable safety of autonomous vehicles is still being limited by a lack of standards, methods and metrics that inhibit reuse and sharing, are insufficient or don't scale," said Ziv Binyamini, CEO of Foretellix. "We are actively supporting ASAM in its efforts to create an open language standard."

Companies using M-SDL include AVL List, Volvo, Unity Technologies, Horiba Mira, TUV SUD, Automotive Artificial Intelligence, Metamoto and Vector Zero, as well as researchers at the Trustworthy Systems Lab of Bristol University, in the UK, and the Advanced Mobility Institute of Florida Polytechnic University.

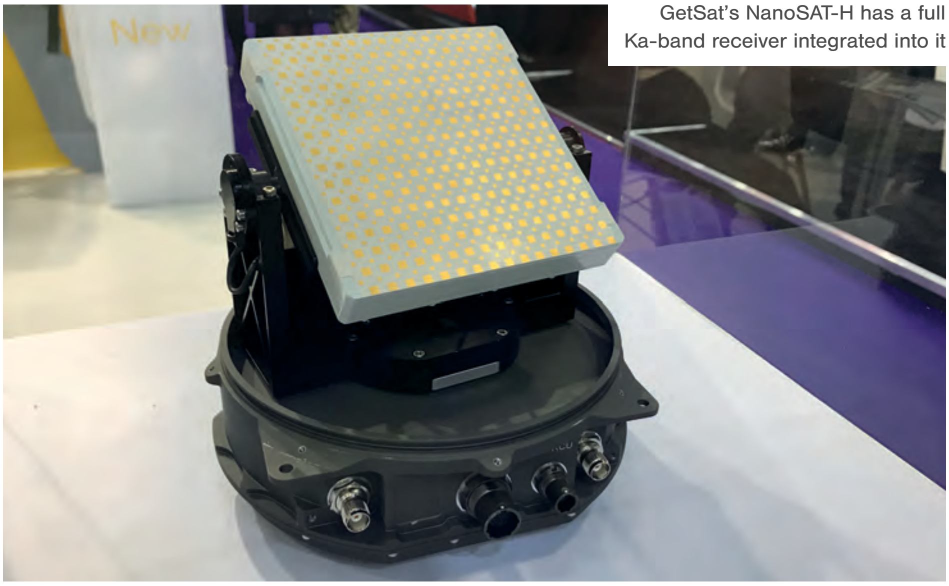
Satcom fits midrange craft

Communications

Israeli company GetSat has developed a full satellite antenna receiver that is small enough to fit into an unmanned aircraft (writes Nick Flaherty).

The company develops phased array satellite antennas that can reduce the size and power of a comms link to a satellite. They are built from circuit boards with specific elements to capture the radio signals, which are then combined with complex digital signal processing algorithms.

The NanoSAT-H antenna weighs 2.2 kg and integrates a full receiver for a Ka-band link, transmitting at 29-31 or 27.5-30 GHz and receiving at 19.2-21.2 or 17.5-20 GHz, with a power budget of 37.7 dBw. It includes an 8 W block upconverter, low noise block and antenna control unit for a total of 3.6 kg.



GetSat's NanoSAT-H has a full Ka-band receiver integrated into it

The tracking gimbal allows the antenna to automatically track the position of a satellite, which with the high power budget supports bit rates up to 4 Mbit/s.

The system is aimed at the satcom systems of midrange UAVs.

The Chaparral is designed to transport 100-225 kg

Cargo carrier is in range

Aerial vehicles

A US company is developing a hybrid vertical take-off UAV that can carry a payload of 100 to 225 kg over a range of 500 km (writes Nick Flaherty).

Elroy Air's Chaparral uses battery power and six rotors for the vertical take-off, and a gasoline turbine powering a seventh rotor for horizontal flight to achieve the range using a conventional 10 m wing.

The cargo would be loaded autonomously and carried in a pod underneath the aircraft. A grasping mechanism grabs the pod, which is winched up against the body of the fuselage for transport.

The system is being tested at the moment for commercial operations next year.

Lidar takes low-power view

Sensors

A European start-up is developing an integrated Lidar laser ranging sensor subsystem that uses a new approach to analysing the high-volume point cloud produced by such sensors (writes Nick Flaherty).

Instead of using a convolutional neural network (CNN) to implement machine learning on Lidar data, the Outsight system is based on a multi-spectral laser using the shortwave infrared spectrum coupled with a dedicated low power processor rather than a large array of graphics processing units.

Outsight is a spin-out of Dibotics, and uses an 'augmented Lidar' processing chip from Dibotics. The chip can work with a wide range of Lidar sensors, but Outsight is working with solid-state Lidar sensor maker XenomatiX to combine the chip and sensor.

The resulting subsystem has a range of 200 m and produces a frame of laser points every 50 Hz. Its field of view is 30 x 10º and it has a resolution of 0.2º.

As with mainstream Lidar systems, it detects road markings, lanes and traffic signs, but the multi-spectral sensor also detects vegetation at the side of the road and the state of the road surface. That includes road hazards such as black ice, snow and debris at a range of hundreds of metres, which are notoriously difficult for laser sensors to detect.

It is hard to prove that CNN networks meet functional safety requirements in the ISO 26262 standard, and they can mis-classify objects. The Outsight sensor and processing identifies – or classifies – the points in the cloud of Lidar data, and can flag up hazards quickly as there is no need to wait for several frames before the system can make a decision.

The embedded chip also has an 'ego-motion' mode that understands on a frame-by-frame basis how the vehicle is moving, and it can work with a reference map to provide localisation without the need for satellite navigation. Another mode creates a moving 3D map around the vehicle, allowing a virtual frame from the sensor to be created by integrating hundreds of the sensor frames.

Because the classification in the embedded software is deterministic, it is easier to demonstrate a high level of safety and ISO 26262 compliance. This output can also then be used for a CNN machine learning network.

UAV revamp cuts upkeep

Aerial vehicles

UAV designer High Eye has redesigned its autonomous helicopter to reduce the number of parts and increase the time between maintenance (writes Nick Flaherty).

The latest version of the HEF 32 uses a redesigned transmission and engine interface. The new gearbox systems are oil-lubricated and maintenance-free between overhauls, and a new air-cooled boxer engine uses the same heavy diesel as the ships it operates from.

This gives the 16 kg platform a flight time of 3.5 h and a range of 50 km with a 5 kg payload.

The main and tail rotor heads are now made entirely of aircraft-grade titanium, and include maintenance-free, oil-lubricated bearing packs. The rotor blades are made using manned-aviation resin transfer moulding production processes.

All the protruding antennas have been replaced with integral antennas in the landing gear legs, stabilisers and other aerodynamic fairings. The comms systems layout has been revised to include a standalone secondary radio system, which adds redundancy.

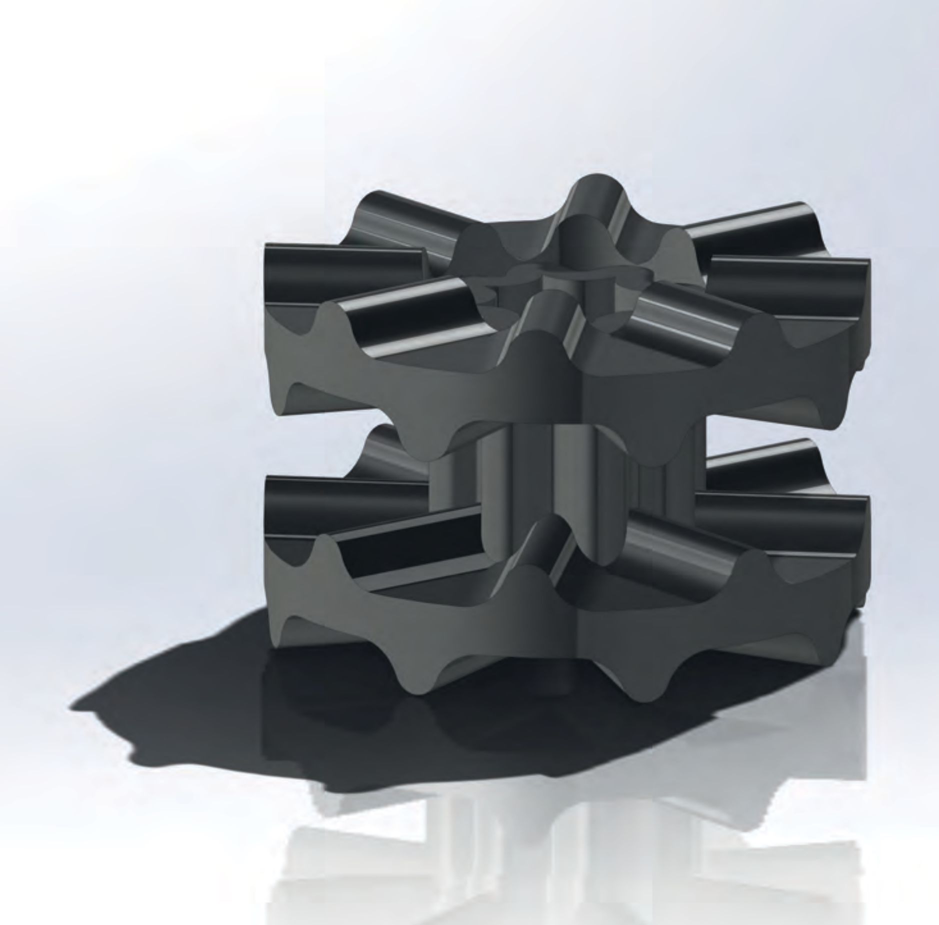
Improvements to the flight control system allow ship-based operations so that the HEF 32 can be operated semi- or fully automatically from smaller or unprepared ship decks. Dead-reckoning capabilities allow the aircraft to maintain automatic navigational capabilities and redundancy if there is a loss of GPS or external heading information.

Integrating a laser-based altimeter as standard supports autorotation with a fully automatic flare-out capability.

Contrary to other UAV designs, High Eye has aimed to minimise the number of sensors on the platform, as the company sees these as a key point of failure. Sensors are protected by full redundancy with EMI shielding, noise filtering and a software back-up.

Two pitot tubes developed in-house provide barometric inputs to the avionics and are electrically heated to protect against icing up in flight.

The autopilot has been updated to support a range of flight modes, all of which can be activated or changed at any time during flight. It provides semi- as well as fully automatic flight modes, including multiple waypoints, automatic take-offs and landings, and clearly defined back-up modes.



The UAV3004 isolator works in much the same way as bubble mounts but uses a ring-and-bushing design

Shock isolation

Component protection

The Greene Rubber Company has developed a ring and bushing isolator, the UAV3004, to protect payloads, IMUs and powertrain components against vibration (writes Rory Jackson).

It can be made from silicone or neoprene, giving it operating temperature ranges of -54 to +149 C and -29 to +82 C respectively.

"More and more commercial UAVs are being presented with problems that require shock and vibration control, as they become more and more complex," said the company's Robert Schleicher.

"The weight constraints on UAV components often rule out the use of most vibration isolators currently on the market, so we're trying to apply some of our engineering knowhow from the military aerospace industry to new trends in the commercial UAV space that focus on micro-mounts.

"The UAV3004 will work in much the same way as the bubble mounts that are ubiquitous in the market, but it uses a ring-and-bushing design that will prevent the mount from separating from the structure, unlike the bubble-style design."

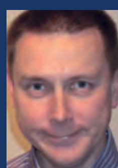
The exact shape of the UAV3004 has come from the company's knowledge of anti-vibration mounts and FEA studies using the Abaqus software for modelling and optimising the dynamic qualities of the unit. It will undergo testing on the company's shake tables, drop-testing machines and other in-house systems to evaluating how it performs in flight.

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.

Commercial UAV Expo 2019

Industry

The Commercial UAV Expo Americas is returning to the Westgate Resort & Casino in Las Vegas for its 5th edition, from October 28 to 30.

With over 2500 attendees from across the commercial UAV solutions supply chain expected at the show, more than 185 exhibitors are expected to showcase their latest innovations and applications across a multitude of industries.

Workshop attendees and conference topics will particularly look to discuss UAVs in construction, energy and utilities, forestry and agriculture, infrastructure and transport, mining and more.

For the critical subject of public safety, thought-leaders from the various emergency services will meet at the Drone Responders Public Safety Summit for strategic discussions and workshops on UAS development and management, training standards and certification, and mutual assistance.

Far-reaching and pressing industry issues such as unmanned air traffic management, AI and urban air mobility will also receive special focus in the conference and its various events.

More than 100 speakers will present their ideas, analyses and experiences at the conference sessions, with organisations such as Airbus, FLIR, Facebook and the FAA represented.

And as well as featuring new vehicles and systems on the expo floor, the exhibition will include product preview presentations for companies announcing their newest technology innovations.

Outside the conference halls, cutting-edge aircraft designs, propulsion systems, data links, Lidars, cameras and much more will be on display for manufacturers and end-users in commercial, governmental and research organisations.

There will be an outdoor demonstration area as well, to serve a similar purpose for new UAV designs.

For more details visit **www.expouav.com**

Amsterdam Drone Week

Industry

From December 4 to 5, the RAI Amsterdam will play host to Amsterdam Drone Week, where thousands of professionals and experts from around the world will gather to discuss the latest news and innovations in global aerial technology.

Companies, researchers and regulators will attend to observe and determine the directions in which UAVs are moving, with visitors expected from 75 different nations.

With a close eye on recent evolutions in the industry, the event's main themes have been announced, with Urban Air Mobility, Digital Infrastructure and Rules and Regulations among the top billings.

The conference events programme will aim to foster cooperation between multiple industries towards the goal of process improvements and cost reductions for end-users of urban aerial transport systems.

Automotive, aviation, telecoms, software and network companies from all parts of the supply chain are expected to take part in discussions about ways of developing and integrating new UAV technologies and systems in a safe and sustainable way.

For more details go to **www.amsterdamdroneweek.com**

InfraTech Germany's unmanned systems zone

Industry

The 2020 edition of InfraTech Germany, Europe's leading exhibition and conference for infrastructural solutions and technology, is to feature a dedicated Unmanned Systems zone on the expo floor.

Generated through InfraTech's partnership with The Unmanned Systems Expo, this addition to the trade exhibition is intended to showcase how well-placed and well-equipped unmanned vehicles, robotics and automation technologies are to deal with the challenges facing infrastructures.

UAVs can conduct surveys for signs of damage across bridges and industrial assets, UGVs can paint lines and place barriers around highway maintenance zones, and USVs and UUVs can inspect and clean canals and other waterways.

And with advanced technologies such as AI algorithms, and 5G and LTE real-time long-distance comms networks, swarms of infrastructure management vehicles can work in autonomous collectives to maintain and improve critical national or private-sector assets and resources.

The 4th edition of InfraTech Germany will be held at the Messe Essen centre, from January 14 to 16, 2020.

For more details go to **www.infratech.de/en**

UST diary

UVID
Thursday 7 November
Airport City, Israel
www.uvidtech.com

Vertical Flight Expo & Conference
Tuesday 5 November – Thursday 7 November
Farnborough, UK
www.verticalflightexpo.com

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

Amsterdam Drone Week
Wednesday 4 December – Friday 6 December
Amsterdam, The Netherlands
www.amsterdamdroneweek.com

CES Tech
Tuesday 7 January – Friday 10 January 2020
Las Vegas, USA
www.ces.tech

TUS Expo (InfraTech)
Tuesday 14 January – Thursday 16 January 2020
Essen, Germany
www.tusexpo.com

Singapore Airshow
Tuesday 11 February – Sunday 16 February 2020
Changi, Singapore
www.singaporeairshow.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

Military Robotics & Autonomous Systems
Wednesday 1 April – Thursday 2 April 2020
London, UK
www.smi-online.co.uk/defence/uk/conference/robotic-autonomous-systems

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

ExpoDronica
Thursday 23 April – Friday 24 April 2020
Madrid, Spain
www.expodronica.com

AUVSI Xponential
Monday 4 May – Thursday 7 May 2020
Boston, USA
www.xponential.org

SOFIC
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

BSDA
Wednesday 20 May – Friday 22 May 2020
Bucharest, Romania
www.bsda.ro

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

ICUAS '20 – The 2020 International Conference on Unmanned Aircraft Systems
Tuesday 9 June – Friday 12 June 2020
Athens, Greece
www.uasconferences.com

Australian Association for Unmanned Systems (AAUS) conference (RotorTech)
Tuesday 16 June – Thursday 18 June 2020
Brisbane, Australia
www.rotortech.com.au

Autonomous Vehicle Technology
Tuesday 16 June – Thursday 18 June 2020
Stuttgart, Germany
www.autonomousvehiclesymposium.com

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

iVT EXPO
Wednesday 24 June – Thursday 25 June 2020
Cologne, Germany
www.ivtexpo.com

Farnborough International Airshow
Monday 20 July – Friday 24 July 2020
Farnborough, UK
www.farnboroughairshow.com

Commercial UAV Expo Americas
Tuesday 15 September – Thursday 17 September 2020
Las Vegas, USA
www.expouav.com

UAV Show
Tuesday 15 September – Thursday 17 September 2020
Bordeaux, France
www.uavshow.com

Beneath the surface

SeaRobotics' development manager for ASVs talks to **Peter Donaldson** about the inspirations behind his work

"I was fortunate to grow up boating around Boston Harbour and Cape Cod Bay, which led to a profound respect for the marine environment and the need to protect it," says Geoff Douglass, development manager for ASVs at SeaRobotics, recalling the experiences that nudged him towards a career in marine engineering.

"As a kid, my father managed a yacht maintenance company and put me to work early, fixing old engines and rigging old motor yachts. It didn't take me long to realise that being a boat mechanic was not my calling, but it did help me develop a mechanically inclined mind and a passion for yacht design," he adds. "I have always been fascinated with design and how it moves people, for example how a vintage Corvette has the power to turn heads."

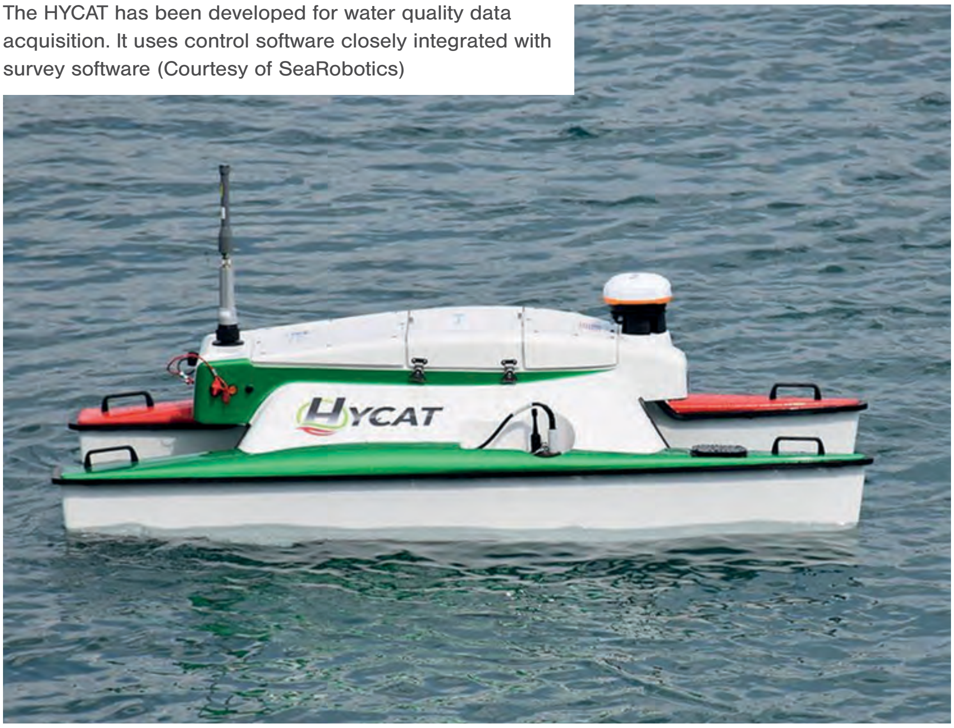
These influences led him to focus on the sciences at school and to take a mechanical engineering degree, although he admits to regretting not taking more art classes to develop his aesthetic sense, which he regards as important in his design work these days.

From yachts to ASVs

He spent the early years of his career designing recreational yachts, an industry mostly made up of small companies like the ones he worked for, which didn't have separate design and engineering departments. That enabled him to get involved with both disciplines from the start.

However, the yacht industry was fairly conservative in terms of adopting modern design principles. He enjoyed it, but wanted something with a faster pace and a more progressive outlook, he says.

SeaRobotics' SR-Surveyor M1.8 is a catamaran ASV developed for high-resolution hydrographic and terrestrial mapping (Courtesy of SeaRobotics)



The HYCAT has been developed for water quality data acquisition. It uses control software closely integrated with survey software (Courtesy of SeaRobotics)

"It was clear to me that autonomy was going to be increasingly important to the future of the marine industry, so I jumped at the chance to work for a navy contractor located in Groton, Connecticut."

The work involved designing and developing ASVs and UUVs for the Office of Naval Research (ONR). "We were doing things that hadn't been done before, and I enjoyed being part of a group of software developers and multi-discipline engineers tasked with pulling integrated systems together," he says.

He worked with teams from other companies on designing the Large Displacement Unmanned Underwater Vehicle, the Low Visibility Craft (LVC) – an autonomous conversion of an 11 m RHIB – and a handful of custom UUVs and tow bodies for the ONR. His own focus in these projects was on composites, propulsion, payload integration and naval architecture.

> I have always been fascinated with design and how it moves people, for example how a vintage Corvette can turn heads

"The RHIB conversion was my favourite," he says. "The physical boat had been in service for years before we got it. It was beat up. It had been dropped from airplanes; we'd find weathered 50-calibre shell casings buried in it. It had served our troops and there was something nostalgic about it. So we designed its ASV conversion to support multi-domain missions and UUV husbandry for mine countermeasures."

Blitz development

He describes working on all three vehicles within a short period as an intense 'blitz' of development that included smaller vehicles and ancillary equipment to support testing.

Intended to be launched from a boat over the horizon from a target shoreline, the LVC was designed to approach on the surface before flooding ballast tanks so that most of it would be under the water to minimise its visible profile. The LVC would then launch small UUVs for mine countermeasures, obstacle detection and targeting. It had a central bay for a tethered UUV and two lateral sponsons for launch and recovery of free-swimming vehicles.

"As part of testing the LVC, we created our own UUVs to use as test platforms. Some of the equipment we needed for them either wasn't commercially

The US Navy's LDUUV is one of three vehicles Douglass worked on in a 'blitz' development earlier in his career during an intense period of rapid engineering and testing (Courtesy of the US Navy)

Working an aesthetic appeal into design is important to me, especially in the world of robotics, where there's a sea of generic-looking systems

available or was extremely expensive, so we developed our own UUVs to test surface-based infrared tracking systems and other techniques for autonomous launch and recovery of unmanned systems."

Controls guru

Douglass' next move was to SeaRobotics, whose founder and president Don Darling he regards as a mentor. "He has probably the greatest wealth of knowledge I have yet to encounter, but I have also worked with him the longest," he says.

"Don has taught me a lot about the ASV market in general, especially about controls. He is a controls guru, and he has helped me bridge the gap from being mainly mechanically centred in my design skills and understanding of the technology to being more systems-based and understanding the big picture."

That understanding, he says, has enabled him to develop a personal philosophy of engineering that puts the user experience at the centre of good design. "Even if a vehicle is unmanned, a human will interact with it at some point. Therefore, I like to prioritise simplified and intuitive mechanics, electronics and interfacing," he says.

"I want people to walk up to our products – whether it be a mechanism or a control interface – and understand it at first glance. I think that is important for user confidence and acceptance.

"Working an aesthetic appeal into design is also important to me, especially in the world of robotics, where there's a sea of generic-looking systems.

"Aesthetic design can be a powerful branding tool that differentiates products at first glance [the Corvette effect]. It's an aspect of design that lets the user know a vehicle is not a proof of concept but a completed product."

In terms of challenges facing the industry, he says higher levels of autonomy, machine learning and cloud computing are all very desirable, but emphasises that the market is not yet making the most of currently available technology.

Merging survey and control

"The hydrographic survey market, for example, is not bottlenecked by the capability of ASVs but by the survey packages and sonar systems currently accepted by industry, while product suppliers have not fully shifted their thinking to capitalise on the advantages of ASVs," he says.

"Because ASVs are an emerging technology, the interfacing of hydrographic sensors and acquisition software is still tailored to manned operation. Most require many mouse clicks during set-up and operation, manned oversight to monitor survey quality, and are disjointed from the autonomy of the vehicles."

SeaRobotics has made addressing that issue an important element in the development of its ASVs. Partnering with hydrographic software houses has enabled the company to write the ASV control software around the survey software that operators are used to, so they can focus on collecting the data.

"We streamlined the workflow so that it kind of cuts the boat out of the picture," Douglass says. "The boats drive themselves, and operators just use the software they already know."

The focus of Douglass' current work is on overseeing the development roadmap for SeaRobotics' vehicles from design through to production, as well as promoting the brand and expanding the company's distribution network. The projects with which he is most closely involved are the newest ASVs – the HYCAT and the SR-Surveyor M1.8 – leading a team of up to seven including himself.

The HYCAT is focused on water quality data acquisition, while the SR-Surveyor M1.8 is a high-resolution hydrographic and terrestrial mapping system. "They were designed to streamline survey workflow and logistics for hydrologists and hydrographers," he says. "They are survey-ready out of the box."

SeaRobotics began development of the 53 kg HYCAT in the second quarter of 2017, with the first boat delivered a year later. The company then started on the 52.3 kg SR-Surveyor M1.8, in the third quarter of 2018, which was ready for the market in the second quarter of this year.

Wrestling with performance and heat

Douglass says one of the toughest challenges in their development was getting the required performance from such small ASVs – both are catamarans about 1.8 m long. "The shorter a hull, the less efficient it is, so we focused on hull and propulsion design to ensure we could get a full day of survey endurance out of a single battery charge," he says.

Another was heat transfer. "These ASVs have more electronics than larger manned boats, but much less air volume in their electrical compartments for cooling. And unlike UUVs, ASVs don't have the luxury of being able to use water to cool hotspots, so we conducted thermal analyses and used very efficient electrical components. Even the sonar was customised to consume as little power as possible but still yield quality data."

EdgeTech developed the sonar for the Surveyor M1.8, and he says it produced impressive results in a survey carried out on a road bridge that carries Interstate 95 across a tributary of the Atlantic Intracoastal Waterway in Florida. It clearly revealed areas of scour, in which the water flow had washed away sediment around the bridge supports, something surveyors have to monitor regularly.

"Finding scour is a diver-based operation in many places, with low visibility and potentially hazardous structures," he says. "There is a huge push to get divers out of the water, and this technology really helps with that."

Douglass' ASV team is currently scheduling local demonstrations and road trips around the US to demonstrate the HYCAT and Surveyor M1.8. In career terms, he wants to keep moving up the ladder. "That aside, I also want to create technologies that promote and protect the marine environment," he says. ◻

Geoff Douglass

Geoff Douglass grew up around boats in North Weymouth, a suburb of Boston, Massachusetts. He spent most summers working at a marina and boatyard. He was educated in schools including Weymouth Junior High and Weymouth High School, where he focused on mathematics and pre-engineering courses.

That was followed by a degree in mechanical engineering from Northeastern University, in Boston, which he attended from 2003 to 2008. This overlapped with the post of design engineer at boatbuilder Boston Whaler from 2005 to 2009, where he learned about production boatbuilding.

After that he spent a year at Zurn Yacht Design, focusing on advanced composite construction methods before joining LBI to work on unmanned maritime vehicle contracts for the US Navy. He joined SeaRobotics in February 2011, where he became acquainted with a more diverse set of engineering disciplines and principles.

These days he directs a multidisciplinary team of engineers and technicians developing ASVs, and spends much of his time responding to requests for quotes from potential clients and exploring new concepts in partnership with customers.

Three of a kind

Peter Donaldson explains how market trends drove the development of the core technology underpinning this trio of AUVs

‘Disruptive’ and ‘democratising’ are terms that Terry Sloane, managing director of Planet Ocean and its offshoot ecoSUB Robotics, uses to describe the family of small AUVs developed over the past four years. He justifies these bold adjectives by alluding to the vehicles’ low cost, tiny but very capable sensors, an endurance that exceeds a full working day and their out-of-the-box autonomous and cooperative behaviours.

The smallest of them, the 4 kg ecoSUBμ5 – 925 mm long and 111 mm in diameter – will be the main focus of this article, but the larger m5 and m25 that share the core technology will also feature. Originally conceived for risky under-ice operations, they are in service with beta testers and early adopter operators for scientific, educational, military and commercial survey missions, with around 40 built so far.

The ecoSUB story starts in 2012 when Sloane received a call from the National Oceanography Centre (NOC) in Southampton, on the south coast of England, saying that one of its engineers had an idea for a small, low-cost air-launched submarine that would be deployed from an aircraft, gather data under ice and be recovered by boat.

The NOC had not been successful in finding funding for it and was busy developing the much larger Autosub family at the time, so it asked Sloane to assess its commercial viability. He concluded that it was not viable because there were

An ecoSUBμ5 is launched from an unmanned surface vessel built by ASV, the project that triggered the development of the smallest of the ecoSUB family (Courtesy of ecoSUB Robotics)

Production-standard ecoSUBμ5s (foreground) and m5s (behind). Note the multi-frequency comms and GNSS antenna on each – horizontal on the μ5s and upright on the m5s (Courtesy of ecoSUB Robotics)

no sensors small enough, the battery chemistries that were available couldn't provide the energy density required and the control surfaces were too small. The idea behind it, however, was good.

Over the next few years, Sloane kept an eye on the enabling technologies in the AUV market, and noted an emerging trend towards smaller AUVs. Meanwhile, market research by the NOC revealed that several suppliers, including some in the NOC with whom Planet Ocean shares facilities, were building micro-sensors that would suit even smaller AUVs, while battery technologies had made great progress.

"As we started to think about it more seriously, Innovate UK and DSTL coincidentally announced a competition calling for the launch and recovery of multiple AUVs from a USV," he says.

(Innovate UK is a government body that helps British businesses to develop, de-risk and realise the potential of new ideas. DSTL is the Defence Science and Technology Laboratory, the government's primary military r&d organisation.)

"We put a consortium bid together led by ourselves and with the NOC, Southampton University and ASV – and we won. We then moved our team into the new Marine Robotics Innovation Centre at the NOC and set to work."

ASV's role was to design the launch and recovery system, while Planet Ocean worked with the NOC to design the little AUV that would become the ecoSUBμ5. Sloane was able to do this quickly, because he had already sketched out a specification for a vehicle based on what he had learned by examining the original concept and the NOC's market research.

He stresses that the requirement for launch from an A-sized sonobuoy tube fixed many of the design criteria. "It couldn't have any control surfaces or fins," he says. "It could have a rudder though because that could be placed inside the cylindrical envelope."

The NOC's team of academics and engineers worked out the hydrodynamics and the mechanical concept for the vehicle, while ecoSUB Robotics engineers worked closely alongside to help maintain focus through the two-year project and develop the electronics and software.

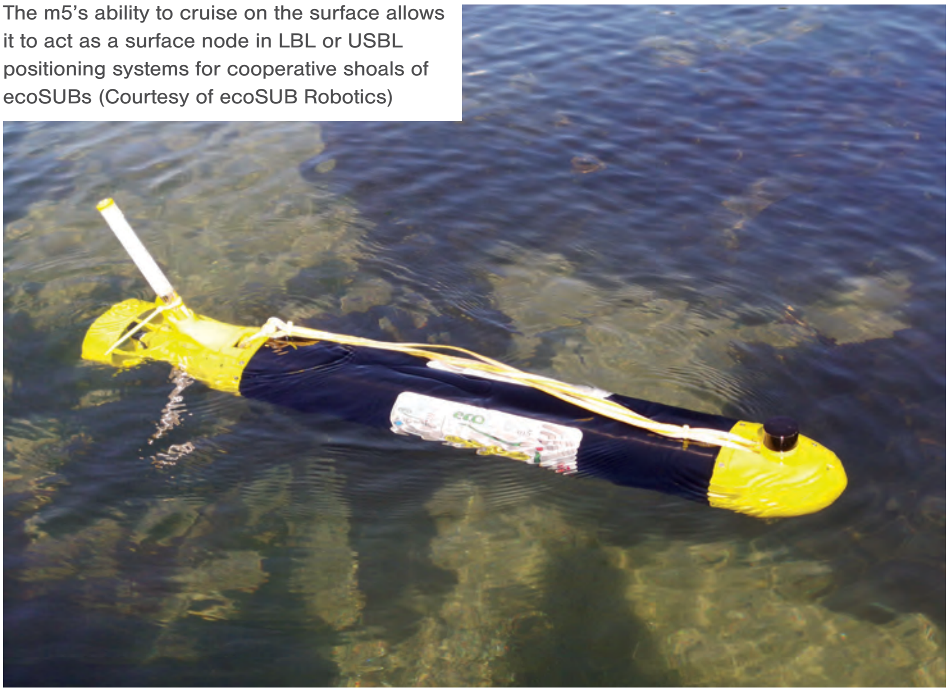
In that iterative process they looked at various propulsion and control configurations, including a moveable duct at the back, but settled on a fixed duct containing the propeller and the rudder, and with the antenna array sticking back horizontally.

The battery pack doubles as moving mass inside the body to provide pitch control. Because the batteries are positioned in the bottom half of the vehicle, they also provide natural stability in roll.

BP comes onboard

About six months into the project the manager of the NOC Innovation Centre discreetly advised Planet Ocean that they might benefit from letting BP know what they were doing, and also told BP that Planet Ocean was working on something that might interest the oil and gas giant, Sloane recalls.

The m5's ability to cruise on the surface allows it to act as a surface node in LBL or USBL positioning systems for cooperative shoals of ecoSUBs (Courtesy of ecoSUB Robotics)



BP said that a very small autonomous submarine was exactly what it needed to help it make a 50% saving on its operational maintenance budget by 2025. However, it wanted a vehicle that could go deeper and carry more sensors, and offered some development money to come up with a larger version. Sloane already had plans for a bigger ecoSUB, so the company accelerated its development, adding more people to the team.

The result was the ecoSUBm25, with a 2500 m depth capability and measuring 1000 mm in length and 146 mm in diameter, with 18-30 hours of endurance depending on the battery type. Without the sonobuoy tube constraint, it can carry its antenna upright, enabling the vehicle to cruise at the surface to maintain connectivity.

The m5 is a version of this vehicle, with a lighter pressure case that enables it to operate down to 500 m.

In May 2016, BP set Planet Ocean a target to build a working vehicle in seven months, which it achieved, putting a demonstrator in the water at Christmas of that year.

This turned out to be the first stage in an approval process that included participation in an oil spill response exercise in the Solent, off the south coast of England, followed by a deployment at the Magnus pipeline off the Shetland Islands in the North Sea to search for leaks using hydrocarbon sensors. With the successful completion of this work, BP indicated that the ecoSUB vehicles were well-suited to its future offshore maintenance plans.

In parallel, Planet Ocean continued to work with the NOC and ASV on the launch and recovery system, successfully demonstrating it at the end of the project. The company then had two vehicles at around Technology Readiness Level 7, Sloane notes, and began a year-long productionising effort.

Navigational challenge

At around that time came a new Innovate UK call for a cooperative project, Robotics and AI in Extreme and Challenging Environments, which sought to develop AI that would enable very small AUVs to navigate accurately in harsh environments.

This is a challenge for small, low-cost underwater vehicles – the µ5 is priced at about £10,000 and the m5 at about twice that – that tend to use inexpensive sensors to keep the price down and don't have the volume, power or weight budget to carry a Doppler Velocity Log. "We have a $100 IMU in there, which gives us an error of 10% of the distance travelled, so in 100 m you could be 10 m out," Sloane says.

This IMU-based dead reckoning navigation is adequate for a lot of missions, he says, when supplemented by frequent GPS fixes. If for example a mission requires the vehicle to travel 5 km, it is programmed to pop up for a fix several times en route. For longer missions though, and for sidescan sonar and camera work in particular, it is vital to know the precise location of everything the sensors are looking at, so something better was needed.

Fortunately, that arrived in the form of tiny, high-performance, low-cost acoustic modems that enable Long Base Line (LBL) positioning when used in conjunction with beacons in known positions. Planet Ocean and the NOC brought the modems' developers at Newcastle University into their team, and their winning bid in February 2018 marked the start of the IUK 2 project, which ended this July.

The NOC developed the acoustic network protocols and navigation algorithms, using an Enhanced Kalman Filter (EKF) that takes multiple inputs from which it derives a solution that is better than the sum of its parts. The EKF takes inertial data from the IMU, and the acoustic range and bearing data from the LBL system, and outputs more accurate positions.

"We did a lot of testing throughout the project, and we now get better than 5 m regardless of how far we've gone or how long we've been submerged," he says.

Three members of an ecoSUB shoal can be designated as surface nodes in an LBL network, broadcasting their GNSS position and other information from their acoustic modems. To ensure they remain in the right place to serve in this role, they enact a specially developed 'stay-in-circle' behaviour.

As Sloane explains, "If they drift more than 100 m from where they are supposed to be, they will power back

into the centre of the circle. That gives you this LBL system, which is reasonably stable. It doesn't matter where they are inside the circle because they've got GPS to within 4 or 5 m."

He says Newcastle University's acoustic modem will soon be available in Ultra Short Base Line (USBL) form, which will support a positioning network with only one surface node over a range of around 2 km. "That means we could use the m5 because it can cruise on the surface like an ASV, with its upward-pointing GNSS antenna and its modem underneath broadcasting USBL to the shoal," Sloane says.

What's more, comparing the position predicted by the INS with the solution calculated by the EKF with the LBL/USBL information enables the navigation system to calculate the speed and direction of any currents to which the vehicle is subject. The acoustic modems also allow the vehicles to cooperate.

Cooperative AI

"That means that as a shoal they can know what the local conditions are, and they can modify their programming in real time, which is where the AI comes in," Sloane says.

He adds that they will be able to apply their collective AI to the set of tasks they have been given and, within constraints, change the order in which they do them.

One constraint might be the inclusion of a mission-essential, top priority 'gold' task, which the AUVs would have to carry out when programmed to do so. Otherwise, they are free to change the sequence in which they perform their tasks if the prevailing conditions make it easier to complete a mission within the energy budget.

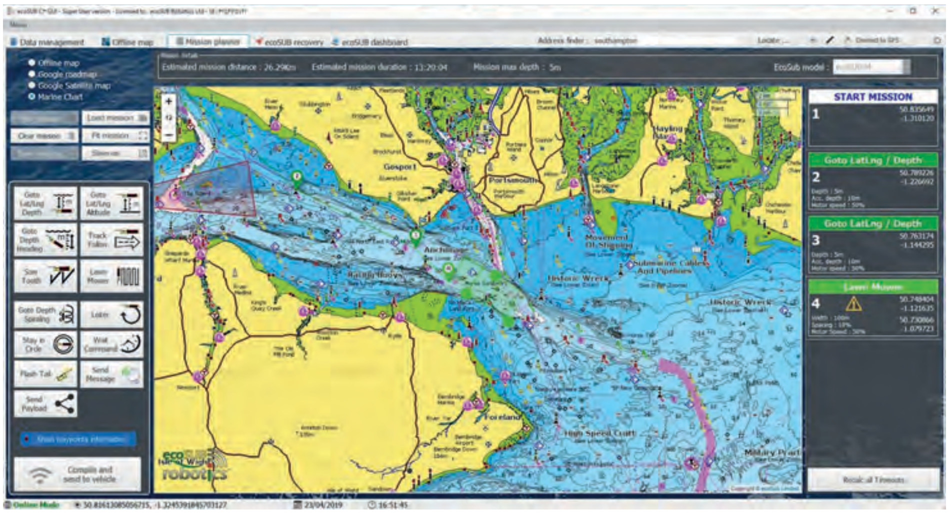
The team tested the enhanced navigation capability in the sea off Plymouth, south-west England, with six ecoSUB vehicles. "We proved the process and signed that project off in July," Sloane says.

In the meantime, the company has been providing ecoSUBs to early adopters in the UK, mainly universities, although BP now has some m25 models. The UK was the initial focus because the company wanted to be able to support the subs easily wherever they were being operated.

For example, at the time of our visit in August, the Scottish Association for Marine Science was operating a µ5 in the icy waters around Svalbard in the Norwegian Sea, sending it close to glaciers to gather data in conditions too risky for people or a larger, costlier vehicle.

The NOC has also bought a few as software test vehicles for Autosub programs, Sloane explains. "It is a lot easier for them to develop and test new behaviours such as avoidance protocols in a lake than to use an Autosub with all its support kit and cranes."


Researchers from the Scottish Association for Marine Science (SAMS) with an ecoSUBµ5 they are operating near the Arctic island of Svalbard, where it can operate close to glaciers (Courtesy of SAMS)



A mission-planning screen from the ecoSUB GUI, with which operators can construct missions by combining programmed autonomous behaviours including various search patterns (Courtesy of ecoSUB Robotics)

Autopilot hardware and remote control

Autopilot hardware is centred on a Variscite DART MX-6 system-on-module processor, a powerful device with camera and wi-fi interfaces built in. The DART replaced the Intel Edison processor that was used in the development programme but became obsolete.

The autopilot is a bespoke system whose main function is to implement a mission according to a user-constructed plan with 'nanny' overwatch of critical systems. It has a library of pre-programmed behaviours developed from scratch by Planet Ocean, initially with guidance from the NOC.

Once the mission is loaded, the system is completely autonomous, Sloane says. However, the vehicle can be re-tasked via wi-fi or Iridium when on the surface. Wi-fi is used at up to about 200 m, and Iridium beyond that, over the horizon or through the acoustic modems while submerged.

Newcastle University's nano-modem provides a range of around 3 km. It operates in the 24-32 kHz band and provides a data rate of 463 bit/s through water.

Command, Control and Communications (C3) for individual vehicles or shoals of them is handled

> The AUVs are supplied with a growing suite of behaviours with which users can simply construct a mission via the graphic interface

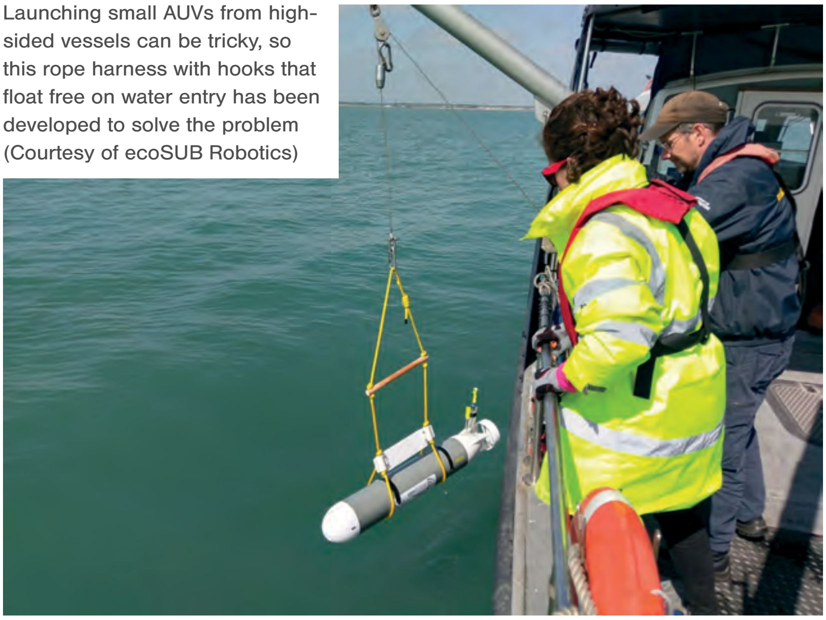
through ecoSUB Robotics' own GUI. It contains offline maps and charts, and allows operators to perform pre-launch checks and diagnostics, mission planning and programming, view data in real time, and guide the recovery boat to the AUV's location.

Sloane emphasises that the ecoSUBs are fully autonomous out of the box and don't require users to develop their own autopilot control systems, sensor interfaces or nanny safety systems. He regards this as the distinction between UUVs and true AUVs. "The AUVs are supplied with a growing suite of behaviours with which users can simply construct a mission using the GUI," he says.

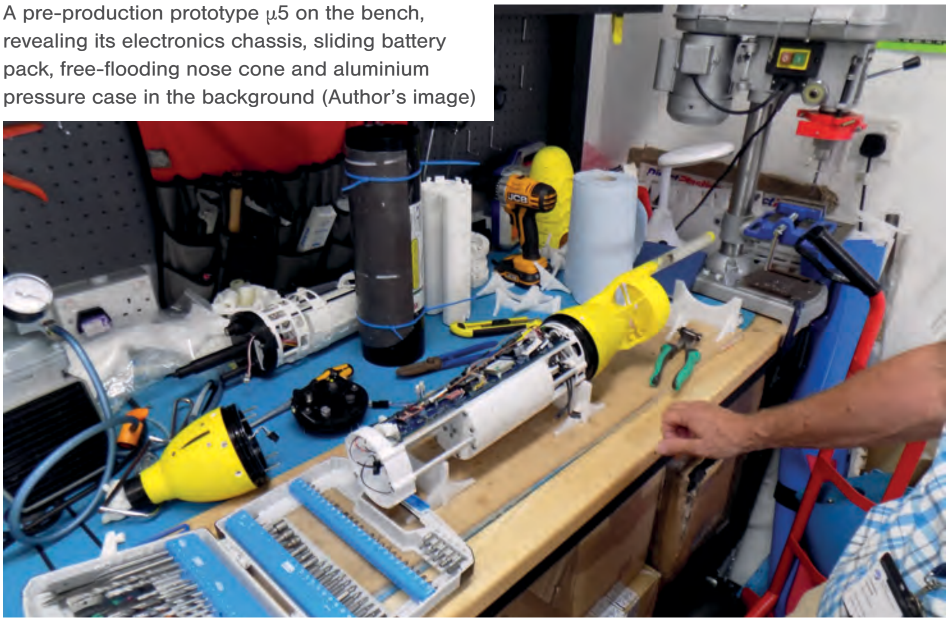
Operators can also connect with ecoSUB AUVs anywhere in the world through the optional Hermes self-contained C3 system. Hermes combines various comms systems including wi-fi, Iridium, 3G/4G, RS-232 and acoustic.

One benefit of Hermes is that it

The Hermes C3 system comes in a box that contains multiple RF and acoustic comms systems and enables direct comms with the AUV over Iridium without an internet connection (Courtesy of ecoSUB Robotics)



Launching small AUVs from high-sided vessels can be tricky, so this rope harness with hooks that float free on water entry has been developed to solve the problem (Courtesy of ecoSUB Robotics)



A pre-production prototype µ5 on the bench, revealing its electronics chassis, sliding battery pack, free-flooding nose cone and aluminium pressure case in the background (Author's image)

gets around a limitation of Iridium that forces operators to send information to and from remote objects such as AUVs via the internet. "We had to figure out a way of fooling the satellite into thinking Hermes is a sub," Sloane says. "Now we can send messages directly from anywhere in the world to the sub, and from the sub directly to us."

All the vehicles are small enough to be launched by hand, while the smallest can be dropped from aircraft, including small UAVs.

To launch from ships with high sides, the company has developed a device that resembles a rope ladder, to the end of which the AUV is attached by cords with floats that lift them off their securing hooks when the vehicle enters the water. A boat hook is used for recovery, hooking through the duct of the smallest vehicle and a webbing strap on top of the larger ones.

Materials and structure

All ecoSUBs have basically the same anatomy. The pressure case is a tube made from 6082-T6 aluminium alloy machined to its final dimensions inside and out, and hard-anodised for corrosion protection.

This material is more than strong enough at a reasonable thickness down to and far beyond the m25's 2500 m depth rating. The company has proved this in the NOC's test chamber, which can create the equivalent of 6000 m of water, Sloane says, having sacrificed four vehicles in this way.

"We take it in stages to the working depth, then to at least 50% beyond, and then keep going until it goes bang. That's quite exciting," he says with a smile.

He adds that ecoSUB Robotics has worked with a company based on the Isle of Wight, off the south coast of England, on some composite pressure case designs that could be used if the vehicles ever need to be made much lighter or stronger.

The pressure case is completed by two end caps, onto which the nose and tail sections are fitted. It is sealed by dual O-rings at each end and a partial vacuum of 500 hPa (hectopascals), or half an atmosphere, that sucks them on.

An internal pressure transducer is part of a suite of housekeeping sensors that also includes a humidity sensor.

The operators can monitor all of these through the GUI at the control station.

"Before you launch it, you check that it is still at 500 hPa," Sloane says. "If it leaks air it is going to leak water, so you know whether it is sound."

Another benefit of this approach is that it eliminates the need for nuts and bolts around the end caps, and the associated threaded holes in the aluminium case, which are potential weak points.

Like all the polymer parts, the free-flooding nose cone and tail sections are 3D-printed in nylon by Digits To Widgets (DTW) in London and then treated by a DTW subcontractor in Germany to make them waterproof. These plastic components also include the tray that holds the circuit board (which is part of the internal chassis), the battery box and, in the larger vehicles, some internal chassis ribs.

While some internal parts are screwed into place, the use of 3D printing has kept fasteners to a minimum. For example, the tray that holds the circuit boards in each vehicle is a single printed nylon component with integral lugs and stand-offs for the boards, which simply click into place.

AUVs are generally operated with a slight positive buoyancy to give them a tendency to float if anything goes wrong. Keeping them down consumes energy, so the buoyancy is carefully calculated to keep it to a minimum. That said, providing enough buoyancy was a particular challenge for the smallest vehicle (the µ5) while still accommodating all the equipment and batteries inside.

"Buoyancy/weight is always a trade-off," Sloane says. "In the deep-diving one with its 2500 m pressure case, making it strong enough to withstand the pressure but light enough to preserve buoyancy has been a challenge."

With the m5, the 500 m-depth version of the larger vehicle, the aluminium pressure case is much thinner and lighter, so the company needed to add some ballast to reduce its buoyancy in a manner that can be easily varied. It did that by adding hollow nylon ribs to the internal equipment chassis that serve to stiffen it, and to carry variable amounts of lead shot as ballast.

"What that means is we can install a really heavy sensor payload if we want, because we can take the ballast out," Sloane says.

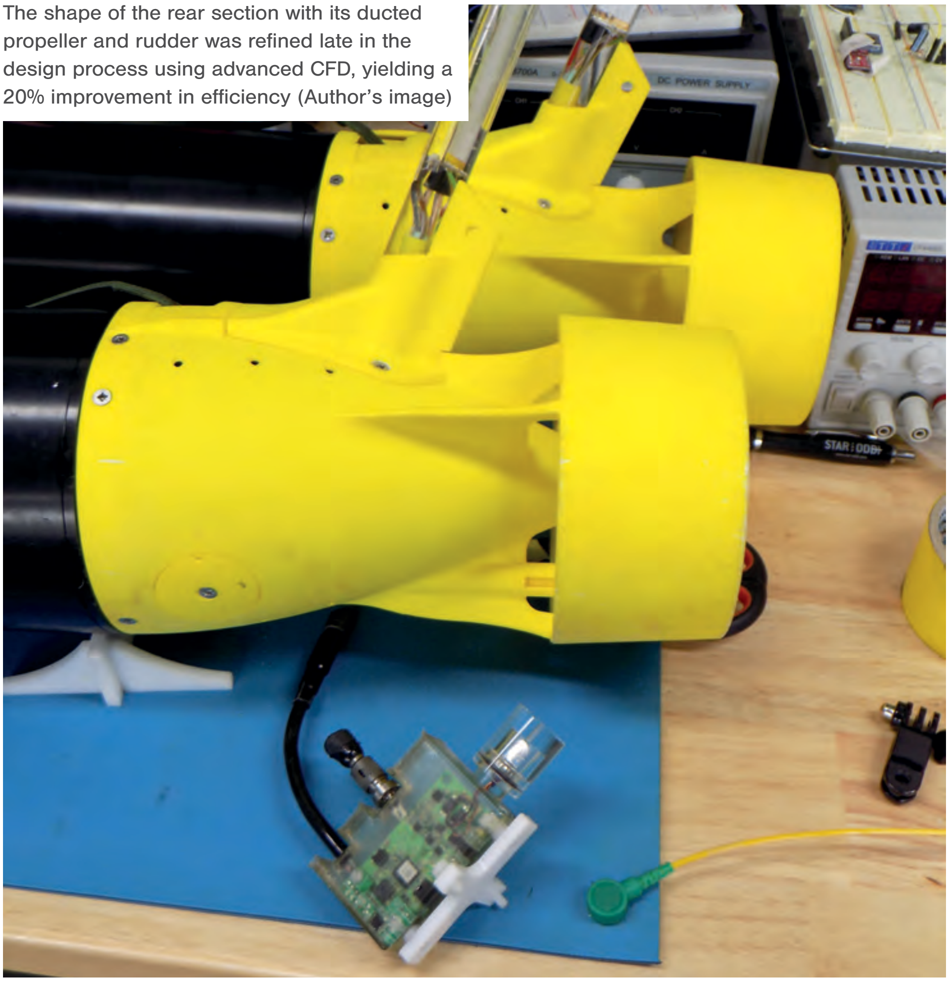
In terms of shape, the most complex and critical nylon part is the tail section. This forms the hydrodynamic duct that contains the rudder and the two-bladed propeller, which are also 3D-printed nylon components.

CFD helped determine the basic form of the vehicle at the beginning of development and towards the end for hydrodynamic refinement of the duct and the propeller, with dramatic results.

Using OpenFoam v6 to optimise the design of this area gave a 20% improvement in efficiency, translating into greater speed, range or endurance within the energy budget. "That was always part of the plan," Sloane says, "but we left it right until the last knockings to make sure everything else was design-stable."

In this process, the combination of CFD and 3D printing proved to be a powerful one. The designers went through multiple iterations with different duct lengths and profiles, and propellers with different numbers of blades and blade profiles from which to choose. They then pitted the best of the new designs against the original in a race along a test tank at Southampton University.

"We took two otherwise identical vehicles with identical motors and settings, one with the old duct and one with the new, and the new one just steamed away. The difference was amazing," Sloane says.



The shape of the rear section with its ducted propeller and rudder was refined late in the design process using advanced CFD, yielding a 20% improvement in efficiency (Author's image)

Propulsion and steering

To avoid the pressure hull being penetrated, which invites leaks, both the propeller and rudder are driven through magnetic couplings, so the only things that pass through the aluminium case are magnetic lines of force. (Aluminium is non-ferrous; magnetic coupling won't work through ferrous metals.)

A single PWM-controlled DC motor from Maxon drives a shaft, around which a series of magnets is arranged. This shaft spins inside a rearward tubular extension of the pressure case.

Outside that extension is a hollow shaft containing a matching set of magnets. It is this second shaft to which the propeller is attached.

In the larger vehicles, the motor drives the first shaft via a gearbox, but the other details are the same as in the µ5, only scaled up.

For yaw control, a linear actuator moves an arm with magnets attached up and down inside a vertical tubular extension of the pressure case, around which is another tubular arm with magnets inside and a linkage that converts the vertical motion to lateral motion for the rudder.

Of the two magnetically coupled systems, the motor-propeller relationship is the more complex to manage.

If the magnetic coupling is to engage, the motor has to be brought up to speed gradually on start-up, as simply giving it full power from a standing start will cause the couple to drop out and the motor will spin rapidly without turning the propeller. Likewise, speed changes when the vehicle is underway also have to be smooth and gradual.

"It takes a whole lot of software and testing to do that," Sloane says. This software has to be adaptive because the coupling's characteristics vary with water conditions, he explains, some making it harder to spin the propeller, some making it easier.

"It would change if you have a slightly different density in the water or if you're working near the surface and have lots of cavitation bubbles," he says. "All the

The propeller and rudder on all ecoSUBs use magnetically coupled actuators, eliminating hull penetrations and shaft seals. The antenna is a potted component assembled in-house (Courtesy of ecoSUB Robotics)

behaviours we have programmed into the vehicle take into account the fact that you can't go from 'zero to hero' in a millisecond, because the magnetic coupling has this characteristic."

The software monitors motor speed and current draw, along with the power demand from the control system, to figure out whether the propeller is turning as it should, without measuring its rpm directly. "If everything else is within limits then we know the prop speed exactly, because we are monitoring the shaft speed," Sloane says.

"One advantage of a magnetic coupling is that if the prop becomes fouled, we go into low-current mode as the drive disengages, whereas direct drive systems go into high-current mode and kill batteries or worse."

Energy storage and management

The batteries in the pack are standard manganese alkaline D-cells, six in the smallest vehicle and 14 in the larger ones. However, ecoSUB Robotics will integrate lithium thionyl chloride batteries as an option, for customers who might need a very long, low-speed transit capability.

While the batteries themselves might be fairly basic, the energy management system is very sophisticated and is designed to squeeze as much energy from them as possible to complete the mission, then to keep the vehicle 'alive' and communicating to ensure its recovery.

One technique used when the batteries are nearly depleted and there is a risk of losing the ecoSUB is to effectively disconnect the batteries from all the loads for a period, which enables them to recover some charge. The power conditioning electronics enable the vehicle to run on supply voltages from 30 V down to 3.5 V.

Generally, the system's logic uses measurements of the batteries' charge state to work out what to do. If it calculates that there is not enough energy remaining to complete the mission it will shut the sensors off but keep the motor, rudder and housekeeping functions running to eke out the endurance and get the vehicle as close to the planned recovery point as possible.

As the energy continues to become depleted, the next decision the system makes is to shut the motor down and allow the ecoSUB to float to the surface, at which point the only systems remaining on line are the GNSS and the Iridium satcom modem.

In this survival mode, Sloane explains, it can stay alive for about a week, occasionally transmitting an Iridium message, from once an hour to once every six hours. When a recovery team is nearby and the vehicle has enough energy left, they can send it a message telling it to broadcast its position more often to enable them to home in.

Payloads and payload support

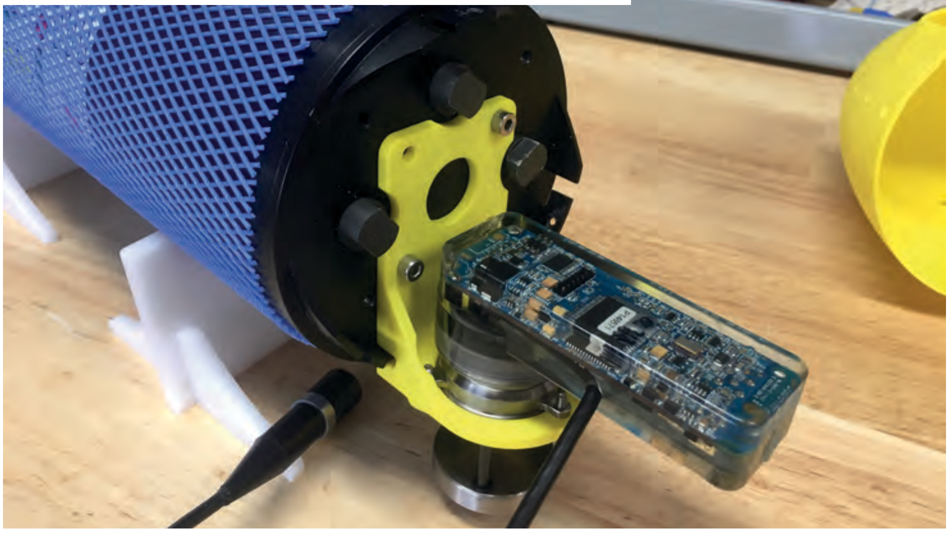
Most payloads sit in the flooded nose cone outside the pressure case,

Datasheet

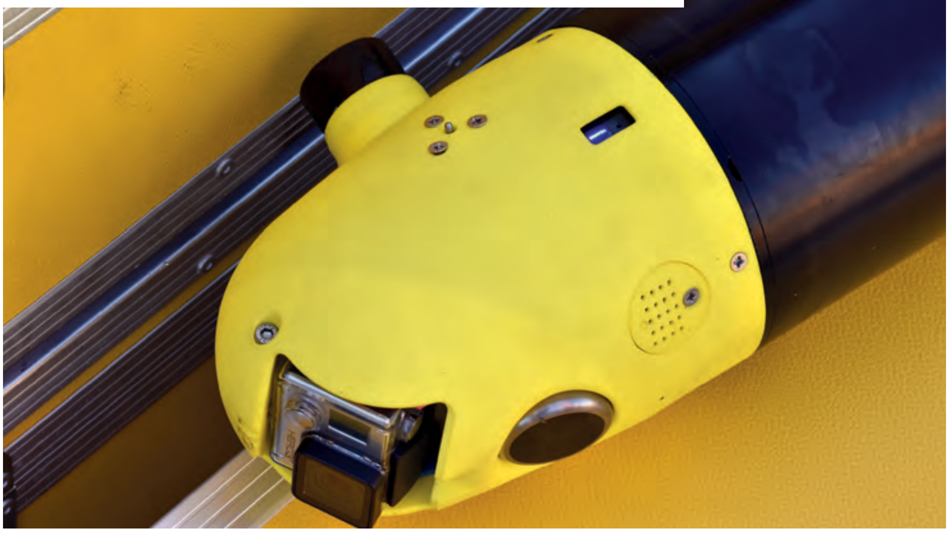
EcoSUBμ5

Length: 925 mm
Diameter: 111 mm
Weight: 4 kg
Maximum depth: 500 m
Maximum speed: 1 m/s
Range: up to 72 km
Endurance: up to 20 hours
Propulsion: DC motor
Propellers: one, with two blades
Surface location: GPS, IR and visible light beacons
Control: autonomous and remote control
Comms: satcom, wi-fi, acoustic, 3G/4G, RS-232, Ethernet, I^2C, USB

Some key suppliers
3D printing: Digits to Widgets
DC motor: Maxon
Command, control and comms: in-house
Sensors: Star Oddi
Sensors: Valeport
Sensors: National Oceanography Centre
Acoustic modem: Newcastle University
Satcom: Iridium
Autopilot: Variscite
Batteries: Varta Industrial
GUI: in-house
Underwater connectors and cables: STS Defence



All the plastic parts, including this forward pressure case end cap and the custom-made adapter plate for this fluorometer, are 3D-printed in waterproofed nylon (Courtesy of ecoSUB Robotics)



Bespoke nose cones for sensors such as this GoPro camera, acoustic modem and altimeter can be created easily using 3D printing, making integration of new sensors simpler (Courtesy of ecoSUB Robotics)

but some can be integrated within it. Payloads that have been integrated so far include CTD sensors, an altimeter, fluorometer, camera and a sound velocity profiler. Several other sensors are currently being integrated.

Again, 3D printing makes it easier to accommodate a growing range of sensors using bespoke nose cones.

Multiple switched power supplies are available, along with various comms protocols, Sloane says. Where they meet the sensors at the nose, they come together in bespoke underwater connectors built to ecoSUB Robotics' requirements by STS Defence, leading into the circuit boards via cables also made to the company's specifications by the same company.

Each connector provides plenty of standard data interfaces including RS-232, I^{2}C, Ethernet and USB, along with power.

Front seat, back seat

Resisting the pressure to build the ecoSUB's electronics around open architecture standards that would enable customers to integrate their own payloads and even autonomous behaviours into the vehicles – largely to retain clarity over who carries the responsibility for any accidents – the team found a different way to accommodate such requests, which they call the "front seat, back seat" approach.

"Think of it like a taxi," Sloane says. "Our driver sits in the front seat, and he's got all the behaviours in the library and all the nannies that watch over things and make sure he can't do anything stupid, and he just takes instructions from the back seat.

"The customer is on the other side, where he has access to this back-seat architecture and can put in anything they like – within reason – and send us instructions. We check them, and if what they want is doable then we'll do it; if not we'll tell them to think again."

This process takes place when the vehicle is delivered, and ecoSUB Robotics gives the customer a programming guide containing sets of instructions that are acceptable to the autopilot. That maintains clarity about responsibilities.

Production and future developments

Completed in batches of 12 at the moment, the ecoSUB AUVs are entering production at the company's facility in Petersfield, England. By the end of this year or early next, Sloane expects to be building between 50 and 100 per year of all variants. Organisationally, everything connected with the ecoSUB AUVs – including staff – will transfer from Planet Ocean to ecoSUB Robotics over the next 18 months.

As to future developments, Sloane believes that much depends on what happens with the enabling technologies. "The materials and battery chemistries will change, and new sensors will come along from universities and other places – all of which will be beyond our control.

"That is the sort of thing that will move us forward more than refining these vehicles anymore, although developers in these fields are continually seeking our input, as they realise that what is good for us will inevitably be good for other sectors." ◻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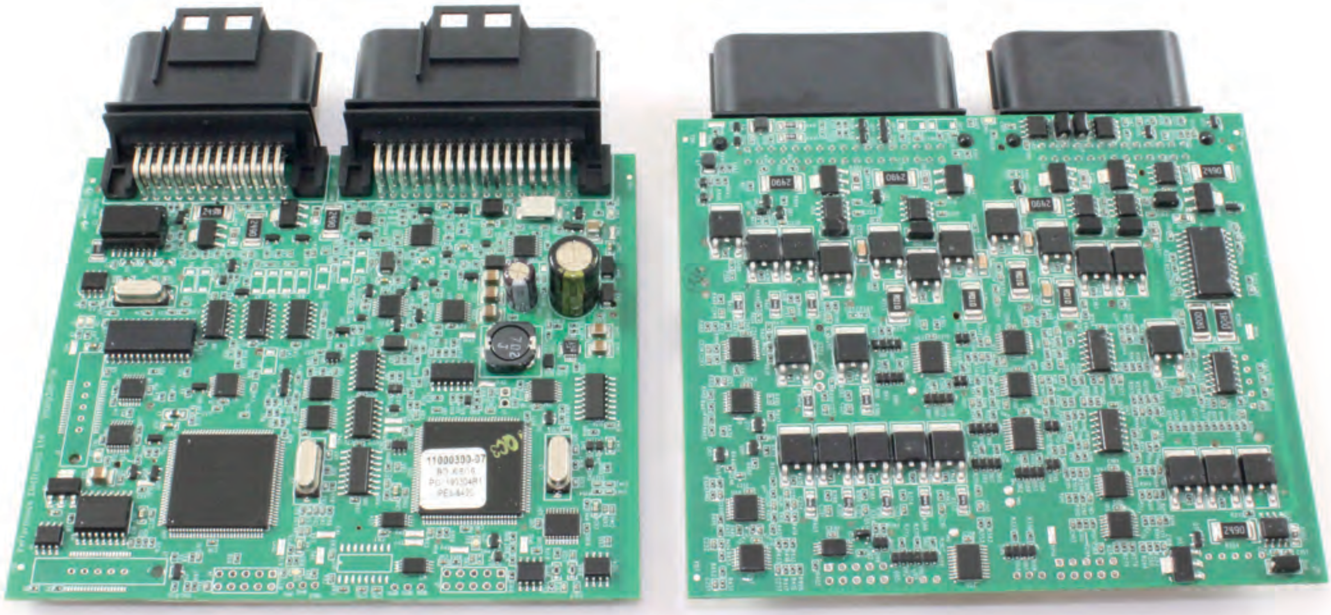
Advances in processor technology and debugging tools mean that new ECUs can be designed, built and calibrated up to 10 times faster than just a few years ago (Courtesy of Performance Electronics)



Demand for supply

Rory Jackson shows how advances in ECU design are tracking the growing demands being placed on sensors and engine components

Over the past two or three years, engine control unit (ECU) developers have been able to leverage continuing advances in ARM processors, which (like the ECUs that use them) have become smaller, lighter and faster in terms of processing speeds and reducing latency. Programming and debugging tools are also now more intuitive for ECU software engineers to use, and there is a growing availability of support services to meet the needs of unmanned vehicle and engine operations.

These improvements have considerably shortened development cycles for new ECUs, with some estimates as high as a tenfold increase in the rate at which control units can be planned, designed and built. At the same time, engine sensors and the associated measurement tools on ECUs have progressed to become more accurate, enabling greater energy efficiency and shorter times between overhauls of fuel engines.

All of this has come at the same time as a magnitude order of increase in the demands that unmanned systems manufacturers and operators are making on their critical engine components. As users turn away from hobbyist-grade ECUs, their rising proficiency in engineering has stepped up requests for greater power-to-weight ratios, endurances, levels of reliability and functional complexity, as well as lower costs of ownership and deeper interactions between aircraft and their ECUs.

Potentially the most impactful and fastest-growing of these requests has been the integration of hybrid-electric technology into the fuel propulsion systems being ordered. Some companies have notable quantities of users asking

ECUs must handle a broad range of inputs and outputs, which is certain to widen as hybridisation and increasingly complex payload systems draw on engine power and torque generation (Courtesy of Moscat Ingenieria)

for electrical generation that is directly proportional to propulsion power.

It is also likely in the years ahead that ECUs will increasingly be expected to incorporate greater autonomy (via longer and more complex decision-making algorithms).

For example, by intelligently understanding the nature of its mission, a UAV could respond to a minor engine fault by determining whether it can continue ascending or loitering, how it might improvise to achieve its objective without exacerbating the problem, or how long it can postpone its return flight before the fault becomes critical.

Improvements in engine health monitoring and data logging are likely to continue, towards the widely touted goal of AI-based predictive maintenance based on analytics software, which is designed to anticipate engine failures tens or hundreds of hours in advance.

Engine and ECU developers will also continue to see higher demand for a heavy-fuel capability, which requires more sophisticated engine control strategies than ECUs for typical gasoline engines. The ability of ECU programmers to quickly access and modify their software stacks to implement complex new requirements will be key in this regard.

Additionally, there will almost certainly be future step increases in demands for electromagnetic insulation in ECU enclosures. This is partially due to the need to reduce EMI between the ECU and other RF-emitting onboard systems, such as electric motors, navigation sensors, data links and so on.

However, it will also improve immunity to electronic countermeasure systems, jamming and interference from high-power ground-based transmission infrastructures communicating with satellites and other off-world structures.

It was still common to use automotive ECUs as the basis for new UAV units as recently as three to five years ago. However, automotive designs fall short of the latter in ways that the market may not now tolerate – not least because they are not weight-optimised in the ways UAVs need.

For example, when it comes to pressure readings, an automotive ECU will read 50 kPa of pressure as an error, because no road in the world goes above 4.25 or 4.5 km – but UAVs do.

Furthermore, UAV engines are used to drive fixed- or variable-pitch propellers, with remarkably different thermal management and gearbox systems than a car. Similarly, ECUs must have built-in fault tolerances, and these also differ wildly between cars and UAVs.

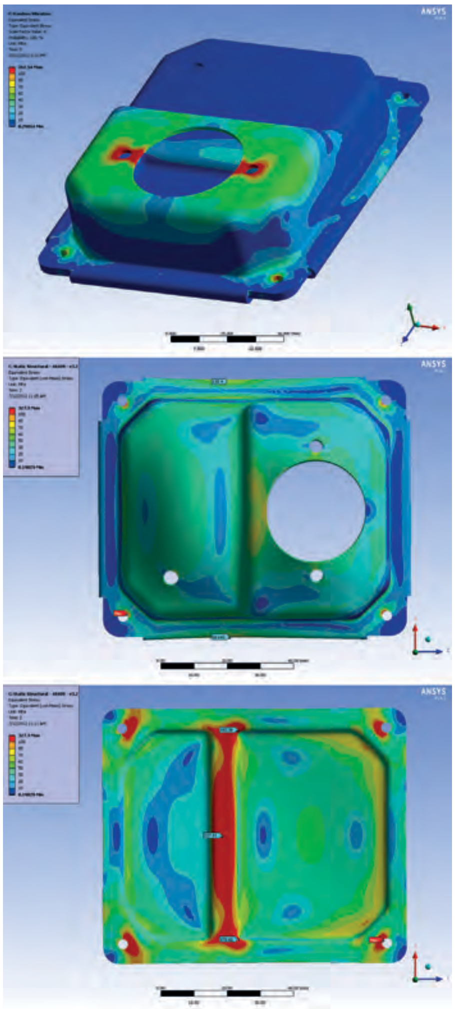
Temperatures and cooling

For example, a cylinder head temperature sensor might need its ECU to be programmed with over-range and under-range temperatures for identifying anomalous levels of heat, as well as for corresponding cooling output commands. Since cars and UAVs operate in different environments with different engine architectures, however, the operating temperatures and cooling requirements will be completely different.

Additionally, many small UAV engines (particularly two-strokes) do not have real-time exhaust gas feedback, and the absence of data feeds such as this could be read as critical errors by an automotive ECU.

Fundamental programming and architectural differences such as these make it more sensible to start from a blank sheet than repurpose an automotive ECU for a UAS. To custom-design an ECU from scratch, or to adapt an existing UAV ECU architecture to a new engine or vehicle, a range of application requirements must be included from the outset.

For one, the environment in which the ECU will operate must be fully understood. This includes accurate estimates of altitude, shock, vibration, humidity and so on. That will establish the requirements of the enclosure (almost always the heaviest part of the ECU).



CAD software can be used for modelling the structural and electrical robustness of ECUs in harsh environments (Courtesy of Orbital UAV)

Ongoing advances in CAD software mean that such physical, environmental and EM forces acting on components can be modelled simultaneously. That will simulate their impacts on the mechanical and electrical robustness of the ECU, making designing for the operating environment faster and more accurate.

Also, considerations such as the expected unit life, expected design support and the required production volumes over a given period will be required – along with agreement on a price point and cost priorities.

The physical requirements would then need to be defined, including constraints for mass, volume, dimensions and the intended installation location.

Naturally, the architecture of the engine needs to be described in detail. Not only should the many sensor inputs and actuator outputs that ECUs are primarily used to handle be made available, so should the operational profiles for speed, power, torque, fuel consumption rates and propeller (or other load) characteristics.

Diagnostics requirements must be established as well. As mentioned, onboard diagnostics are vital for handling engine faults during flight for either the engine or operator to react appropriately.

Also, ground-based diagnostics tools can be designed to make UAV maintenance faster and more effective, by identifying the nature and optimal solutions for engine problems before communicating them to technicians.

Similarly, the presence of systems for tracking operating hours and the engine power levels being used can be helpful when engine manufacturers issue warranties to UAV manufacturers and operators. These will record closely whether a customer was using the engine in a responsible or reckless way, so the kinds of data to be logged on an ECU should be discussed.

Lastly, software considerations such as the target language and interfacing, as well as the quality assurance level (such as DO-178) must be weighed up. As the degree of data, analytics and software functionality to be handled by ECUs steadily increases, growth margins may need to be established for memory and processing, to offset the need to replace microprocessors or SD cards in the future.

Caution should also be taken in other ways when designing an ECU. For example, as mentioned, there have been great advances and new releases in key computing technologies such as multi-core processors, and it can be tempting to ask to have these installed in a next-generation ECU to provide a step increase in software speeds and functionalities.

However, it can take years for fundamental problems with new hardware to be discovered. It's a perennial issue, and is the main reason why research aircraft testing new equipment often go to the 'extreme' of using technologies that are many decades old for their other onboard systems.

For example, a new CPU design could start emitting unexpectedly high heat or EM noise during high processing loads after 1000 running hours, significantly shortening the lifecycle of its ECU.

Adding too many components and too much protection can also run against the need to cut weight on UAVs. Determining what an end-user does not need can help establish which processors, resistors, connectors, heat sinks and so on can be removed. Cutting just 25-30 g from an ECU can enable a significant payload camera upgrade for a UAV.

Issue of redundancy

Some ECUs will not incorporate any significant degree of redundancy, and will therefore bear a lot of single points of failure, such as having only one crank speed sensor or cylinder head temperature sensor.

That means there are a lot of pathways and wires that could cause the unmanned vehicle to be lost if it's damaged. As UAVs handle increasingly harsh environments and expensive payloads, this lack of redundancy becomes more likely to lead to problems.

Checks should also be made for all the important functions that are unique to flight requirements. These could include ensuring that the flight controller does not close the throttle in response to engine heat if the UAV is cooling too quickly during a descent, or something simpler such as opening the throttle proportionally with altitude (which nonetheless might not occur to automotive engineers).

And when integrating an ECU into an engine, it is common to calibrate it with a propeller mounted, particularly among users and manufacturers of small fuel-injected engines in the UAV realm.

However, changes in the propeller – if it's swapped out or receives minor damage from gravel or bumps on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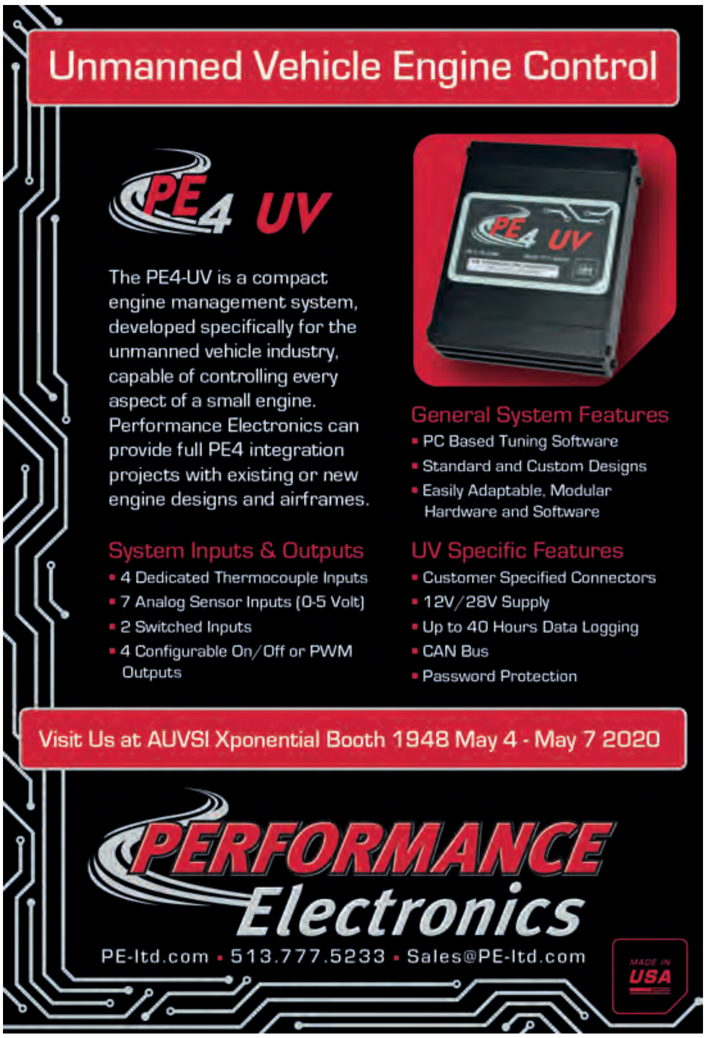
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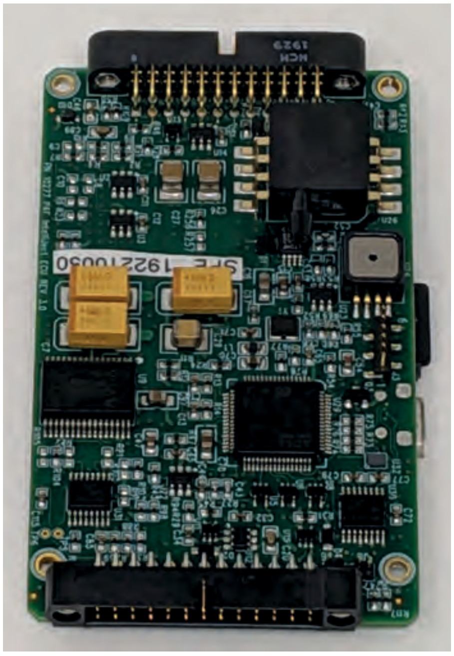
An ECU's enclosure is often the heaviest part. Some are made from a carbon composite to save weight, which can also help protect against EMI from other avionics (Courtesy of Ecotrons)



Control algorithms must be carefully updated for variations in the conditions, timings and componentry needed for heavy-fuel and hybrid-electric engines (Courtesy of Power4Flight)

the ground during take-off or landing – could then throw off the ECU's embedded maps and load lines, such as for rpm versus throttle.

That can lead to major inaccuracies in the fuel feed, air feed, and spark timing of the engine.

Differences between ECUs for reciprocating engines and rotaries tend to come down to their embedded software, particularly in terms of how the injection and ignition advances are synchronised, and how to estimate the required fuel for preparing the combustion mixture.

For example, a speed density scheme can be used to calculate fuel injection in a two-stroke gasoline engine. That would be a sub-optimal approach though, owing to the difficulty of estimating air mass flow, as the manifold air pressure (MAP) of a two-stroke typically has a narrow range.

On the other hand, the MAP in a four-stroke has a far wider range, enabling more precise air mass flow estimations, so speed density is much more applicable for this engine type than for two-strokes.

The use of adaptive closed-loop control algorithms can confer several advantages on ECUs for engines that have slightly different calibrations. The algorithms can enable calibration maps to be quickly adapted to compensate for differences in performance specifications between engines, making the testing and mapping phase of a new engine much quicker.

For heavy-fuel engines though, such algorithms may not be sufficient. While gasoline engines tend not to vary too much in the leanness of their air-fuel mixture, even at the 'richer' ends of their operating ranges, heavy fuel must be spark-ignited within a much more narrow range of mixtures.

That means the calibration tools and methods must be far more precise. For example, cylinder head temperature sensors (and other temperature sensors) for heavy fuel two-strokes should be more accurate than those of gasoline in order to alter the air feed proportionally to how hot the engine is.

Knocking

In addition to the quality of fuel injection and calibration, the ignition on heavy-fuel engines can more easily trigger knocking when combined with a higher-than-average cylinder head temperature.

It may therefore be important to program an ECU with temperature-correlated limits on when to advance the spark timing, or even an input interface for a knock sensor. The latter is particularly worth considering if the craft is to carry expensive payloads, experimental sensors or people (in the case of an autonomous urban air taxi), given that knocking can destroy an engine.

To enable unmanned vehicle powertrains to be hybridised, control algorithms must account for how the engine will interact with the different components required for generating several kilowatts of electrical power from its crankshaft.

Perhaps the simplest of these is how an ECU and motor controller will work together in response to load. If a UAV is flying at a gentle cruising speed, outputting 2 kW, and the starter/generator is supplying just a few hundred watts to the electrical systems, a sudden jump in the electrical load of just 100-200 W could trigger a critical error message in the ECU, or cause dramatic speed deviations or even stop the engine.

Instead, the ECU should be designed to advance the throttle in proportion to the electrical load. As the generator can process and record measurements of that load within a few hundred milliseconds, the measurements should be sent to the ECU, so that the throttle (or fuel injection) can be adjusted before the engine begins to slow down, to match the change in torque and keep the propeller and crank at the right speed.

Such design care will keep the engine running and reduce the burden on the flight controller. Striking a balance between the need to widen the throttle to provide more electrical power to the airframe, for example, and the need to slow the engine during survey or descent can be challenging, and result in significant lags in control feedback.

ECU design and programming then becomes more complex for parallel hybrid or full-hybrid systems generating upwards of 10 kW of electricity. For example, if a UAV in flight needs to go from cruise to climbing mode (changing the load by orders of kilowatts), or quickly evacuate unsafe airspace, the flight controller might respond by going to wide-open throttle.

And although the current draw will probably have shot up, the engine might not be able to turn fast enough to provide the jump in power. At that point, the ECU may need to interact not only with the engine and motor controller but with the battery, to have the generator temporarily run off battery power.

That would allow the engine to spool up to the required speeds for the power required, or perhaps for it and the generator to deliver their maximum power outputs to the propeller at the same time.

Increasing the number of I/Os on the ECU might be necessary to account for the extra sensors, transistors and commands in high-power hybrid powertrains. However, it largely falls to UAV manufacturers to decide whether they want to place the intelligence for handling complex power systems on the ECU or the flight controller.

One of the most notable additions being seen across ECUs designed and built for UAVs are systems for electronic logging and tracking maintenance.

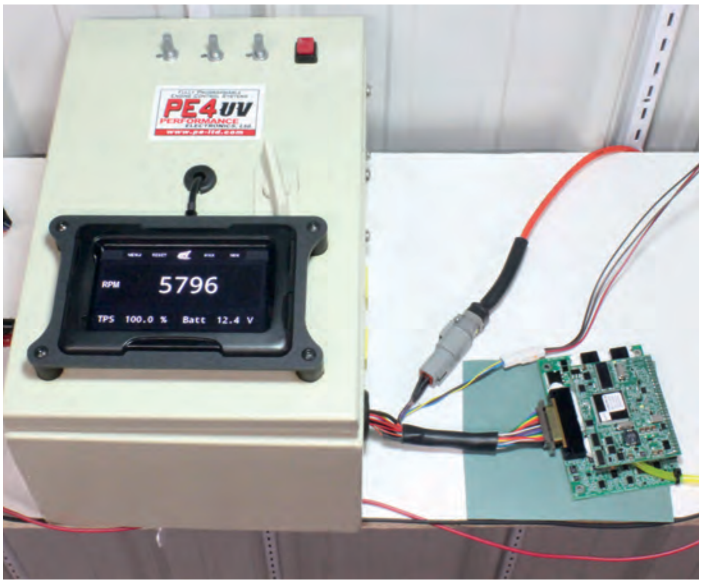
The growing adoption of fuel-powered UAVs has driven more customer requests for easier ways to track and reduce their operating costs. Adding an SD card to an ECU means it can precisely record fuel consumption, with a 16 Gbyte card capable of taking 50 kbit/s and holding 15 days' worth of ECU logs.

Maintenance

To help with maintenance tracking, the ECU can have the SD card automatically record when maintenance has been performed. It can also track engine wear and anomalies such as overheating or knocking, and send alerts to the GCS or ground technicians if maintenance is required.

Even if those recordings are not automatic, having an engine 'log book' functionality on the ECU would still encourage more UAV technicians to

With SD card technology continually getting smaller and lighter, some ECUs now come with data loggers for recording an engine's running history and aiding in maintenance tracking (Courtesy of Northwest UAV)



Aggregating engine data via the ECU from flight hours or test cycling accelerates the development of predictive models that help prescribe maintenance for engines and ancillary components (Courtesy of Performance Electronics)

keep maintenance records, potentially reducing operating costs and improving operation safety.

For more accurate analytics as to when maintenance is needed and what kind should be performed, a wide range of ECU inputs can be logged after measurements are received.

That can mean not just the number of engine hours but the total number of revolutions, the hottest cylinder head temperature recorded in flight, the lengths of time spent at excessively high temperatures, time spent at high load and even the number of engine starts.

That information can then be fed into an onboard maintenance scheduling system, and update it so that it 'knows' when to send alerts to the user, in a similar way to how a 'check engine' light works on a road vehicle.

The ECU could then take the pertinent data and output it as a detailed record for the UAV's technicians or even for the engine manufacturer (if the unit is sent back to them).

Designing and installing more detailed logging systems such as these onto ECUs would also make it easier to integrate engines onto vehicle chassis. As an example, by looking broadly at how long the engine spends at high heat, it could be determined fairly quickly whether adequate cooling will be available for the vehicle and its operating environment.

True 'health monitoring systems' for predictive maintenance analytics have yet to be implemented in any UAV ECUs. However, the spread of data recording systems means ECU manufacturers can begin amassing the vast quantities of engine logs needed for accurately modelling which combinations of measurements and anomalies would need preventative measures.

Depending on the willingness of end-users to share their data, ECUs might start coming with true predictive maintenance algorithms within the next five years.

Testing and screening

Once an ECU is manufactured, its PCB should be closely checked for any soldering defects, either visually or (preferably) by functionally testing every part of the circuit board.

The conformal coating should also be examined, under UV light. UV blue tracer additive is used in the coating, and any section of the ECU not fluorescing under the light shows that the coating was not applied properly. Such areas will be vulnerable to environmental damage and must be addressed.

Assembled ECUs should undergo environmental stress screen tests, in which they are subjected to repeated temperature and vibrational cycles to weed out early-life failures before they enter service. These failures can be reviewed, so that over time, patterns can be identified in the types of defects happening, to unearth flaws in either the design or manufacturing process.

During stress screening, ECUs will often be powered up and operating with dynamically representative sensors, actuators and loads while undergoing extremes or near-worst cases of heat, cold or turbulence. That allows abnormal operating conditions to be tested more easily so that fault detection and accommodation systems can be updated to compensate if necessary.

Some ECU manufacturers are going as far as putting new ECU models through highly accelerated life testing (HALT). This places units in a test chamber and subjects them not only to great extremes of temperature and vibration but also wide swings in those variables.

While there are no standards requiring

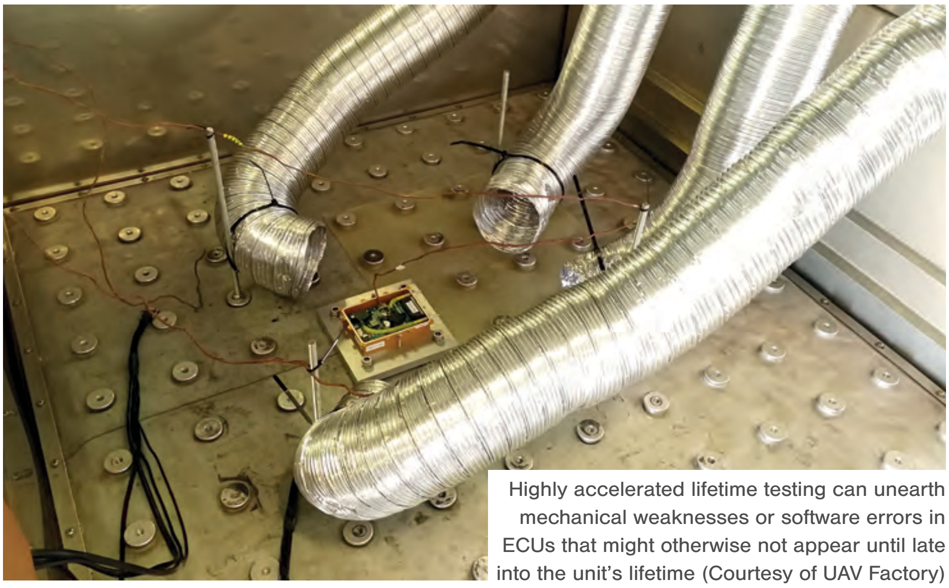
HALT, it puts the ECUs through several years' worth of stress and unearths any weak spots that would otherwise not appear until thousands of running hours had been accumulated.

The availability of altitude engine testing facilities can be key, as this would help with regular and highly accelerated testing by accurately simulating environmental conditions at flight altitudes up to 20,000 ft (6 km), ensuring the ECU operates correctly across every part of its expected flight envelope.

By adopting automated testing equipment, data from tests and screenings can be more seamlessly recorded, and in huge quantities. In addition to providing more material for analysing and correcting problems found during testing, mapping data for different performance outputs can be amassed from testing engines and ECUs on dynamometers.

That means ECUs can be recalibrated more quickly when an end-user wants to run their engine in an unusual way, such as with a different richness or leanness of fuel, and at a certain altitude or speed.

Regardless of data recording, using testing machines such as dynos or environmental chambers, as well as the ECUs and their load simulators, can be labour-intensive. Without automated equipment, dyno speeds and cooling fans must be manually operated, and environmental and load variations



Highly accelerated lifetime testing can unearth mechanical weaknesses or software errors in ECUs that might otherwise not appear until late into the unit's lifetime (Courtesy of UAV Factory)

Examples of ECU manufacturers and suppliers

AUSTRALIA

Currawong Engineering
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Orbital Corporation
+61 8 9441 2311 www.orbitalcorp.com.au

AUSTRIA

Bosch General Aviation Technology
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GERMANY

Sky Power
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ITALY

Zanzottera Technologies
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Moscat Ingenieria
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must be typed into control consoles to test the ECU against them.

It can therefore be very cost-effective and time-efficient (and not hugely complicated) for ECU developers to produce software algorithms and maps aimed at putting tested ECUs through the appropriate ranges of environmental conditions and engine power levels, temperatures, faults, altitudes and so on.

A single test cell running a new ECU operational profile can then generate a full and detailed data set, and map out the speed against power or specific fuel consumption for a wholly new engine configuration in less time than ever before.

Conclusion

The growing diversity and customisation of unmanned vehicle designs is spurring similar diversity in the requests for how their engine systems are configured to run.

As powertrains evolve to meet the demands of the rapidly changing unmanned space, it will be vital that ECU engineers can design systems to handle the increasing complexity of ECU tasks without upsetting the balance between the avionics and other electrical systems on UAVs.

Acknowledgements

The author would like to thank James Bossard of Orbital UAV, Ross Hoag and Bill Vaglienti of Power4Flight, Brian Lewis of Performance Electronics, Denis Makarchuk of UAV Factory, Sergio Moscat of Moscat Ingenieria, and Jim Ratcliffe of Northwest UAV for their help with researching this article.


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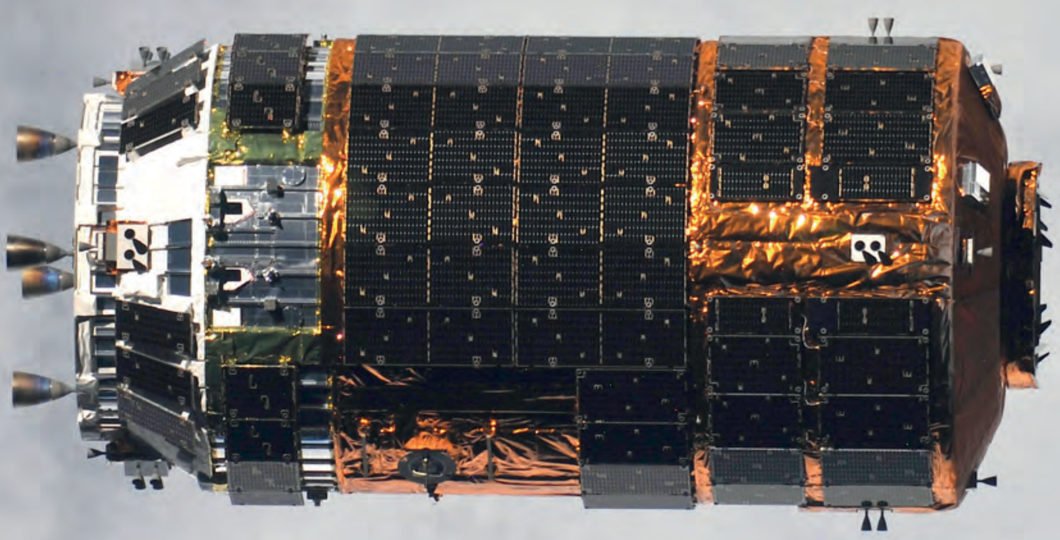
The Kounotori 8 mission was the latest to use the Japanese space agency's autonomous cargo spacecraft, the H-II Transfer Vehicle. It carried a 5.3 t payload to the ISS (Courtesy of NASA)



Planet gear

The race is on for developers of unmanned space systems to stake their claims in Earth's neighbourhood, reports **Rory Jackson**

While programmes aimed at studying the outer Solar System are ongoing, recent months have seen organisations around the world surging forward with plans for consolidating their places in the near-Earth regions. In particular, the Earth's orbit, the Moon and Mars will host a range of new orbital and ground systems within the next couple of years.

Many fully autonomous and partially automated vehicles are under development, as scientists and engineers seek to lay the groundwork for the anticipated off-world industrial and colonial work expected to play a part in humanity's near future.

Orbital logistics

As research and tourism in Earth's orbit increase in scale and ambition, so the need to conduct orbital resupply operations reliably and consistently is greater than ever. More and more organisations are using autonomous spacecraft that are capable of precise navigation and calculations for docking with provisions, removing the risk to human astronauts during lift-off or return.

In one of the latest prove-outs of such capabilities, Mitsubishi Heavy Industries has sent an unmanned spacecraft to the International Space Station (ISS), to supply onboard astronauts with about 5.3 t of provisions.

The supplies, carried by the Kounotori 8 robotic cargo spacecraft, included fresh food and water, equipment for carrying out experiments, and six lithium-ion orbital replacement unit (ORU) batteries to replace the ISS's nickel-hydrogen battery packs.

The mission was launched on September 24 from the Japan Aerospace Exploration Agency's (JAXA) Tanegashima Space Center off the south-eastern coast of Japan. The name 'Kounotori 8' was designated for the 8th iteration of JAXA's H-II Transfer Vehicle (HTV), designed and built to supply the Kibo Japanese Experiment Module as well as the rest of the ISS.

After it has delivered its supplies, it is intended that astronauts will offload their waste and refuse onto the HTV, before it returns to the Earth to be destroyed upon re-entry.

The latest Soyuz resupply mission to the ISS was used to trial a humanoid FEDOR robot in the unmanned capsule and a modified launch-abort system on the Soyuz-2.1a booster rocket (Courtesy of NASA)

The HTV is arguably the largest such vessel in existence so far, among others such as SpaceX's Dragon and Northrop Grumman's Cygnus. It is about 9.8 m long and 4.4 m in diameter, with an empty weight of 10.5 t and a payload capacity of 6 t. It will be followed up by a Kounotori 9, which will carry similar supplies and the next ORU batteries.

One of its payload bays is outside the hull, which after docking is accessed by a robotic arm that transfers supplies into the Kibo module. The HTV uses the MDA Space Missions Canadarm2 to do this, with the robotic arm also serving as a grappler to assist during docking.

The HTV's four main thrusters are powered by monomethylhydrazine fuel and mixed oxides of nitrogen as oxidiser to produce 500 N each for orbital manoeuvring. The fuel and oxidiser are also used by the HTV's 28 attitude control thrusters, each of which produces 110 N, with roughly 2.4 t of propellant carried onboard across four tanks.

Earlier in September, an unmanned Soyuz MS-14 spacecraft returned from the ISS, having been launched from the Baikonur Cosmodrome in Kazakhstan and flown autonomously with a payload of about 658 kg of cargo for the onboard crew.

The craft also housed a humanoid FEDOR (Final Experimental Demonstration Object Research) robot, developed by the Russian Foundation for Advanced Research Projects in the Defense Industry, in collaboration with non-profit organisation Android Technologies. It was commissioned by Russia's Ministry of Emergency Situations.

The FEDORs have been created as all-purpose stand-ins for humans operating in high-risk mission vehicles, conducting rescue work and other hazardous tasks requiring leverage and hands.

As the robot can work amid radiation, chemical contamination and in the absence of oxygen, it spent the MS-14's launch and return missions monitoring and reporting on conditions at the commander's seat.

The FEDOR is about 180 cm tall when standing upright, weighs 160 kg and operates on a 20 hp power output.

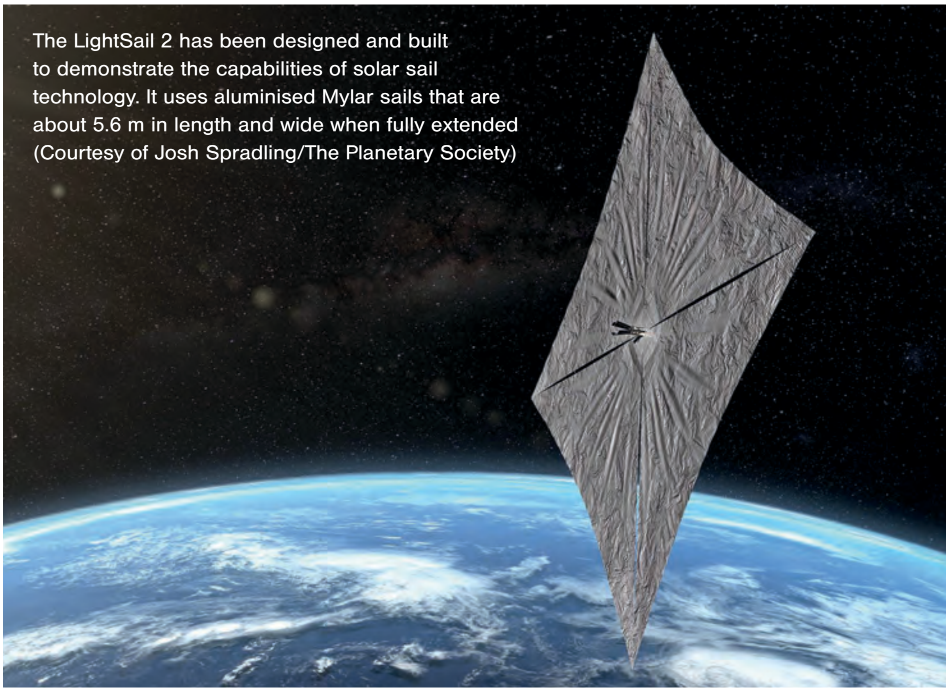
The 660 kg MS-14 was also used to test a Soyuz-2.1a booster rocket with a modification to its launch-abort system. The booster will be used from next year to transport crews to the ISS.

Orbital research and exploration

The US Air Force Research Laboratory (AFRL) has launched 24 experimental unmanned orbital craft, as part of the Department of Defense's Space Test Program mission.

A SpaceX Falcon Heavy rocket was used for the launch. It was that craft's first ever night flight and third launch overall, as well as its first flight using reused boosters.

Included in the rocket's payload of experimental spacecraft was the



The LightSail 2 has been designed and built to demonstrate the capabilities of solar sail technology. It uses aluminised Mylar sails that are about 5.6 m in length and wide when fully extended (Courtesy of Josh Spradling/The Planetary Society)

LightSail 2, the first project aimed at demonstrating controlled solar sail-based propulsion in low-Earth orbit.

Although a LightSail 1 had been launched in 2015, with identical physical dimensions (10 x 10 x 30 cm when stowed; 32 m^2 with sails deployed) it was only intended to test and demonstrate the sail deployment mechanism.

The LightSail 2 was launched from Prox-1, a small carrier spacecraft, and a few days later the sails were unfurled. Once deployed, the sails are kept at 165° relative to the LightSail 2's central hub for the rest of the year-long mission, to present a hemispherical view to the sun sensors and allow enough solar power to be generated to maintain attitude.

The system's solar sails are made from an aluminised BoPET (biaxially-oriented polyethylene terephthalate) known as Mylar that is manufactured in four triangular sections 4.6 microns thick. Their deployment is powered by an electric motor that drives a spindle, which in turn actuates an extending boom made from an alloy known as Elgiloy.

As it moves away from the Sun, the LightSail 2 autonomously points its sail normal vector directly away from it, to maximise the solar radiation pressure on the sail, ensuring that the projection of the thrust onto the orbital velocity increases the orbital energy.

When moving towards the Sun, the craft autonomously switches to a 'feathered' configuration to prevent the solar radiation pushing into the open sails.

The onboard electronics use a 5.6 Ah battery pack which, combined with the typical 8.5 W produced by the solar cells (up to a maximum of 24 W; 6 W per sail at maximum solar exposure), enables power to be accumulated.

> HAN is intended to provide a non-toxic and higher specific impulse fuel than the more common hydrazine-based propellants

Also launched in the AFRL mission was the unmanned Green Propellant Infusion Mission spacecraft, which is trialling the first ever in-orbit use of hydroxylammonium nitrate (HAN) as a key propellant component.

HAN is intended to provide a non-toxic and higher specific impulse fuel than the more common hydrazine-based propellants. Specific impulse is the total impulse – or change in momentum – delivered per unit of propellant burned, and data thus far suggests that HAN's specific impulse is nearly 50% higher for a given tank volume than typical hydrazine monopropellants.

Its propellant, nozzles and valves were developed by the AFRL, Aerojet Rocketdyne and the Glenn Research Center, with Aerojet being responsible for the propulsion demonstrator payload.

The propulsion system incorporates four 1 N thrusters for attitude control, and a single 22 N primary divert thruster. The propellant feed configuration is largely typical of hydrazine-based systems, though with a few redesigns to make it compatible with the dynamics of the new fuel, such as its higher viscosity.

Meanwhile, the Indian Space Research Organisation continues to develop its Gaganyaan orbital spacecraft, with the design of the crew module having been completed earlier this year. The project is projected to undertake its first launch by December next year, for which it will be uncrewed and fully autonomous.

The Gaganyaan is a 3.7 t capsule-type craft which, on its first manned mission in December 2021, will carry a crew of three into orbit before returning to Earth after up to seven days.

The crew module is attached to a 'service module' that incorporates two liquid-propellant engines, the two modules being collectively referred to as the 'orbital module'. The service module is expected to weigh about 3 t.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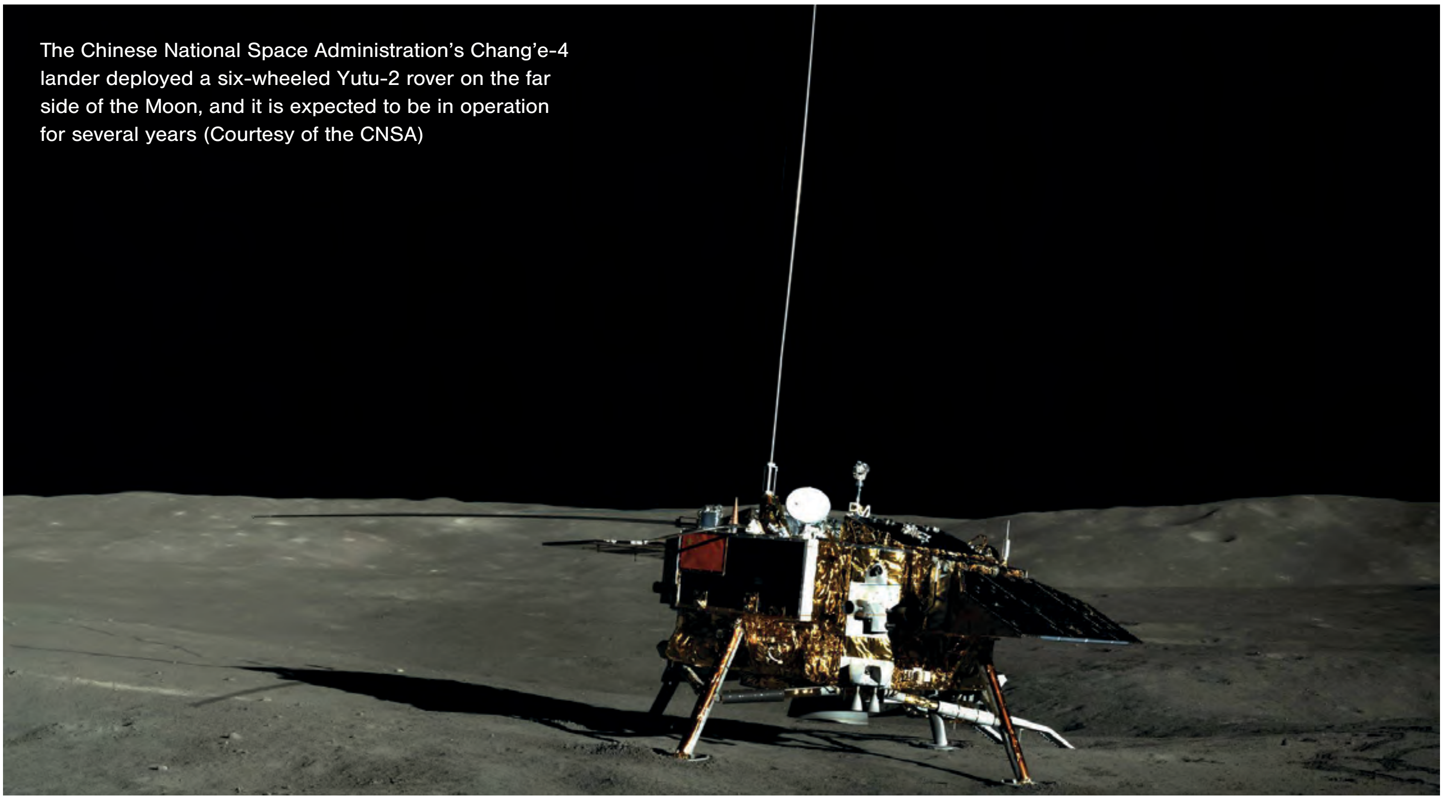


The Chinese National Space Administration's Chang'e-4 lander deployed a six-wheeled Yutu-2 rover on the far side of the Moon, and it is expected to be in operation for several years (Courtesy of the CNSA)

Lunar geology

The China National Space Administration has successfully deployed its Yutu-2 rover to the far side of the Moon, where it has discovered mantle rocks indicative of an impact having breached the Moon's crust billions of years ago.

The Yutu-2 weighs about 140 kg, measures roughly 1.5 x 1 x 1 m, and was carried to the Moon's surface by the 1200 kg Chang'e-4 lander. Both are equipped with radioisotope-based heaters for thermal management of subsystems during the lunar nights, and solar panels for generating electrical power during the day.

The two unmanned vehicles landed inside the 180 km-wide Von Karman crater, which sits within the Moon's South Pole-Aitken basin.

As direct data links between the Earth and the Moon's far side are currently impossible, the Queqiao relay satellite was deployed in a halo orbit around the L2 Lagrangian point of the Moon relative to the Earth, to serve as a continuous comms relay between Earth and the Chang'e-4.

Through this link, initial telemetry received from the Yutu-2's visible and near-infrared spectrometer sensor suggests that the rocks contain low-calcium (ortho)pyroxene and olivine, minerals that are found in the mantle rather than the crust. A ground-penetrating radar designed for use on the Moon was also integrated as part of the vehicle's survey sensor suite.

The rover has a panoramic camera on its mast as well, which has a spectral range of 420-700 nm, for acquiring 3D images by binocular stereo vision. It also carries an energetic neutral atom analyser from the Swedish Institute of Space Physics, which was integrated to study how the solar wind interacts with the lunar surface, potentially to help investigate the process behind how lunar water is formed.

Lunar exploration

Progress is continuing on the partially autonomous Lunar Orbital Platform – Gateway (LOP-G), with Maxar Technologies having been contracted to produce and demonstrate the power, propulsion and comms section of the system. The contract was awarded by NASA, which leads the project in collaboration with international development partners including the ESA, Russia's Roscosmos, JAXA and the Canadian Space Agency.

The technologies to be developed by Maxar will include a 50 kW solar-electric propulsion system, which will be about three times more powerful than typical systems. It is much more energy-efficient than traditional chemical power systems, so it will use far less propellant than in NASA's past lunar operations. Also, the comms system will provide an automatic relay between the Moon and the Earth's South Pole.

The Gateway is designed to provide habitation and laboratory space for research astronauts to use between experiments and explorations on the lunar surface, with stays lasting for about three months.

Being just less than a third of the size of the ISS, its modules will include a robotic arm for berthing and inspecting vehicles, and installing scientific

The Orion crew module will be attached to the ESA's Orion service module using an adapter (pictured); another one is being built to connect the service module to the Space Launch System rocket (Courtesy of NASA)

payloads. It will also have an allocated docking port for a robotic sampling vehicle, which will be used for automated transport of payloads – typically research samples and equipment – from the lunar surface to the Gateway.

Maxar's contract will start with an initial 12-month period for spacecraft design, after which optional periods will be drawn up for the development and launch, as well as demonstrations of core technologies. The latter will probably include a full year of in-space flight trials, during which Maxar will have ownership and control of the Gateway.

NASA also continues to pursue its other lunar exploration programmes, having awarded a $2.7 billion contract to Lockheed Martin in September for a third, fourth and fifth Orion Multi-Purpose Crew Vehicle to support the new Artemis crewed space exploration programme.

The first Orion craft (Artemis 1) is likely to be launched in November next year, and will be entirely unmanned for the three weeks or so it will spend in space. Of the three latest craft to have been ordered, the first (Artemis 3) will land astronauts on the lunar surface using the aforementioned Gateway platform.

The maximum launch mass of the crewed Orion capsule craft is 33.4 t. It is 3.3 m tall and 5.03 m in diameter, and contains about 9 m^3 of habitable space.

Artemis 1 and 2 will be launched atop a 'service module' measuring 4 m tall and 4.1 m wide, which will provide power and propulsion for the capsules until they are discarded at the end of each mission. The modules are based on the design of the ESA's previous Automated Transfer Vehicle, with the bulk of the design and production to be conducted by Airbus Defence and Space, although Airbus will also collaborate with Thales Alenia Space on several onboard thermomechanical systems.

Lunar mining

The ESA has signed a one-year contract with European launch services provider ArianeGroup to study the feasibility of mining the Moon for helium-3.

Intended for launch by 2025, the mission will use a planned Ariane 64 rocket, a version of the ArianeGroup's Ariane 6 design but renamed owing to its use of four strap-on boosters. It will have a payload capacity of 8.5 t.

Planetary Transportation Systems will provide the autonomous landing and navigation module (ALINA) for the Ariane 64. That has eight thrusters, four solar panels and a payload capacity of up to 300 kg, and is designed principally for transporting and deploying two Audi Lunar Quattro rovers.

The rovers weigh 30 kg each (with 5 kg of spare payload capacity), and have electric four-wheel drive, active suspension, variable-angle solar panels for recharging its batteries, and HD EO cameras. The cameras and rovers can be operated in real time through an LTE data link installed on the ALINA, with navigation imagery and other telemetry streamed directly to ESA scientists.

Lastly, Belgium-based Space Applications Services will provide the ground control facilities, comms systems, and associated services.

The mission is designed to inspect the lunar regolith for helium-3, which could be vital as a fuel for nuclear fusion. Current estimates suggest that there are 250,000 t of extractable helium-3 on the lunar surface, enough to satisfy humanity's current energy needs for at least 200 years (and currently valued at $5 billion per tonne).

Martian geology and astrobiology

Further afield, NASA's Mars 2020 rover has completed its first round of camera calibrations. These are among the earliest steps towards its planned launch for next July, and it is set to land in the Jezero crater on Mars in February 2021.

The trials involved placing a chart consisting of a grid of white dots on a black background in front of each camera at 1-40 m away, enabling the rover's engineers to test the resolution and geometric accuracy of each sensor.

At the time of these trials, the system included two navigation cameras

(Navcams), six hazard cameras (Hazcams), a remote micro-imager (SuperCam) and two multi-spectral imaging sensors (MastCam-Zs).

The NavCams and MastCams are mounted on a mast above the centre of the rover. The latter will take 2 MP multi-spectral images and 3D imagery by algorithmically stitching together the feeds from each MastCam to identify rocks and regolith worth sampling. Each MastCam weighs about 4 kg and consumes 17.4 W.

The Hazcams act as FPV sensors to prevent the rover colliding with rocks or other obstacles, as well as providing directional imagery to keep the vehicle from losing its track as the mast circles around.

The SuperCam will assist further in the mission, by using a laser to clear away surface dust and thus more easily identify the chemical composition of rocks and soils, including their atomic and molecular make-up. That system weighs 5.6 kg and typically consumes 17.9 W.

The samples of rocks and regolith collected will be used to analyse the geological processes and potentially the past habitability of Mars.

The rover will also carry the Mars Helicopter Scout, a 1.8 kg solar-powered helicopter UAV that will help find the best routes for the rover, as well as trial the feasibility of flight on Mars.

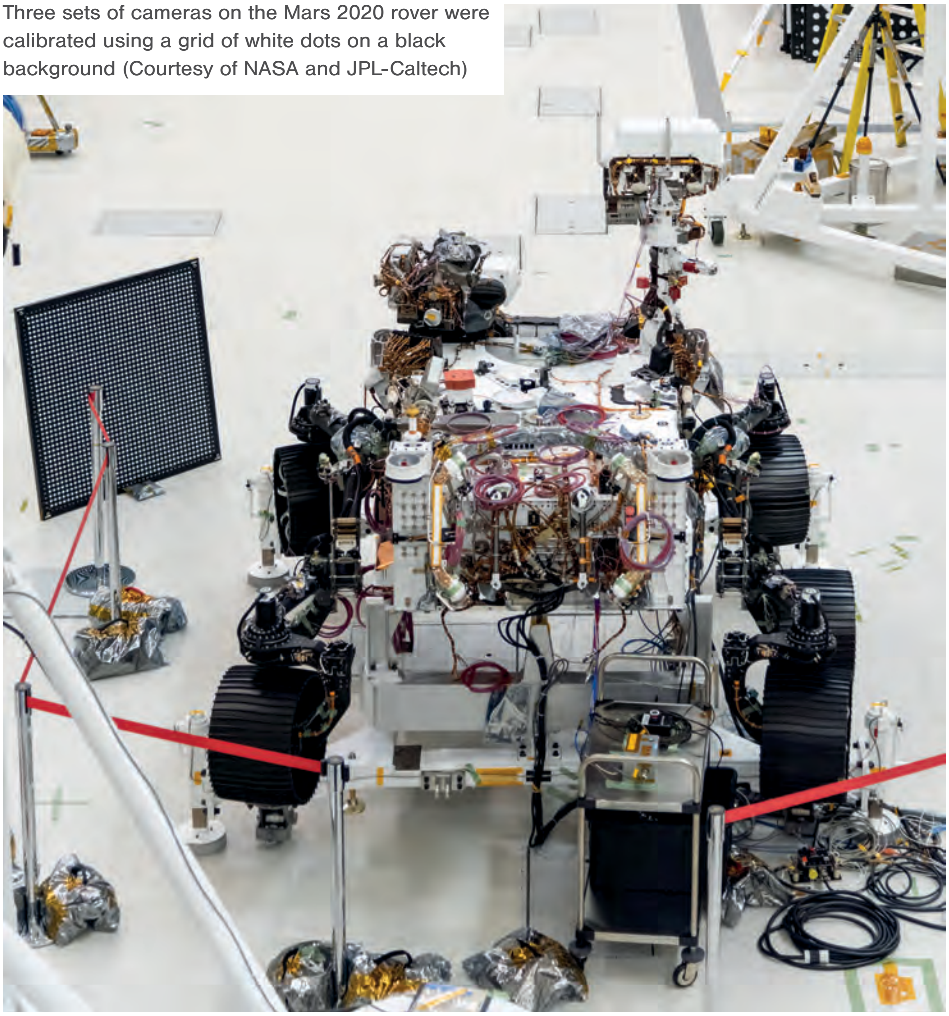
Meanwhile, the ESA's ExoMars rover (now named the Rosalind Franklin rover) has been completed. Current plans are for it to be launched at about the same time as the Mars 2020 rover next July, using a launch vehicle from Roscosmos, an ESA-developed carrier module and a Russian lander module.

The Rosalind Franklin weighs about 300 kg and carries a 1.14 kWh lithium-ion battery, which will be recharged during operations by a 1.2 kW solar array.

As maintaining a consistent data link with the rover is unfeasible, it has been designed with autonomous navigation capabilities.

Two pairs of stereo cameras– its NavCam systems atop its mast, and LocCams at the mast's base – will be used to build a 3D map of the surrounding terrain. The map will then be assessed by the rover's navigation software to plan routes to destinations specified by the ground controller while avoiding obstacles, with dead reckoning provided by an integrated three-axis accelerometer and gyroscope.

Three sets of cameras on the Mars 2020 rover were calibrated using a grid of white dots on a black background (Courtesy of NASA and JPL-Caltech)



Like the Mars 2020 rover, the Rosalind Franklin has a drill for sampling soils and rocks, as well as an array of scientific payloads for studying signs of past habitability – particularly of the morphological and chemical varieties.

These sensors include an IR spectrometer for characterising bulk minerals and identifying water-related minerals, and a neutron spectrometer for finding subsurface water ice and hydrated minerals. A ground-penetrating radar will also help the latter spectrometer to look directly beneath the rover for ideal drilling and sampling sites.

Another infrared spectrometer, inside the core drill, will observe the walls of the boreholes the drill produces, to analyse the subsurface stratigraphy as well as the distribution and condition of water-related minerals.

The combined material analyses from the various sensors will then be used to interpret the original conditions in which the Martian rock formed.

Conclusion

These programmes show how essential unmanned vehicles are becoming to planting the seeds of industry and human habitation beyond our planet, and for withstanding hazards to keep astronauts from harm's way. With that in mind, space could soon become the biggest growth market for autonomous solutions.

AMZ Driverless originally developed the gotthard for an electric racing season in 2016, and updated the design with systems for autonomy to compete in the 2018 Formula Student driverless season, which it won (Images courtesy of AMZ Driverless)

The driverless version of this Formula Student electric racecar has proved impossible to beat. **Rory Jackson** looks at its development

Autonomous ruler

Since its founding in 2006, the Academic Motorsports Club Zurich (AMZ) has annually taken part in the various Formula Student competitions across Europe, which are aimed at encouraging innovation and enterprise among student engineers.

In 2017, Formula Student announced a driverless group of racing competitions, and the AMZ Driverless team was formed to design, construct and enter an autonomous racecar in the event.

AMZ Driverless has since won first place in all three Formula Student driverless racing seasons, developing considerable in-house hardware and software (and judiciously selecting third-party components) to power their cars to victory.

While the 2019 season had not yet ended when we spoke to AMZ Driverless, the 2018 season had. Thus the team – specifically CTO Miguel de la Iglesia Valls, automation engineer Hubertus Hendrikx and SLAM engineer Andreas Buhler – were happy to talk to us about their 2018-winning car, the ‘gotthard’ (the team names its cars using lower case letters).

The gotthard was originally designed and built in 2016 for electrically powered racing, and was revived and updated for the 2018 driverless season. Key aspects of the updates included a new high-voltage accumulator, sensors for its perception architecture, and actuators for braking and steering.

The gotthard is a four-wheel-drive, electric open-cockpit vehicle, capable of accelerating from 0 to 100 kph in 1.9 s.

"The 'empty' car weighs about 173 kg, but that's gone up to 182 kg with the weight of the sensors and processors for autonomy," says Hendrikx.

The core objective that AMZ Driverless had to tackle was a 10-lap race, each lap being 500 m long – with multiple straights, turns, chicanes, and hairpins – to be completed in the shortest time possible. The course is entirely unknown to them before the race begins.

The team was told that the left side of the track would be marked by blue cones measuring 228 x 335 mm, and the right side by yellow cones of a similar size. It therefore had to ensure its car would not only drive and accelerate quickly, but intelligently recognise and react to the track markers at high speed.

The chassis is made predominantly from carbon fibre-reinforced plastics, which have a sandwich structure.

"Throughout much of the vehicle, you start with carbon composite on top, then you have a honeycomb-like layer of aluminium, then carbon again underneath," Valls explains. "The three together provide superb strength-to-weight, with the general hollowness of the honeycomb proving especially good for weight reduction.

"For the aero wings we use plastic as the honeycomb material. Where the honeycomb has to be bigger, say up to 20 mm in diameter, we need more rigidity in the material than plastic can provide, so a metal foam filler – aluminium, for its strength-to-weight ratio – was used in the body," he says.

Buhler adds, "The fasteners are mostly steel, as per the rules, and we use air springs with aluminium casings."


The vehicle's chassis is made largely of a carbon-aluminium-carbon 'sandwich'

The sandwich structure gives superb strength-to-weight, with the honeycomb being especially good for weight reduction

The chassis was designed in-house, with the larger sections of the fuselage manufactured at Swiss-German composites company Connova. Smaller sections such as the wings were produced using autoclaves at ETH Zurich, and the base materials were supplied by an unnamed Italian company.

To make the gotthard as aerodynamic as possible, the engineering team used STAR-CCM for CFD modelling. This enabled each component of the car to be simulated individually and optimised for downforce and aerodynamic efficiency. After that, the entire vehicle was simulated and analysed to ensure that the aerodynamic balance of the car – particularly the centre of pressure – was as desired.

"We wanted the centre of pressure to be a bit behind the centre of gravity, to enhance overall stability, and we ran hundreds of simulations during the design process to line everything up correctly," Valls recounts.

"We've also been using ETH's scientific compute cluster servers. They'd run simulations for us in their cluster, which has much higher computing power than you'd find in a typical engineering office," adds Buhler.

The ETH scientific computing clusters are located in Zurich and Lugano, with a total of about 50,000 processor cores made available to researchers and academics for scientific calculations.

Much of the gotthard's architecture has been determined by the rules of Formula Student. For example, all the sensors have to be mounted in protected

The Lidar sensor is a Velodyne VLP-16, mounted beneath the nose of the car

areas in case the car rolls, and these are located mostly around the nose and the centre of the chassis.

"We did however move the Lidar around from where it was originally, in various locations around the front of the vehicle, to improve the aerodynamics based on what our CFD simulations recommended," Valls notes.

Data links

In all, there are three links between the vehicle and its control station.

"The most important of these is the 'safety' link, which is a system supplied by the Formula Student competition authority," Hendrikx explains.

"It's an EU-certified comms link that runs at a constant radio frequency, between 430 and 440 MHz, and if it cuts out, a safety stop in the racecar is triggered."

Sensor data is currently delivered over a 5 GHz wi-fi link. The vehicle used to have an 800 MHz telemetry link that AMZ designed in-house, which would send information such as battery voltages, temperatures and motor performance over an RS-232 interface, but competition rules now dictate that all processing and calculations have to take place on board the car, so streaming telemetry back to the team during races is banned.

> Most important is vertical resolution – we don't need to detect dense objects close by; we need to detect small objects far away

Perception sensor architecture

For perception, the vehicle can use Lidar, an optical vision camera, or both for redundancy. Although the two systems operate independently of each other, and each confers different modes of operation and different advantages on the vehicle, Valls notes that the Lidar is more accurate for this application.

"The Lidar is a Velodyne VLP-16, mounted on the front of the car, right under the nose," Valls explains. "The most important thing was the vertical resolution – it's not that we need to detect very dense objects close by; we need to detect very small objects far away."

The Lidar's algorithmic 'pipeline' for discerning the colour and position of the cones first subjects the incoming steam of point cloud data to a few pre-processing tasks. These are centred on estimating the ground plane, and identifying and removing ground-based points to leave only cone-based points.

The point cloud then passes through a cone detection algorithm. This recovers any cone-based points that have been accidentally removed to make cone colourisation and detection easier, and then check that the points detected do indeed correspond with those typical of cones in terms of height, width and angular resolution.

Lastly, a convolutional neural network is used to estimate the cone colour pattern and thus the direction of the course.

A key advantage provided by the camera is the richer level of colourisation it captures, especially in the first lap. The easier the sensor can tell the blue cones from the yellow, the better the car's autonomy stack can plot its forward direction.

"Our chosen camera model was a Basler 1600-pixel, 60 Hz system," Valls says. "The key thing here was having a camera with a global shutter, which would move and update very quickly – again because we need to perceive the cones at a significant distance while the car is moving very fast."

Three cameras in total are integrated into a housing, with two connected and configured into a stereo arrangement and one working as a monocular system.

The stereo cameras serve to detect cones at close range. To that end they use lenses with focal lengths of 5.5 mm and horizontal FOVs of 64.5° for optical accuracy at close proximity.

The monocular camera is intended for medium-to-long range cones

The vision sensor is mounted atop the 'driver's' seat, in the roll hoop, to ensure the highest and therefore greatest FOV while still keeping it in a reasonably protected space where it won't affect drag

Exploded view of the camera sensor's architecture

(particularly between 7 and 15 m away), and integrates a lens with a 12 mm focal length and 54.5° horizontal FOV.

Each camera arrangement has its own algorithmic pipeline for detecting and positioning the cones.

For the monocular pipeline, points are detected and arranged in 'bounding boxes' (to group them together according to their cone) using keypoint regression calculations. The 3D position of a cone is then estimated via a PnP (perspective-n-point) algorithm.

For the stereo cameras, detected features are matched in corresponding bounding boxes and triangulated to get 3D position estimates of the cones.

The camera unit is mounted in the roll hoop behind where the driver's head would ordinarily go, to give it an optimal field of view by keeping it as high as practical.

In addition to these perception sensors, a laser-based ground speed sensor is mounted between the nose and front wheels. Wheel speed sensors are installed in the wheels, and a steering angle sensor is installed in the steering rack.

The team used a modified version of the YOLOv2 convolutional neural network to help the autonomy engine recognise the colour and shape of the cones, and plot an effective path through them at rapid pace via the vision sensor.

To process all the raw data and output optimal commands to the drivetrain, through an electronic control unit, two CPUs were installed in a master-slave configuration. The slave runs only non-essential software such as processing the monocular camera data, in case of a failure of that system.

The master system is a PIP39 rugged industrial computer from MPL, while the slave system is an Nvidia Jetson TX2. An Nvidia GTX 1050Ti served as the GPU, as such a system is critical for the machine vision software. A small fan, a heat sink and a water block for the CPUs and GPU, as well as an Ethernet switch, were included in the housing design.

SLAM

To localise itself within the course, the main computer integrated the fastSLAM 2.0 algorithm, chosen for its particle filter's ability to provide multi-hypothesis data associations. This was key for compensating for the scarcity of unique landmarks on the cone-marked track.

The SLAM engine required inputs of cone detection (either laser- or vision-based, or both), as well as velocity estimates. The latter of these was calculated using data from the wheel speed sensors, ground speed sensor and the onboard navigation system.

The navigation system uses a spatial dual GNSS-INS from Advanced Navigation, which integrates a dual-antenna system to gather information about the vehicle's heading.

"That heading data is critical for velocity estimation, so maintaining measurements accurate to 0.08° was a core objective for the navigation component," says Buhler.

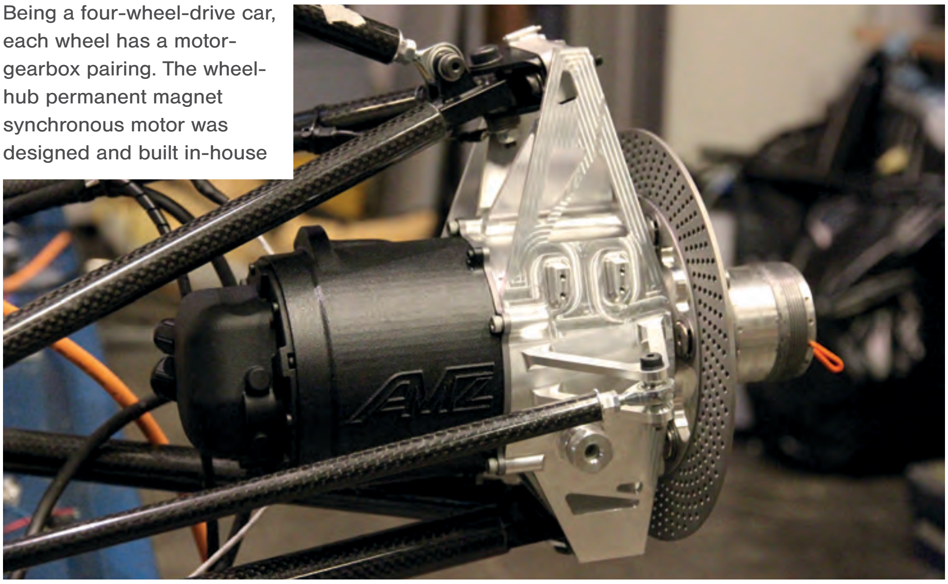
The actual mapping is largely complete after the first lap; after that, subsequent measurements of cones provide no significant improvement. Once the vehicle detects a closure of the first lap (by ascertaining similar cone positions and heading to them at the start of the race), it switches to a localisation-focused operating mode.

This mode is centred on vehicle dynamics control for the remaining nine laps, to get the fastest possible time and eliminate the chances of accidentally hitting a cone. It selects the steering and throttle actions based on minimising key 'cost' variables such as the time taken to progress along the track, the 'slip' of the car and so on.

Power and drivetrain

The gotthard is powered by lithium cobalt oxide battery cells, which deliver energy to four wheel-hub motors.

The key advantage of having two motors in the front – apart from the extra acceleration this provides – is that the vehicle can also decelerate quite hard,



Being a four-wheel-drive car, each wheel has a motor-gearbox pairing. The wheel-hub permanent magnet synchronous motor was designed and built in-house

and thus recuperate energy through regenerative braking.

"While driving normally, we hold off on the brake and just decelerate – and recuperate energy – with our motors," Valls says. "In an emergency we actuate the emergency braking system, which is behind the braking pedal."

For the 2018 season the team redesigned its in-house accumulator to reduce its voltage and energy density, to 420 V and 2.7 kWh. That was to optimise the packaging and to better suit a change in the competition that reduced the length of the longest course it had to drive to 5 km.

The accumulators in the competition are generally designed for high specific energy; AMZ's are about 190 Wh/kg. The charge/discharge rate – which is key for rapidly recuperating energy during braking – was extensively tested to ensure it did not degrade the lifecycles of the battery cells.

Under the front axle is an actuator for steering. That enables the vehicle to steer from full right to full left in 0.9 s. This, along with the drag reduction system actuator and the gearbox, is supplied by Maxon Motor.

"The four wheel-hub motors were built in-house," Hendrikx says. "We're up to our ninth generation of the motors now, and because of the very specific design and performance requirements of Formula Student, ours have among the highest power-to-weight ratios of any ever built."

Each motor weighs 3.4 kg, has an electrical frequency of 1.6 kHz, and is capable of a power output of up to 40 kW. They are permanent magnet synchronous motors, featuring an inrunner (internal rotor) design with 12 magnets made from a proprietary type of neodymium, and five pole pairs on each stator.

"Our inverter has a 16 kHz switching frequency to make sure we have stable control over those motors," Valls adds.

AMZ has also recently designed and produced its own motor controllers, in order to increase the switching frequency towards the limits of what their inverter allows. "For our old COTS motor controller we replaced the cooling system with our own cooling plate, which was lighter and better optimised for our specific cooling requirements," Valls notes.

"We also use an active cooling system of fans and radiators throughout the powertrain, to keep the motor temperature below 80 C." Doing that was critical to preventing the magnets from degrading due to the heat, he adds.

Buhler says, "There aren't a lot of motor controllers configured for Formula Student requirements. It's something of a niche, as you can imagine, and using COTS motor controllers means a lot of compromises, so we developed our own to overcome those. We're now working on the second generation of them to reduce their weight."

AMZ also used a liquid-cooling system for the inverter and an air-cooling system for the accumulator. The temperature field between the two components was very different – for one, the accumulator stops working at just 60 C, as per the rules, compared with the 80 C maximum for the inverter, so the thermal management systems had to be different too.

The maximum powertrain voltage allowed by the competition is 600 V, and within such constraints the team plans to optimise cooling and reduce the size and weight of the inverter to help with thermal management and lower weight.

At the time of writing, the 2019 season of Formula Student's driverless races had finished, and AMZ Driverless had won again, with its new 'pilatus' car. It has the same overall architecture as the gotthard but incorporates iterations of its technologies.

Specifications

4WD all-electric, open-cockpit
Empty vehicle weight: 175 kg
Operating weight: 192 kg
Dimensions: 2943 x 1425 x 1159 mm
Maximum speed: 117 kph
Maximum acceleration: 14.62 m/s^2
Endurance: About 5 minutes (typical track time), 20 minutes (maximum)

Some key suppliers

Battery: Melasta
Navigation: Advanced Navigation
Lidar: Velodyne
Camera: Basler
Composites manufacturing: Connova
Steering motor: Maxon Motor
Reduction motor: Maxon Motor
Gearbox: Maxon Motor
Processors: MPL
Processors: Nvidia

A range of intriguing UAVs and technologies, along with innovative services, were being promoted throughout the InterDrone expo hall

Take five

Rory Jackson returns from the fifth InterDrone expo with highlights of the wares on display there

The International Drone Conference & Exposition, or InterDrone, returned to the Rio Hotel and Casino in Las Vegas for its fifth edition. Nearly 3500 professionals and more than 135 exhibitors attended the 2019 expo floor to showcase their latest unmanned aircraft and commercial solutions throughout the show hall.

Vertical Partners West (VPW) attended the show to launch the prototype of its QBatt family of batteries, which is currently in the early stages of production.

"The QBatt is leveraging our partnership with Teledyne Energy Systems to provide a modular system of batteries targeted at applications such as robotics, materials handling, automation equipment and other autonomous systems," said Keith Wallace.

"The system can be configured according to the user's application, is chemistry-agnostic, programmable and scalable to almost any voltage and capacity."

The Teledyne-developed QBatts are available in two form factors. The first is called the Rigid series, which are built to house cylindrical 18650-type cells and can be scaled from 4S 3P to 14S 3P per pack. The packs can also be combined into modules to provide higher voltages and capacities.

Each pack is rated to IP67 and contained in an extruded aluminium housing that gives the option of using passive or active cooling and heating for extended operational temperature ranges.

The second system is the Prismatic series. As the name implies, it uses industrial-grade prismatic cells, which are also housed in similar extruded aluminium cases and meet the IP67 rating. Busbars have been designed to minimise the number of failure points while lowering the overall DC resistance of the battery.

"We are introducing a 6S and 7S pack built on a 53 Ah and 75 Ah NMC cell, given the popularity and flexibility of the system, although we can easily change to an LFP cell if the customer's application requires it," Wallace said.

"It really comes down to the electronics: without the high level of BMS control that Teledyne's technology allows, this type of system would not be possible. A CAN interface protocol also allows direct comms with the host application and any other required systems."

The company envisions the QBatt Prismatic being used for larger scale applications in particular, in which weight is less of a concern. To help that, the battery is designed to have several of its packs connected in (theoretically) endless series or parallel to create the capacity or voltage needed by the vehicle and application, with the largest system thus far being a 666 V battery for a manned aircraft.

The 7S, 75 Ah pack weighs 12.5 kg and delivers 1.943 kWh for a module-level energy density of 155.4 Wh/kg. The system can be configured in series or parallel without the need for an external master BMS.

To that end, VPW also promoted its BCMS battery management and charging system, which monitors all cell-level voltages, temperatures, currents, states of charge and states of health. It uses proprietary algorithms to use that data to protect against overcharging, over-discharging, temperature fluctuations in excess of the safe operating range and other issues.

Ballard Unmanned Systems displayed the H2-6 multi-rotor UAV, which it has developed in collaboration with UAS manufacturer BFD Systems as a platform for the former's liquid-cooled hydrogen fuel cell.

"It's a prototype hexacopter aircraft, and two of the six arms on the airframe body feature cooling fins that work to dissipate the heat from the 1.2 kW fuel cell stack installed in the hub," explained Phil Robinson from Ballard.

"The air pull of the propellers cools the liquid as it runs outward from the hub, before the coolant runs back towards the fuel cells to counteract the 1.2 kW of heat they're also generating. There was initially a tiny bit of thrust loss but we tuned the electric motors to compensate for that."

The earlier designs of the demonstrator had cooling jackets and fins on all six arms, but the company found it could save 250 g of aircraft weight by removing four of them, while keeping approximately the same effectiveness of thermal management. De-ionised water usually acts as the coolant, although methanol can be added for operations in sub-zero environments to lower the coolant's freezing point.

Currently, the demonstrator carries a 4.7 litre tank of compressed hydrogen gas, and can also hold up to 2 kg in payload weight within a 15 kg MTOW, with a maximum flight time of 90 minutes.

"The core fuel cell technology has remained largely unchanged from last year," Robinson said. "The most recent major upgrade involved integrating some of our membrane electrode assembly technology into what was previously the overall Protonex system.

"Going forward, we're looking to develop the technology surrounding the fuel cell, such as the tank, the regulator and the refuelling system."

To that end, Ballard also displayed its new refuelling rig, which was custom-designed by UK-based NanoSun as a flow-reducing filling hose to prevent the build-up of heat that typically occurs when hydrogen gas rushes from its storage vessel into a fuel tank. The device gradually fills a 4.7 litre tank over 20 minutes, avoiding any thermal damage to internal components such as the pressure vessel liner or regulator.


The Ballard-BFD H2-6 fuel cell-powered UAV

Hitec showcased the Endurance UAV from Straight Up Imaging, a UAV that the latter company has designed for a range of users including first responders, construction companies and oil & gas surveyors.

"The aircraft can carry a 1 lb [454 g] payload for about 40 minutes, which is notably higher than the average," said Eric Maglio from Hitec. "The power system has been optimised for the size of the Endurance quadcopter. For example, the electric motors and

DroneInch's software is designed to improve agricultural surveys

propellers have been carefully selected for energy efficiency, but most important is optimising the weight.

"The battery is the heaviest object on the airframe's body. Straight Up Imaging cut weight from the hull and from all the wires and other peripherals as much as possible, to dedicate the extra empty weight to carrying a small camera for as long as possible."

Several design iterations, prototypes and multiple rounds of flight tests were carried out in order to balance and optimise the different objectives of the Endurance's development programme. The aim was to ensure that the modelling and calculations by the design team were proven correct in the real world before offering the UAV to the public.

"We've also adopted a higher voltage power system on this than you'd find with most commercial UAVs of this size – 25 V DC on a lithium-ion battery to be specific – whereas you don't usually find anything higher than 15 V, unless it's a larger or older system," Maglio said.

"That means the current-to-energy output ratio is lower than the industry average, and with a lower current you can use smaller wires and PCBs, saving a lot of weight on copper and silicon."

The Endurance's empty airframe weighs 3.2 kg, and the battery holds about 200 Wh of energy; a smaller pack with 130 Wh is available for those who want to transport the UAV and its equipment by commercial airliner. The UAV also uses the P-DDL encrypted data link from Microhard for telemetry and control, as well as a handheld GCS built in-house for the ground receiver component of the data link.

DroneInch was at the show to explain how it has developed software aimed at improving the autonomy and data gathering of UAVs in agriculture, having identified some critical shortcomings in typical unmanned aerial farm survey operations.

"A successful farming operation requires an ecosystem of geographically separate specialists, including agronomists, bio-scientists and locally distributed field supervisors who know closely how, when, and where problems with different crops can be found," Srivatsan Desikan explained. "An effective drone survey thus requires the ability for all of them to collaborate in the data collection process without needing everyone to travel to the farm.

"Also, most NDVI and other UAV agricultural survey software gives no indication to farmers what altitude or angle to fly at to give the best results."

By consulting with such specialists, DroneInch has designed its software to enable farmers to input key variables such as the crop to be surveyed, the time of year, the amount of cloud cover and the approximate geographical location of the field. The UAV's flight automation software will be updated with the correct flight path, altitude, angle and speed at which the fruit or vegetables should be photographed.

For example, strawberries will typically be surveyed from 7-8 ft above, while orange trees would be surveyed from 40 ft.

Data collected during flight is uploaded to DroneInch's cloud data visualisation web portal. Here, the agronomist, bio-scientist and others can view it, perform their own analysis and send a map with prescribed actions to the local farm supervisor.

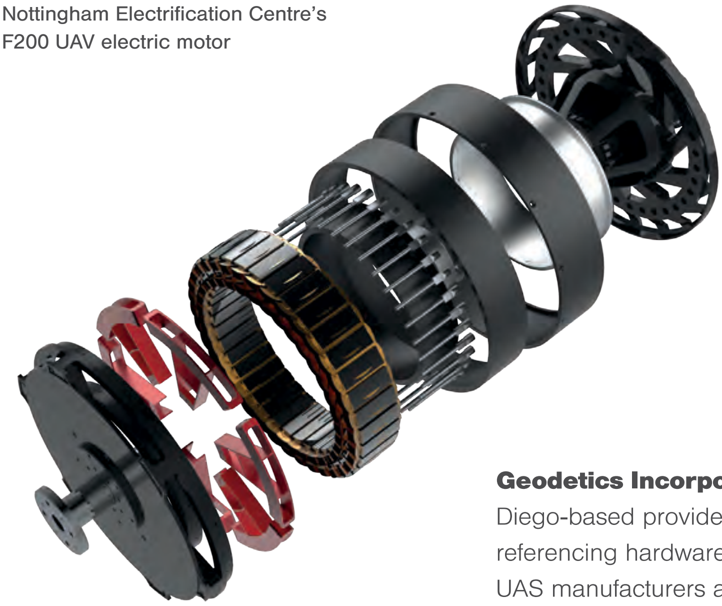
"We collected the best practices from a range of farmers, using our in-house machine learning systems to identify which practices yielded the best results, in order to ensure our software could prescribe the right flight paths for each crop," Desikan said.

"It's very difficult for any one farm to have expertise in UAV operation and how to apply it optimally to every type of crop, but by analysing large quantities of crowdsourced anonymous data in the way we have, our software can provide that expertise and make adoption of UAVs in agriculture that much smoother."

Nottingham Electrification Centre, a spin-off company from the University of Nottingham, in the UK, develops a range of electric motors and motor control systems for UAVs, which it exhibited at the show.

"Our core technology is centred on sensorless field-oriented control, which when compared with typical BLDC motor control methods that rely on a non-sinusoidal square-wave, provides much higher power and energy efficiency. It also generates much less vibration and noise," said Tianhao Wang from the centre.

Nottingham Electrification Centre's F200 UAV electric motor



Geodetics has added new Lidar sensors to its portfolio to provide post-processsing for UAVs

The company's newest and largest electric motor is the F200, so named for the 200 kgf of thrust it can provide at maximum output.

The motor originated from one of the company's PhD projects, and is designed with a dual radial rotor configuration. The stator features two circumferences of copper windings (one facing inwards, the other outwards), enabling the integration of one permanent magnet rotor inside the stator and a second, external rotor surrounding the stator.

That makes the product suitable for coaxial lift motors in heavy-lift UAVs, as it has better power-to-size and torque-to-size ratios than using two electric motors on each multi-copter arm.

The company also uses silicon carbide (SiC) MOSFETs in its motor controllers, the aim being to provide high power-to-weight ratios for meeting UAV design requirements.

"Usually the pole count in UAV motors is quite high, which can mean drive frequencies as high as 1.5 kHz. Combined with regular silicon MOSFETs or high-voltage IGBTs, this makes overall efficiency fairly low," Wang said.

"SiC MOSFETs greatly reduce switching losses and give far better thermal performance, meaning much less current loss from heat."

Geodetics Incorporated, a San Diego-based provider of custom geo-referencing hardware integrations for UAS manufacturers and operators, told us at the show that it has added three new sensors to its portfolio of Lidar options that it can install on UAVs and ground vehicles providing geo-referencing, colourisation, and other post-processing solutions.

"We can now install and work with the Velodyne Puck 32MR, Quanergy M8 and Teledyne Optech CL-90," said Shahram Moafipoor.

"While a sensor distributor would mainly just focus on how to mount new hardware, when we received these new Lidars we focused on developing algorithms in order to take their raw data and process them to output actionable information for end-users. That includes generating .LAS files or combining it with data from our GNSS-IMU solutions to geo-tag and time-stamp points of interest, or colourise them for better visual analysis."

The Puck 32MR has a range of 120 m with two returns per pulse, the M8 has a range of 150 m and a maximum of three returns per pulse, and the CL-90 has maximum range options for up to 176 m when operating at 500 kWh or to 633 m when operating at 50 kHz, and detects up to four returns per pulse.

Luminell was exhibiting its redesigned LED illuminator UAV payloads with integrated batteries. The upgrade was requested by end-users who want to avoid having to find space on a UAV airframe for mounting the illuminator's battery while still maintaining the centre of gravity.

"We designed a bracket on the backs of our different illuminators to hold the user's choice of battery in place, with an elastic strap that snaps on and keeps it tightly there," said Vegard Humlen.

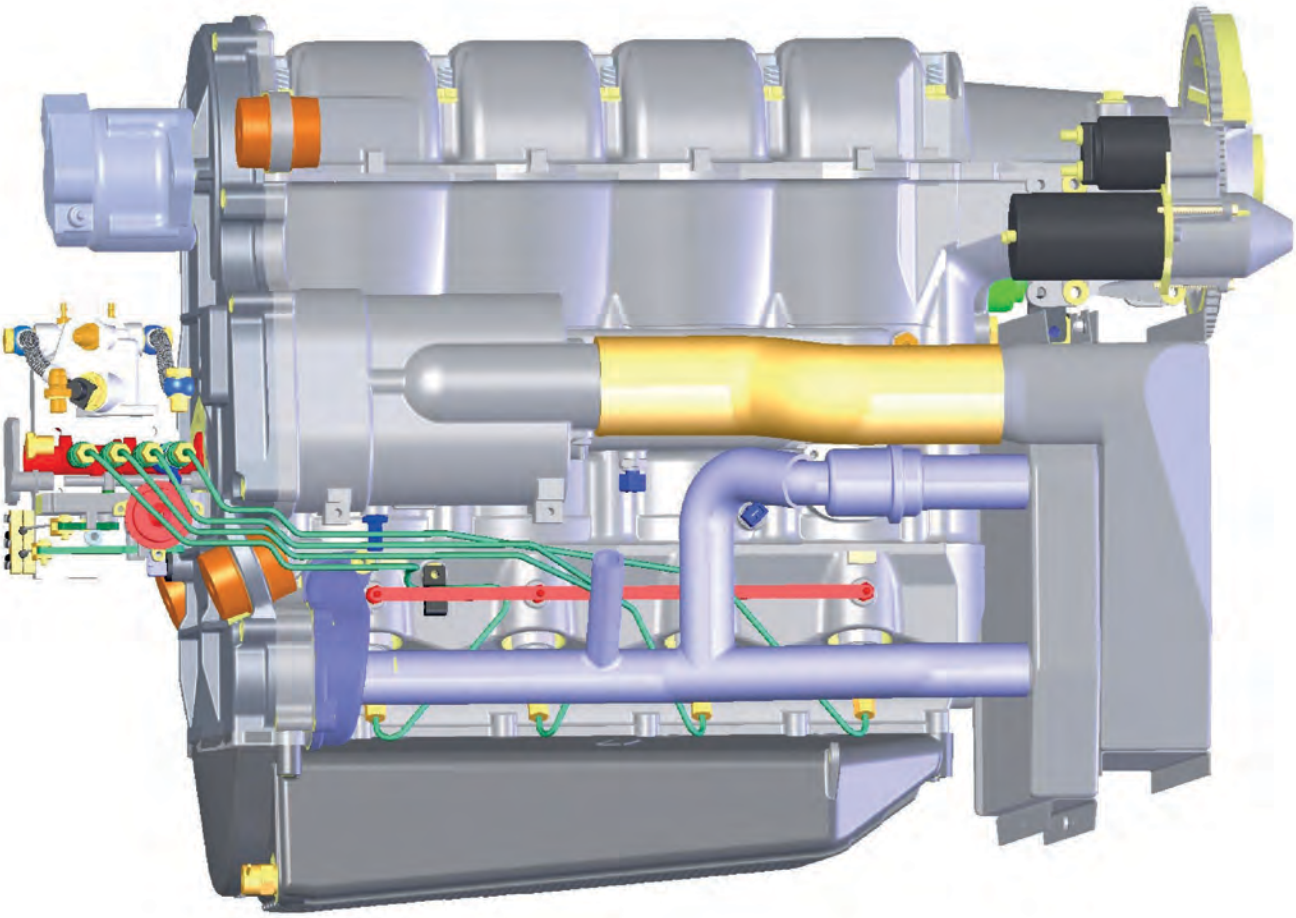
"We save the end-user time and engineering work by making the battery integration for our systems much simpler than before. The centre of gravity on the illuminators is the same as before as well; we just kept the battery bracket in the middle for simplicity.

"Luckily, the previous illuminator designs all had enough unused mounting holes on the PCB in order to fasten the bracket on, making it a one-day job."

The company has also developed a new remote control for the illuminator, which contains a 2.4 GHz transmitter to send commands to the illuminator's receiver independently of the flight controller, and which can be pre-programmed with different settings for strobing and brightness. It is designed to be held in one hand, and to date the prototype has been tested to a range of 608 m range for VLOS operations.

The device is based on the same control PCB as on the company's illuminators, with an additional break-out board on top that provides a physical interface and mounting space for the brightness dial, buttons and charging port on the remote control. ◻

The WAM-167BB is a four-cylinder two-stroke diesel engine with uniflow scavenging, indirect fuel injection, and an integrated turbocharger and supercharger (Images courtesy of Apple Tree Innovation)



Rory Jackson reports on the development of this two-stroke diesel and the advantages of its inverted engine block

Top-down approach

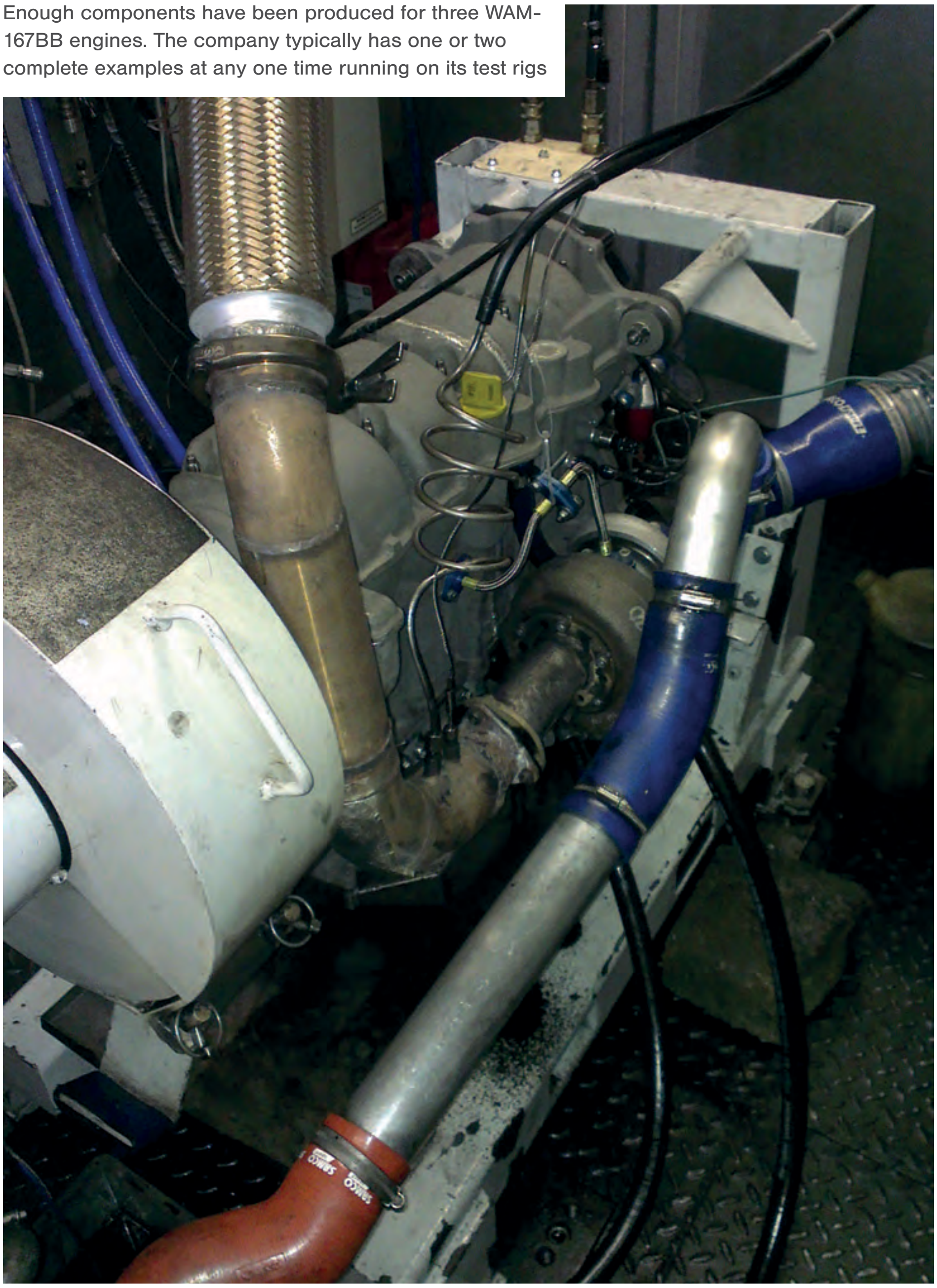
Apple Tree Innovation (ATI) a company based in Cheshire, UK, oversees the development of the WAM series of engines, which were previously best known for the WAM-120, a three-cylinder uniflow-scavenged two-stroke diesel engine for light recreational aircraft. Originally conceived by Mark Wilksch of Wilksch Airmotive (who has since left to pursue other engineering projects), ATI acquired the company in the mid-2000s, with an eye to developing a more commercial-grade (or potentially military-grade) version of the WAM-120.

These efforts have resulted in the WAM-167BB, a 3.0 litre inline four-cylinder uniflow scavenged two-stroke diesel engine version for UAVs and light aircraft requiring multi-fuel capability.

The engine incorporates several interesting design features that have remained consistent throughout all four WAM versions (including the WAM-100 LSA for light sport aircraft, and the WAM-125BB as the first next-generation design).

Most notably, the WAM engines are designed with an inverted engine block. This arrangement places the crankshaft at the top, and the cylinders and pistons underneath, although with the sump still at the base.

A key advantage of the inverted



Enough components have been produced for three WAM-167BB engines. The company typically has one or two complete examples at any one time running on its test rigs

crankcase is that the propeller can be kept further from the ground more easily while being directly driven, compared to a conventional (automotive) crankcase design (reducing damage from grit and gravel during take-off and landing).

This inverted configuration means the pistons thrust up into the cylinders. Also, the uniflow scavenging system means there are air ports around each cylinder, which are opened and closed by the passage of the piston, and poppet valves at the bottom of each cylinder, actuated by a camshaft near the bottom of the engine, above the oil sump.

As the name indicates, uniflow scavenging has gas flowing in one direction only – downwards. Charge air enters through the air ports, and exhaust gases are drawn out through the poppet valves at the end of the combustion stroke. Induction is forced via a turbocharger-supercharger combination, with an intercooler positioned between the two to cool and densify air going into the engine.

"Its currently-rated top speed is 2750 rpm, with 167 hp [124 kW] as its maximum output power," says Mike Newton, director of ATI.

"There's no gearbox or clutch needed to drive the propeller since it's designed as a direct-drive system; we wanted to eliminate as many potential failure points as possible.

"On a lot of engine designs, the clutch can slip a bit on each firing pulse, so there's a real risk that something will wear out or break eventually, but that's eliminated with a direct drive."

In addition to the mechanical simplicity this entails – Newton estimates four man-hours to strip the engine, and four more to reassemble it – having no transmission or gearbox parts also meant saving weight, another key objective over the original design.

The engine assembly and main radiator together weigh 118 kg; another 30.4 kg in total can be added by extra cooling units, hoses, a propeller (and nuts and washers for it), fasteners and through-bolts, and a straight exhaust pipe. Oil and coolant add a further 5.6 kg and 4 kg respectively.

Cast LM25 aluminium alloy is used for the engine block, before it is heat-treated and machined to the specified measurements.

"We've succeeded in making this about 80 kg lighter than engines of similar power output out there, which gives any UAV using it another 80 kg of payload capacity or 80 kg of fuel," notes Phil Franklin, chief engineer at ATI.

The WAM-167BB measures 914 mm at its longest, 528 mm in width and is 657 mm tall, with the centre of gravity between about the third and fourth cylinders, in the upper-rear of the system.

To further improve simplicity and lightness, every WAM engine has incorporated indirect injection (IDI) in its fuelling system.

"We could certainly integrate direct injection if an end-user requested it, which would probably reduce fuel consumption by 5%, but you'd be carrying 20-30% extra weight when you account for the extra complexity and

The company's original engine was the WAM-120, a three-cylinder unit produced mainly for light sport aircraft, with many of the same design points as the WAM-167BB

The original engine used a 'pepper pot' type of pre-combustion chamber; this has since been replaced with a chute-type pre-chamber on the Gen 2 WAM engines

componentry designed into the engine," Newton adds.

"Comparing SFCs [specific fuel consumptions] is only part of the story, though – it has to be something like a fuel consumption-to-weight ratio."

As Franklin explains, "A direct injection version would almost certainly require heavier steel (rather than aluminium) pistons to survive the thermal and pressure loading on such a highly rated engine. These have a knock-on effect on the internal balance masses, together with the mass of electrically actuated injectors, sensors, high-current wiring harness, dual [redundant] ECUs and higher capacity dual [redundant] batteries and brackets, and so on."

IDI also means it can run on different fuels. As well as diesel, Avtur and JP-1, the company has successfully tested heating oil, kerosenes and a few biofuels.

"It's particularly challenging for a direct injection fuel pump handling kerosenes to survive anything less than the most perfect Jet A-1; battlefield environments aren't exactly rich with that," Newton notes. "But whatever you're using for tanks, helicopters and jets, you can use in the WAM too."

Second-generation WAM engine

The original engine was a 120 hp (89 kW) inline series dual-charged triple-cylinder two-stroke, aptly titled the WAM-120, and commonly referred to by ATI staff as the first-generation (Gen 1) engine. That engine had been widely used in light recreational aircraft for many years since its inception in 1997 and first flight in 1999, being issued as a 'kit-built' aircraft diesel engine.

"While it worked well and met all the performance criteria of that application, our goal was to get it to a 2000 h TBO, taking it from a recreational system to a more commercial-grade one," says Newton.

"With proper maintenance, that engine was capable of up to 1000 h between overhauls, but the bigger aim of doubling the TBO is what spurred the development of the Gen 2 design qualities – what we call our 'big bore' engines."

The core aspect of the bigger bore involved widening the Gen 1's cylinder by 7 mm, in order to increase the ratio of power generation to cylinder pressure within the existing bore spacing.

Another key design change was spurred by a peculiar defect in the original pre-combustion chamber, which has been subject to an in-service replacement programme but never solved, despite hundreds of hours of investigation and considerable assistance from Engine Developments Ltd and Cranfield University, in the UK.

The original 'pepper pot' type pre-chamber would sit in the cylinder head. At its end, a series of holes would spray burning fuel up into the firing end of the combustion chamber, onto the face of the piston as it closed its compression stroke (with a chamber formed in the piston crown, the floor of which was formed by the head flat).

The IDI pre-chamber which ATI has since switched to has a single, tangential chute-like hole, which imparts a tangential velocity (or swirling motion) on the ignited fuel-air mixture, entailing a complete redesign of the pre-chamber body and injector. The pre-chamber is installed just to the side of the cylinder, rather than under it. The piston crown now has a different chamber, and the head has also been revised to fit the redesigned pre-chamber body.

ATI weighed up redesigning the engines with stronger, specialised materials, coatings and heat treatments, but eventually determined that it was better to replace the pepper pot pre-chamber with the chute-type on the Gen 2 engine.

Previously, the WAM architecture had a piston that was free to rotate around the cylinder axis, using a spherical joint to the con rod, but the chute pre-chamber required a stable receptacle, and rotation was no longer permissible.

As Franklin explains, "The surface [bearing] area of a spherical joint can be appreciably higher than that of a gudgeon pin, and is hence suggestive of a more robust joint – which in practice actually turned out to be incorrect. Several other engines and air compressors have used the layout, however.

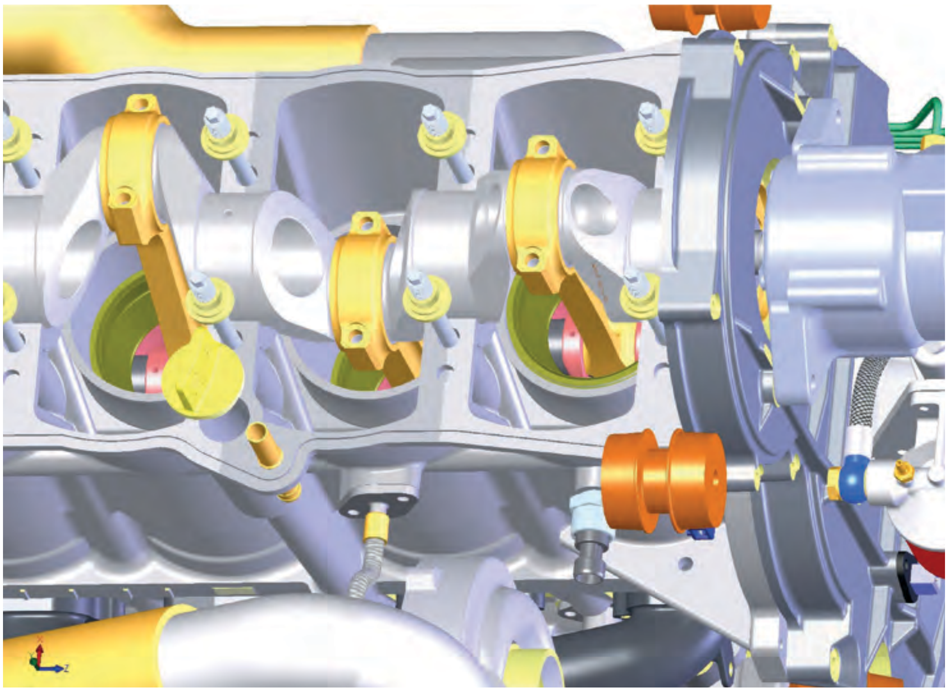
"So we went from the spherical connection to a more conventional gudgeon pin con rod, which is made from EN40B nitriding steel and has a split-cap big end," Newton comments.

In the interest of adding a further 40 hp, a design was generated that added a fourth cylinder to the rear of the standard engine. The architecture was designed from the start to be modular, to enable a series of longer and more powerful versions to be produced.

"We could easily explore a six- or eight-cylinder version with 300-400 hp, maybe inline or even a flat-six or flat-eight configuration if the right opportunity arises," Franklin says. "The standard, fully inverted piston arrangement is more challenging to model and engineer than a horizontal piston pack. We've done plenty of simulations, and it clearly works."

The first updated version of the engine to be put in metal was the three-cylinder WAM-125BB. It proved far quieter, more reliable and with less vibration than its predecessor as a result of the bore, pre-chamber and piston joint changes. Although that engine has not gone into full-scale production, it underwent thousands of hours of dyno testing and test stripping, with the first run in March 2008.

Once the WAM-125BB was tested and



The first-generation WAM design used a spherical joint between the con rod and piston, which has been phased out in favour of a standard gudgeon pin joint

proven sound, further development work followed, with the four-cylinder WAM-167BB project starting in 2014. "It was about a nine-to-12 month exercise to create a four-cylinder proof-of-concept prototype, with the proof-of-concept testing on that first prototype being completed by the end of 2014," Newton recounts.

Enough parts and components have been machined for three WAM-167BB engines, with typically one or two at a time running on the company's test rigs. More than 2000 hours of testing have been conducted to date.

"We consider 160 hp or above to be more viable commercially for a full production engine than 120-125 hp, particularly for the UAVs that would use it. The 167 hp on the WAM-167BB is a conservative figure; we may well revise that to 180 hp in the future," Newton notes.

"The underlying technology has also long been proven on the Gen 1 engine. We've changed the bore, pre-chamber and piston joint, and added a cylinder, but tests have shown that the Gen 2 hits all the targets for power output, SFC and so on that we'd hoped for.

"At the time, it meant a 30% increase in manufacturing cost – and that wasn't from simply adding an extra cylinder. Time had passed, the 2007 financial crash had been and gone, and so many parts were different and not being bought in similar volumes, but it gave us a 40% increase in power output."

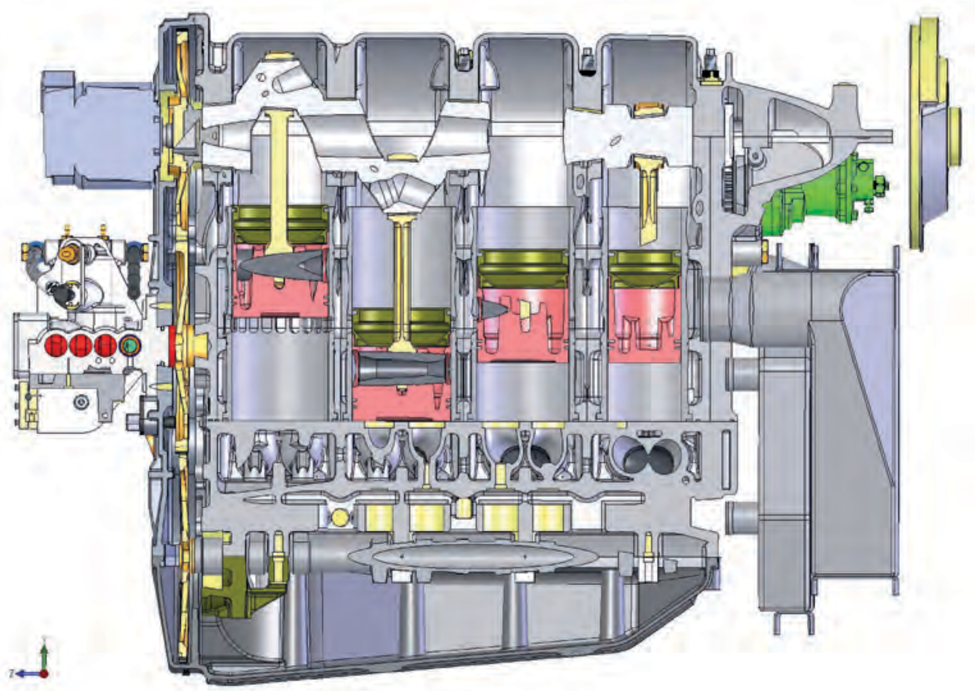
Engine performance

The power band of the engine encompasses an 'economy cruise' mode and a maximum continuous power output rating.

The former produces 82 kW of power (110 bhp), and 325 Nm of torque, at an engine speed of 2400 rpm. The latter works at a speed of 2560 rpm while outputting 100 kW (135 bhp) and 375 Nm of torque.

The naming difference between the two is explained by comparing their SFCs – 240 g/kWh at economy cruise speed; 250 g/kWh at maximum output.

As mentioned, peak output is achieved at 2750 rpm, which gives 124 kW (167 bhp) and 433 Nm of torque for up to five minutes, for all-up weight take-offs and potentially for use as an escape velocity or pursuit speed.



ATI has developed the WAM-167BB with the aim of a four-cylinder engine producing a more commercially desirable power output – currently 124 kW at maximum power rating

As Franklin notes, however, "The actual power rating we'll give a manufactured engine will very much depend on the user and how arduous their intended duty cycle is. In performance terms, we've proved that the cylinder architecture is well-capable of more than 150 bhp on the three-cylinder engine, so more than 50 bhp per cylinder. But it's all going to depend on the structural durability required for that particular application.

"Alongside that, there are some proprietary material changes that we can make which will give the higher power output, but they're more expensive. If a user is willing to pay, we can put the more expensive material in to enable the engine to handle the higher loads of the higher power capability."

A mechanical control unit (MCU) provides a 'power lever' for controlling and stabilising engine fuelling (this being a diesel engine, the power output is almost directly proportional to the fuel input). As well as that lever/actuator, there is a 'stop' lever for (immediately) shutting down the engine if there's a problem.

Both levers are linked to a 'rack' control rod in the fuel pump, the power lever via a sprung link that also incorporates a linkage to a pneumatic actuator, giving an engine speed governing function for idling and low-speed operation.

The stop lever is directly linked to the rack in the no-fuel direction. The rack itself is sprung in the 'full-fuel' direction so that failure in the system results in maximum power, with an override capability to reduce power and stop the engine being retained by the stop lever. As the standard configuration of the WAM-167BB comes without an ECU, all the key timing functions of the engine are factory (mechanically) set on build.

The 840 mm crankshaft, for example, is CNC-machined, from EN40B nitriding steel, with 90° crank pin angles so that the first cylinder fires at one-quarter turn, the second at half-turn, and so on.

The crankshaft notably features six multi-layer plain bearings – one between each cylinder, one either side, and one bearing further on the front for the propeller governor. The big-end bearings are also plain multi-layer shells running on the crankpins and held in the horizontally split big-end eyes. All the bearings are pressure-fed with oil.

As mentioned, the fuel is injected into a pre-combustion chamber beneath each cylinder. Although injection timing is also factory-set, with injection pressure fixed at 300 bar, the company has declined to disclose an injection angle (or angles) for the chute or injection timing.

The fuel flow valve on the fuel pump is entirely mechanical, and is controlled through a governor. The company is aware though that some commercial and most military UAV operators would probably want to control the fuel pump electronically to provide bespoke power bands, rates of response, optimise the SFC or other factors. And being a compression-ignition engine, no throttle is used of course.

To that end, ATI has deliberately kept to relatively simple mechanical controls, leaving the architecture open for end-users and their engineers or preferred suppliers to design their ECUs according to their mission-specific requirements, or for them to request that of ATI.

As Franklin says, "It's relatively easy, if a customer requests it, for us to write an algorithm for an ECU that will swing the power lever or stop lever to reduce or stop the engine power when needed."

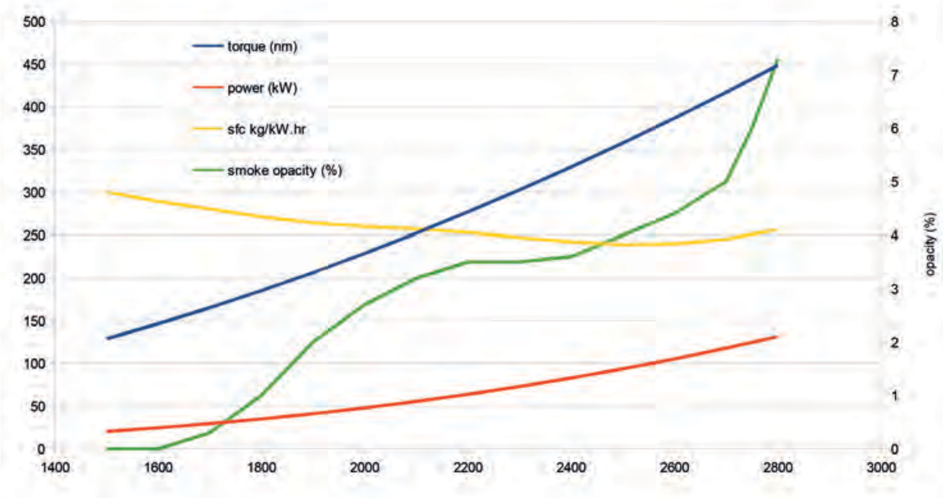
The air-fuel mixture during flight will typically vary between 18:1 and 50:1, from highest to lowest operating power output (and if no fuel is injected, the engine stops of course).

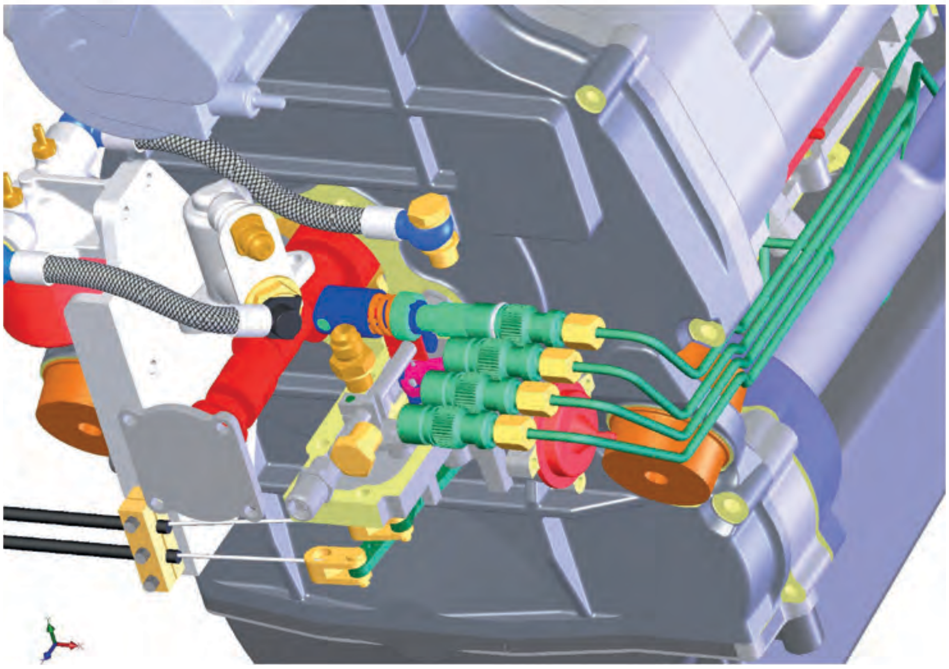
Engine operation

A 2.5 kW starter motor on the forward lower-right of the crankshaft provides initial power for turning the crank, via a ring gear on the forward counterbalance, with minimal counterbalancing designed along the shaft itself. A Roots-type twin-rotor supercharger provides initial air compression before the turbocharger can activate.

On the back end of the crankshaft is a timing drive gear. As the crank turns, the gear interacts with a second gear of equal size and shape – 20 cm in diameter with 113 teeth – which controls the fuel pump. The gear

Performance chart for the WAM-167BB





The engine has a mechanical control unit on the back, which has levers for power output and stopping the engine, both of which are linked to a 'rack' control rod in the fuel pump

also provides the rear crankshaft counterbalancing. A third, 113-tooth gear below it drives the exhaust camshaft.

The air intake for the cylinders is achieved by a belt (or ring) of ports running around the circumference of the middle of the cylinder liner. A total of 18 ports run around each cylinder, with actual airflow coming from the turbocharger (via the supercharger) and flowing into and through the crankcase, before being routed down to the inlet ports.

The cylinders consist of cast iron liners treated using the Laycarb process for wear resistance.

It may seem odd that the cylinders have no reed or rotary intake valves but the WAM-167BB is not a crankcase compression-type two-stroke. Instead, it has long trunk pistons that close off the air ports (except around bottom dead centre) when they are opened to allow scavenge.

With no crankcase compression, a blower is needed to provide positive airflow at cranking and low engine speeds, although the turbocharger 'takes over' and provides all the differential pressure needed once the engine is producing power.

"Many two-stroke diesels have used this same technique, such as those from Detroit Diesel, Electro-Motive Diesel, and MAN Marine & Industrial Engines," Franklin notes.

The fuel pump is installed on the back of the engine, with the MCU attached. The middle gear drives the fuel feed into the pre-combustion chambers via compact injectors, and is responsible for the factory setting of the injection timing.

"Those pre-combustion chambers aren't the easiest thing to pull out and inspect – you have to pull the oil sump off," Newton notes. "But it's a good idea to do that anyway, at every 50-hour service, to wash it out, replace the oil and so on."

The third gear is fixed at the end of a camshaft and provides the actuation for the WAM 167-BB's eight exhaust poppet valves. These have 30° seats arranged in a row down the length of the head, with two at the bottom of each cylinder leading to a bifurcated exhaust port (with one port for each cylinder).

An exhaust manifold runs the length of the cylinder head. It carries the exhaust to a centrally mounted turbocharger turbine and separates the exhaust pulses as far as possible for best turbine performance and engine breathing.

"A single exhaust valve would need to be large to provide sufficient flow area, and that's not easy to design in, whereas two valves fit more easily into the arrangement and provide the area required," Franklin says.

As one might expect, the exhaust cam is driven directly by the fuel pump gear, and thus indirectly by the crank-mounted gear.

"Any timing adjustment of the fuel or exhaust is done by altering the gears and the relative positions of their teeth," Franklin explains. "There are three of those identical gears in total running down the back of the engine, each with 113 teeth. Moving a gear by one tooth means one 113th of 360° worth of different timing, and a Vernier adjustment means we can get to within 0.5°."

While many people are familiar with two-stroke engines that use crankcase compression and valve-less ports for exhaust and air intake, the WAM-167BB has exhaust valves to give an end-to-end or uniflow scavenge arrangement. That leads to better scavenging and hence less contamination of fresh charge air by exhaust products, which is vital to enable high power to be developed from a relatively small and light engine.

Each exhaust valve is 35 mm in diameter, and sits atop a 7 mm stem. The port throat is about 31 mm across, and the camshaft lifts each valve by about 11 mm.

"Each piston obviously has to come up to 'open' the air ports before coming back down for compression and combustion. After combustion, the cam lobes open the valves for the exhaust gas to come out," Newton says.

A system of cam-follower 'buckets' and tappet shims sits between the cam lobes and the valve stems. The exhaust camshaft runs in the cylinder heads, in plain bearings, and is machined from EN40B nitriding steel, hollowed to save weight.

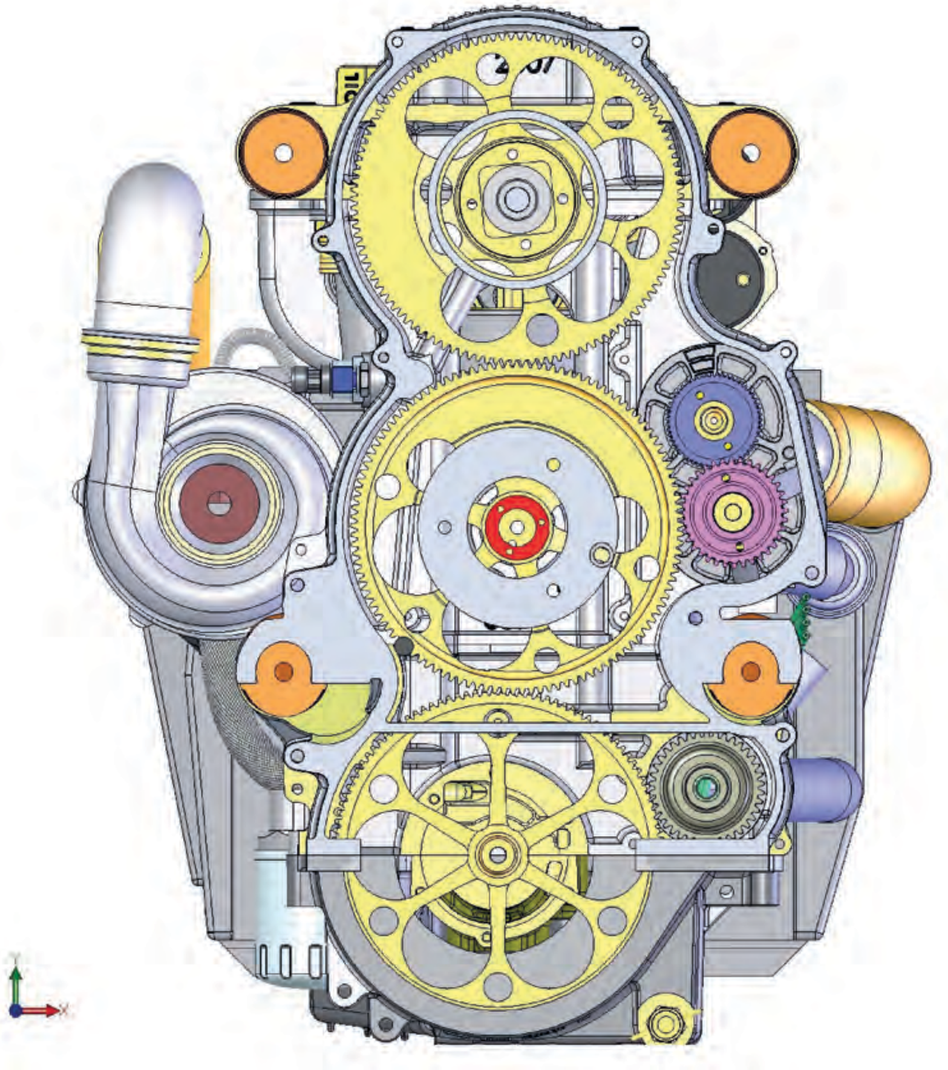
"The Gen 1 engines used Nimonic-headed exhaust valves, but the Gen 2 engine doesn't need the Nimonic, just standard-grade exhaust valve steel, which we found perfectly adequate," says Franklin.

"Given the bigger bore in the Gen 2 engine, we took the opportunity to separate the valves a bit more. By increasing valve separation, we get less heat concentration between the valves and thus better cooling. That was actually what largely eliminated the need for the Nimonic."

"Since the bore was widened by about 7 mm we could have spread the valves 7 mm further apart, but we found 3.5 mm to be good enough for the broader cooling passage we wanted."

The typical operating oil pressure of the engine is 3 bar, provided by a multi-lobe gerotor-type pump installed at the end of the camshaft, and driven by the large cam gear.

As lubricant comes out of the oil pump head, it is sent to an external oil cooler on the UAV airframe, then routed back through an oil filter on the forward lower-left of the engine before going into the oil galleries.



Three timing gears sit at the back of the engine. The top sets the timing for the crankshaft, the middle for the fuel pump (which also drives the supercharger) and the bottom holds the exhaust camshaft (and also drives the oil and coolant pumps)

"The oil galleries carry oil up to the crankcase, which ferries it to the crankshaft and its bearings, to the nose bearing and the prop governor," Franklin explains.

"And there is an oil feed to all the pistons – oil cooling jets squirt oil at the aluminium alloy pistons. Because the pistons are upside down, the oil gets thrown back out and, like the rest of the oil, finds its way by gravity down through drains to the sump."

In technical terms, the engine has integrated a lossless oil system, as no oil needs to be mixed in with the fuel and burned, unlike two-stroke engines with crankcase compression. As Newton and Franklin note, however, as in a four-stroke engine a minute quantity of oil does get past the piston rings and is burned.

Some of the oil lubricates the three large timing gears at the back on its way down before arriving in the sump. Some of that is captured in a small vee-shaped 'catcher' though, to direct it back towards the fuel pump and through the roller bearing carrying the fuel pump shaft, before it continues by gravity down into the sump.

Most of the oil, however, runs through a series of 'drain points' directly or semi-directly to the sump. Because an open wet sump sits just below the camshaft, the cam is easily lubricated by indirect splashing or misting from the pool below, without the need for galleries or pipes running across it.

A wet sump has been used because it generally requires fewer pipes, joints and other components than a dry sump, making the engine simpler.

"If required, however, it would also be relatively simple to fit a dry-sump system, by using a low-profile collector tray at the bottom of the cylinder head, just below the camshaft and pumping oil to an external tank," Newton adds.

The main oil gallery for the engine also feeds oil to the propeller governor through drillings on its mounting flange, for lubrication and for users looking to integrate a hydraulic variable-pitch propeller. The gallery then runs along the left side of the engine and is tapped to provide oil for the turbocharger, with a temperature sensor and pressure sensor inside.

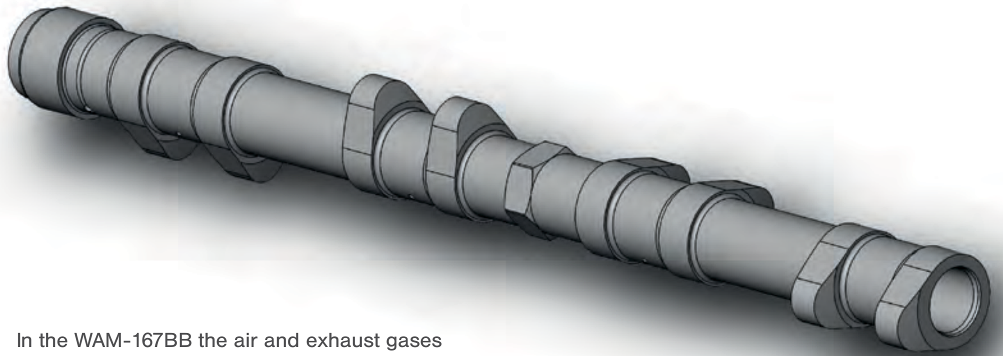
Wherever possible, ATI has sought to use COTS turbo parts, but chose to design and manufacture its own turbine housing after it had determined that there was more weight on the turbine than was optimal for an aircraft engine.

"That housing is integral with the manifold, and is made from thin stainless steel to be both lightweight and strong, whereas a typical COTS turbocharger will use cast iron for that," Franklin notes.

"The bearing system, and the middle and rear section, are COTS. As commercial turbines are designed to last the lifetime of a commercial diesel truck, which is a million miles at an average of 50 mph, it lasts a long time, consistent with our TBO goal."

The supercharger is a bespoke design and incorporates a low-stiffness drive system to enable it to be driven by one of the timing gears. It was created by the ATI design team specifically for this engine, as commercially available units of correct flow capacity were too heavy to allow weight targets to be met.

Although no muffler is provided, the turbocharger takes a lot of noise out of the exhaust on its own, with the expansion path through the turbine suppressing exhaust noise significantly. "We've had a couple of customers who decided to use straight-through pipes and have had no noise issues whatsoever," Franklin says.



In the WAM-167BB the air and exhaust gases flow in a single direction, towards the exhaust poppet valves, which are actuated by this exhaust camshaft

Cooling

A number of different configurations and components have been designed into the WAM-167BB in order to dissipate heat. As mentioned, the exhaust valves at the bottom of each cylinder have been moved further apart than in the previous generations for better cooling, and the oil injected onto the pistons also serves a cooling purpose.

The engine is liquid-cooled throughout, typically using premixed Cool-Elf-Supra (a standard aerospace grade antifreeze). On the front of the engine, mounted beneath the propeller governor, is a water radiator.

The radiator has a broad surface area with a honeycomb matrix of vanes about a network of flow passages, to maximise the area across which the heated water-antifreeze fluid can cool down. The velocity of a fixed-wing UAV, once airborne, provides sufficient airflow over the radiator to cool the fluid, before it is piped back towards the main areas that need cooling.

Of perhaps greatest concern are the fuel injectors, as they are mission-critical components sitting directly next to the area of combustion. A coolant jacket is therefore fitted around each pre-combustion chamber to provide cooling for the injectors.

Given the proximity of the pre-chambers and cylinder heads, coolant pipes run from each jacket between each exhaust valve to provide cooling. Another set of fluid jackets run up and around each cylinder to mitigate heat build-up through the crankcase.

Coolant pressure is provided by a water pump at the rear-base of the engine, which injects the water-antifreeze mixture into the jackets surrounding the pre-chambers and cylinder heads before it runs up into the cylinder jackets.

After cooling the engine block, the fluid comes out of a flange and into a wax thermostat that regulates the flow, sending it to the radiator if it's too hot or back to the pump if not. Should a customer require more sophisticated coolant control, an external inline thermostat can be used.

"Each cylinder's jacket is essentially a tube, which we've designed to be fairly narrow in order to get a high flow velocity, because that greater velocity improves the heat transfer coefficient," Franklin says. "So you get more heat out of the same area."

As mentioned, the engine integrates an intercooler that sits between the turbocharger and supercharger to cool the air from the turbocharger's compressor.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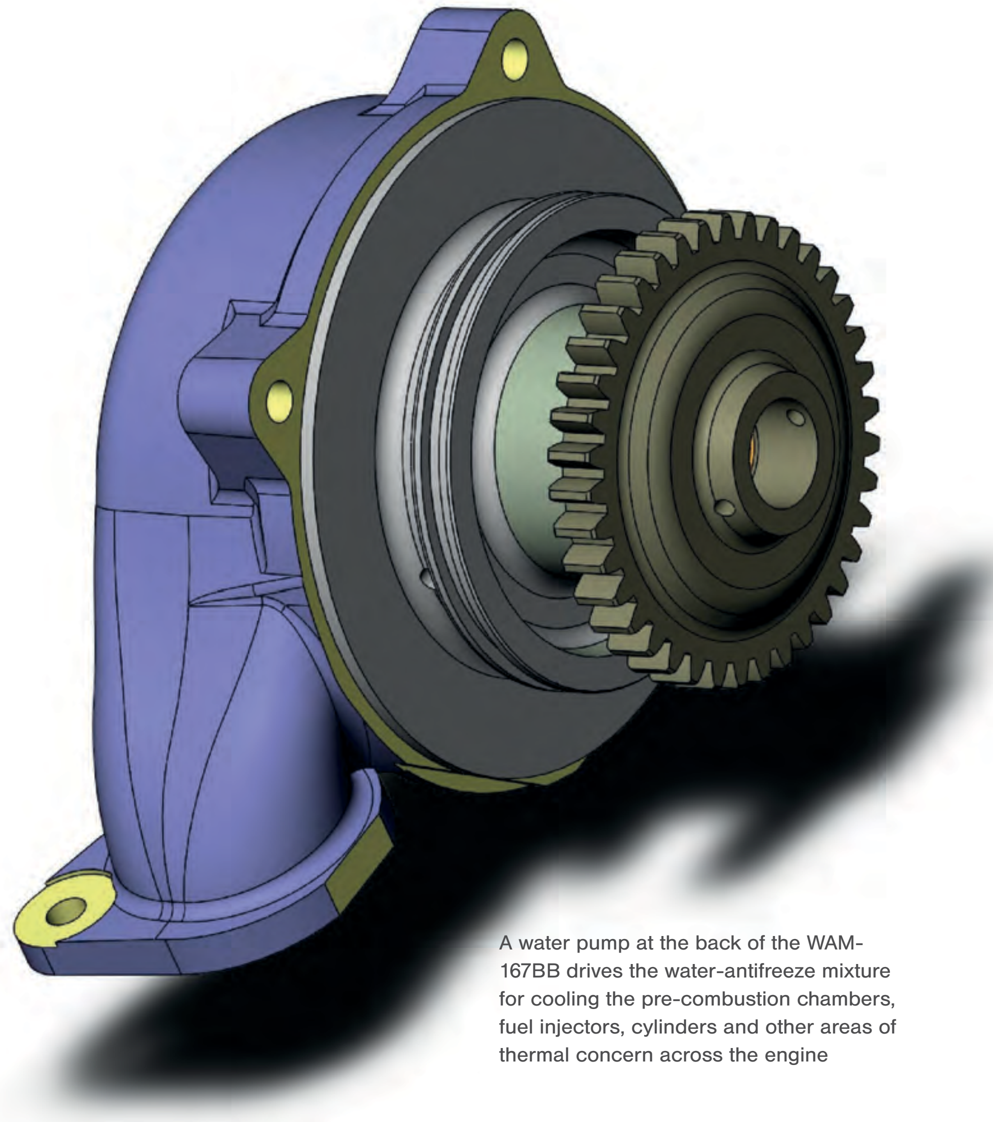


A water pump at the back of the WAM-167BB drives the water-antifreeze mixture for cooling the pre-combustion chambers, fuel injectors, cylinders and other areas of thermal concern across the engine

Future developments

In addition to further testing, to potentially increase the maximum power rating and gauge the engine's performance with a prop mounted, the company is turning towards hybridisation.

"We're particularly interested in developing an independent parallel hybrid of the WAM-167BB," Newton says. "For example, if you combined the engine's output with an electric motor, two to 10 minutes' of extreme power output could be achieved.

"In addition to the obvious redundancy, that could give a far more powerful escape capability, which is key for some users. You might break a motor or severely damage a piston along the way, but you'll still have your UAV and engine back at the shop in largely one piece."

ATI also foresees such a system's redundancy enabling successful returns to base even with one of the propulsion units out of action.

Newton and Franklin see a parallel hybrid system as helping commercial aircraft maintain clean air and quiet operation around airports and urban areas. If approach, take-off and landing can be conducted under electric power, the diesel engine can be used after clearing 8 km of the emissions-restricted area (depending on what distance regulations require) for propulsion and driving the generator to recharge the battery.

With a simplified, lightweight base design, ATI will be able to modify, upgrade and repurpose the WAM engine for a range of potential uses and innovations well into the future. ◻

Specifications

WAM-167BB

Two-stroke four-cylinder reciprocating engine
Twin charged with intercooler
Diesel, heavy fuel, biodiesel
Weight: 118 kg
Size: 914 by 657 x 528 mm
Maximum continuous power output: 100 kW
Maximum continuous torque: 375 Nm
Bore x stroke: 97.5 x 100 mm
= 2986 cc (746.6 cc per cylinder)
Compression ratio, undisclosed
Compression ignition, pre-chamber
Indirect injection
Maximum rpm, 2750

Some key suppliers to the WAM-167BB

Crankshaft: Arrow Precision Engineering
Crankshaft: Farndon Engineering
Con rods: Arrow Precision Engineering
Con rods: Farndon Engineering
CNC machining: CNC Solutions
Camshafts: Kent Cams
Camshafts: Newman Cams
Camshafts: Retro Track & Air
Valves: G&S Valves
Aluminium castings: GPD Developments
Aluminium castings: Aeromet Group
Cylinder liners: Laystall
Propeller governor: Jihostroj
Propeller governor: MT Propeller
CAD/FEA: SolidWorks
CAD/FEA: Advanced Analysis

Bird's-eye view

The head of UAS survey services provider SkySkopes shares his passion for the work with **Rory Jackson**

Having been raised on stories from his grandfather who flew missions for the US Navy during World War II, Matt Dunlevy – the founder and CEO of SkySkopes, North Dakota's first FAA-certified UAS flight solutions provider – was fascinated by aircraft and aerospace engineering from a young age.

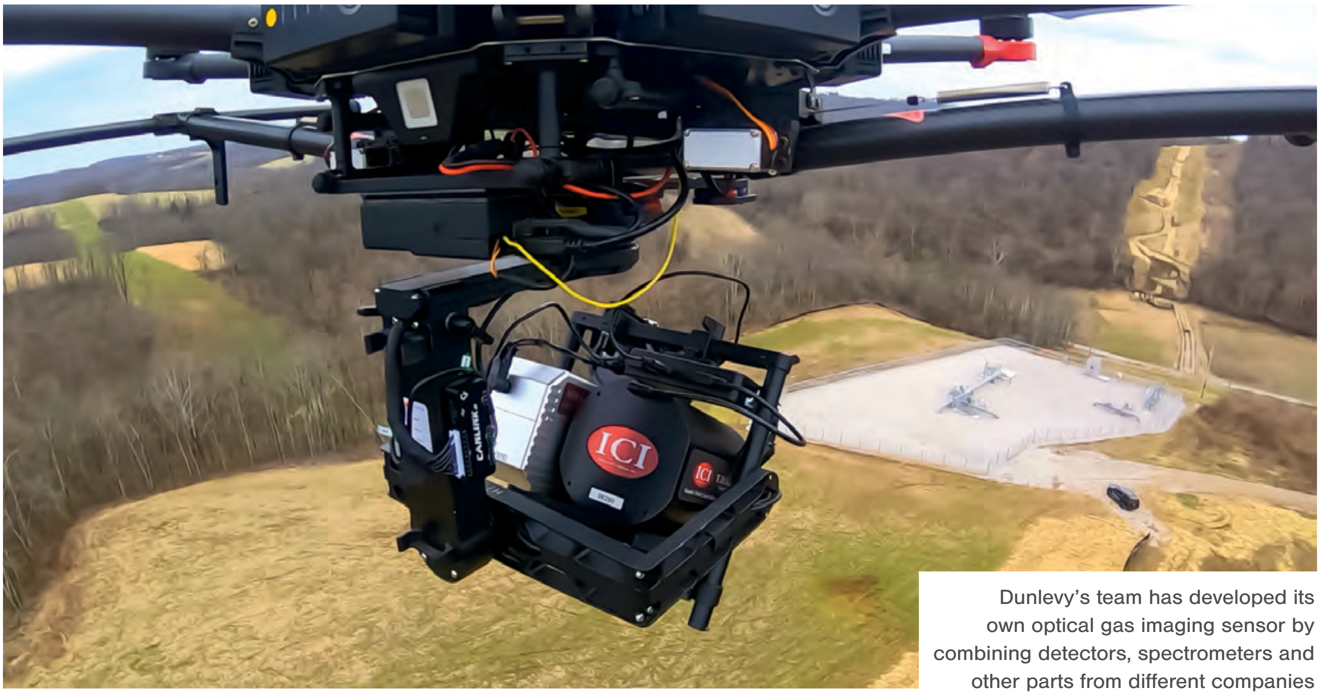
"My first hobby as a kid was constructing plastic model aircraft, and I moved on to gas-powered remote-controlled aircraft not long after," he recalls. "I loved the concept of aerial vehicles being operated and used remotely; back then I didn't think it would become a career, but my passion for all things aviation has never waned."

A few years later, Dunlevy began studying at the University of North Dakota (UND), initially intending to go into commercial aviation. But having already piloted aircraft recreationally for many years, his interest in tinkering with them drew him to enrol in the mechanical engineering programme at UND, with a focus on aerospace.

Towards the end of his university studies, he had read a lot about entrepreneurship, sat in on business-focused classes and developed an ambition to found his own company. He also became involved with the UND's Center For Innovation, which he recounts as having been "a very interesting place, especially concerning unmanned aircraft systems".

"It housed many different UAS start-ups that have gone on to do great things. I was there recently, and I saw a lot of familiar activity, only now with more AI-driven projects aimed at automating complex commercial UAV services.

"Being in the center's entrepreneurial, UAS-focused ecosystem – let alone in North Dakota, with its airfields and



Dunlevy's team has developed its own optical gas imaging sensor by combining detectors, spectrometers and other parts from different companies


The MFD 5000 from Watts Innovations has long been the workhorse of SkySkopes' energy infrastructure operations (Images courtesy of SkySkopes)

unique legislation designed to foster and develop unmanned aircraft – I really couldn't have been in a better place and time to implement the UAV-driven commercial services I envisioned. I felt there was a void in terms of real business impetus to offer the benefits of UAS surveys nationwide, which is why I founded SkySkopes in October 2014."

The 'value statement' that SkySkopes offered was that of providing aerial video-recording services for special occasions and buildings.

"One of our first clients was the Grand Forks County Historical Society, to take scenic videos and photographs of their museum grounds," Dunlevy says. "That was back in the days of the FAA's Section 3.33 exemption, long before Part 107.

"In a lot of ways, that was what got me hooked on doing this for a living. I was witnessing so many unique and beautiful spaces from the ground and the sky, and seeing how UAVs could have a positive impact on society solidified my determination to find long-term, large-scale users for commercial UAVs and the data they could capture."

The company was too far from Hollywood to realistically engage with UAS cinematography projects on a large scale, but didn't want to move, given its proximity to the wealth of expertise and networking opportunities at UND, Grand Forks Air Base and the Northern Plains UAS Test Site.

After conversations over a couple of years with his engineering and aviation colleagues, Dunlevy and his team started investigating how energy industries could make use of UAV survey data.

"To do justice to our engineers and pilots, we had to get into the right industry, in terms of scalability and repeatability of operations," he explains. "One of our first missions in the energy sector was an electrical substation survey for one of the largest electric utility companies in the US, not far from where we were located.

"Back then, a lot of energy companies still had reservations about working with small start-ups, or even regarding working with UAVs at all. But we soon started getting regular work from a utility company called Minnkota Power, and more partnerships stemmed from that."

Demand for Lidar

SkySkopes now offers a variety of aerial survey solutions. The greatest demand is for its Lidar mapping services, in applications such as generating terrain models for vegetation encroaching on power lines and other infrastructure, or producing 3D models of buildings and utility assets to inspect their condition and look for possible points of wear or damage.

"It's absolutely critical to use the best UAV and sensors possible. A huge amount of effort therefore went into picking a heavy-lift platform that would carry the Lidar payloads our business offerings were to be based on, while still being under 55 lb [24.9 kg] to comply with Part 107," Dunlevy notes.

At the time of writing, the workhorse for SkySkopes' Lidar mapping flights – and indeed, for all SkySkopes' missions – is the MFD 5000 from Watts Innovations.

Although it can be customised,

SkySkopes is using UAVs to carry lead lines for power wires onto power poles, a far safer and cheaper alternative than the usual ladder or helicopter methods (Courtesy of SkySkopes)

the typical design of this hexacopter UAV features a carbon fibre frame with an empty weight of 23 lb (without batteries), and is controlled by a DJI A3 Pro or Pixhawk flight controller with a triple-redundant GNSS-IMU. It also integrates data links for pilot control and gimbal operation, and six DJI E5000 motor-ESC-propeller combinations.

For power, the system tends to carry four battery modules, each containing six cells in series with 8-16 Ah each of capacity. These typically give a maximum flight time of 30 minutes and a top speed of 72.4 kph; its payload capacity is 18.14 kg, and it has a MTOW of 34 kg.

The company's Lidar sensor is Phoenix Lidar's Alpha Series AL3-32 scanner, a 3.2 kg package that captures 700,000 points per second. This spec is key to why it was chosen, as the density of the point cloud directly correlates with the detail and accuracy of a data set, and thus how 'actionable' it is by the engineers or other workers in charge of the energy assets being surveyed.

The AL3-32 has a maximum range of 120 m, and is accurate to 55 mm at 50 m range. It is designed to scan over a vertical FOV of +10º to -30º, and over a horizontal FOV of 360º, although on SkySkopes' MFD 5000 the sensor is 'tilted' 90º forward in order to generate a 3D cloud about the UAV's flight path as it travels forwards.

"We use that in tandem with a 24 MP EO camera, to generate RBG colourised point clouds – this is really where I feel autonomy comes into its most crucial use-case," Dunlevy says. "We've gone through a lot of different autopilots, from DJI, Pixhawk and others, and different GCS software to match those, but really they all boil down to planning and executing the autonomous flight profiles that the missions need.

"The Lidar missions are 90% autonomous, and the UAV needs to follow precise 'lawn-mowing' waypoint patterns in the air, or down-and-back corridor flights. The data generated from those flights and technologies are what the energy companies need. They're insatiable when it comes to Lidar data, and are always looking for improvements in how it's collected."

Musing on some of his team's proprietary processing capabilities, he says, "Even after in-field processing through fog computing – with LTE links to move packets of data back and forth between the GCS and the edge-computing processors – AI can increasingly be applied during post-processing to detect and remove faults, and apply refined analytics to reveal more useful information for the end-user."

The newest survey offering from SkySkopes is the use of optical gas imaging (OGI) sensors, for oil companies concerned about leaks (or 'fugitive emissions' in industry jargon) of hydrocarbons from their pipelines and oilfields that cannot be clearly detected or quantified using most thermal sensors.

Rather than use a COTS sensor, SkySkopes has built its own OGI package by integrating several technologies. These include thermal and OGI components from Infrared Cameras Incorporated, laser spectrometers and an EO camera for added visual context in surveys.

The result is a system that collects radiometric temperature data in 640 x 512 resolution, and offers an 'enhanced mode' to clearly depict gas leaks in real time as the MFD 5000 flies.

"We were first introduced to OGI while working in Minot, ND, where there was a grant programme that funded companies to acquire equipment that would expand their capabilities," Dunlevy says. "Since our core capability is data capture, we applied to the programme for an OGI sensor, which resonated with city officials who wanted more UAS activity in Minot and improved surveys of the Bakken oilfields.

"That sensor is flown in a similar way to the Lidar missions, albeit at about 75-100 ft, around 125-200 ft lower than the Lidar. Since end-users tend to want to zoom in on leaks in real-time, however, the payload tends to be controlled manually, with the flight itself being handled fully autonomously."

Since 2017, the company's

UAVs have also been integrated (via a proprietary interface) with ultrasonic sensors for obstacle avoidance in most of the flights. If these systems detect that the craft is too close to the ground or a structure, the flight controller can be preset to override the GCS and automated flight path, and veer away.

Pulling power

Dunlevy makes particular note of his company's new 'line-stringing' capability, which was publicised earlier this year after a successful mission for power line company Xcel Energy.

This solution involves using an MFD 5000 to help lift electrical wires onto pylons. As Dunlevy explains, "We use the unmanned aircraft to carry a lead line – a rope that's smaller and lighter than the potentially dangerous conductor wire – and string the lead line into a fixed pulley on the power line tower, so that the lead line can then be used to reel up the electric cable."

Statistics estimate that at least two people a year are killed in the US alone in accidents relating to the conventional method of line-stringing, which typically involves a crew on a helicopter or using a ladder or cherry-picker. Using UAVs avoids the operating costs of helicopters and cherry pickers, and the need to lift utility workers to precarious heights.

As these missions take the MFD precariously close to utility infrastructures, several eyes on the ground are present at all times, and a second UAV – a Firefly Alta 8 – is flown simultaneously to provide the operator with a second aerial vantage point.

That 'support craft' has an MTOW of 18.1 kg, and its arms and props can be folded to a diameter of 66 cm (from its 132.5 cm operational diameter) for easier transportation in road vehicles to power line sites. Each of the eight props is driven by a Freefly F45 motor that produces 350 W of continuous power (950 W peak), with six 3.7 V battery cells connected in series (for 22.2 V in total) to provide the power.

Matt Dunlevy

Matt Dunlevy was raised in Shoreview, a suburb of the twin cities of Minneapolis and St Paul. He spent his early childhood assembling model aircraft, before turning towards building and operating remote-controlled planes, and progressed to flying gliders and recreational aircraft in his mid-teens.

He started his bachelor's degree at the University of North Dakota in 2006, signing up to undergraduate programmes in aviation and aerospace-focused mechanical engineering, where he learned about the design, componentry and control systems for air vehicles.

In the following years he worked to establish partnerships and win contracts for researchers in and around Grand Forks to explore the feasibility of using UAVs to inspect utility infrastructures and detect any damage.

Dunlevy founded SkySkopes in 2014, and in that time the company has grown from just a few employees to several dozen, comprising UAS engineers, pilots, technicians and experts across many fields of aviation. During the same period, he has also taught at the University of North Dakota on a variety of courses, including Unmanned Aircraft Systems Engineering, New Product Development, and Technology Entrepreneurship.

As well as overseeing thousands of successful unmanned aerial missions for SkySkopes, Dunlevy has led UAS teams flying BVLOS research missions for NASA. He also oversaw the first commercial UAV flight at the Grand Sky aviation technology park at Grand Forks Air Force Base, now a well-known UAS testing centre that's in high demand.

Ongoing engineering

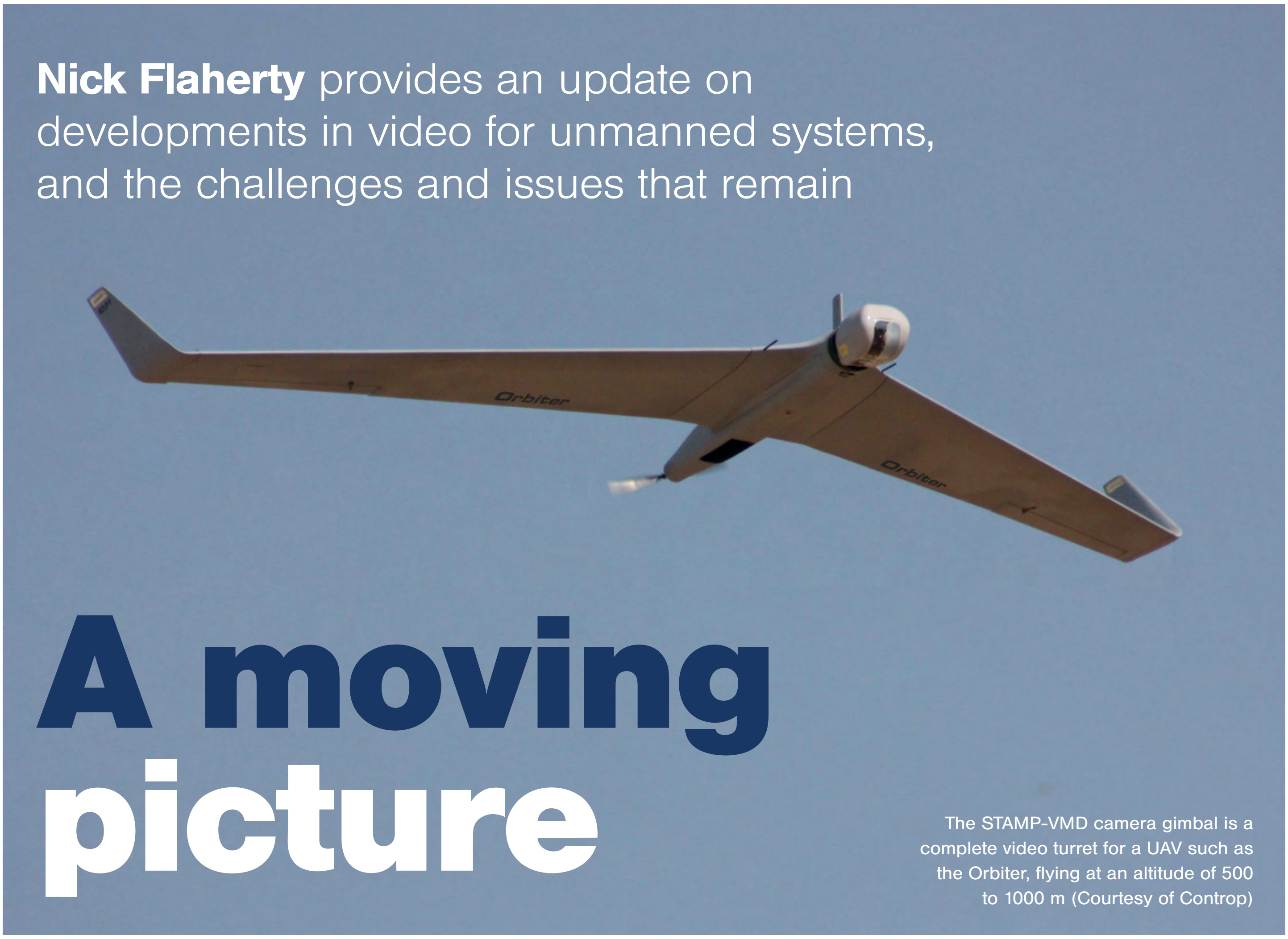
To help make future operations safer and more efficient, Dunlevy and his team are now working to reconfigure their batteries and propeller geometries to reduce the power consumed (and the risk of battery failure) per flight.

The use of a new UAV is also under consideration. Dunlevy highlights the xFold Dragon x6 Hexa, a hexacopter powered by a 4 or 2.4 kW two-stroke gas-electric engine from Pegasus Aeronautics, as being a future potential lead UAV that could carry more lead lines or sensors. At the time of writing, SkySkopes had bought one Dragon x6 for its commercial operations.

As Dunlevy explains, "That could well be the future of unmanned aerial surveys. The Dragon x6 can carry up to 15 kg for 3 hours, and we'll be able to integrate our Lidar, 24 MP camera and OGI sensor, and operate them simultaneously, to generate a vast amount of critical data for energy companies. That's what's been made possible with these new heavy-lift, long-endurance UAV designs that are now coming out."

Nick Flaherty provides an update on developments in video for unmanned systems, and the challenges and issues that remain

A moving picture



The STAMP-VMD camera gimbal is a complete video turret for a UAV such as the Orbiter, flying at an altitude of 500 to 1000 m (Courtesy of Controp)

A major change is taking place in how video for unmanned systems is managed. Video compression technology is evolving so that the bandwidth required for HD video can be further reduced compared with current systems, which will allow high-quality video over narrower bandwidth links and support higher resolution streams over current links. This is appropriate for many applications, especially unmanned ground vehicles, for autonomous control as well as through a remote operator.

At the same time though there remain considerable technical challenges for video. One is the latency of the links and the use of satcom. For current satellite links, the latency is 600 ms each way, giving a total delay of 1.2 s for controlling a gimbal for example. That makes it very difficult to position the camera accurately to track an object of interest.

There are also internal issues with gimbal systems in unmanned aircraft. The 1.5 Mbit/s bandwidth across the gimbal's slip rings limits the quality of the video.

For example, systems using HD video at a frame size of 720 pixels and a frame rate of 60 Hz (called 720p60) can be delivered over the slip rings reasonably easily. Video with frames 1080 pixels wide at 30 Hz (1080p30) are still possible, but system makers want to deliver 1080p60 video over the slip rings. That is why many of the sensor makers are trying to embed the video compression inside the turret that houses the camera.

Both of these issues are leading to a dramatic increase in the use of machine learning (ML) and AI approaches to avoid having to send the whole video. These algorithms can identify areas of interest such as people or vehicles and then just send the relevant areas of the video frames. This can significantly reduce the bandwidth required for a link, allowing satellite links of 600 kbit/s to be used and maintain a high quality of video stream or even send a series of still images.

That means AI processing chips are also being used for video systems alongside (or instead of) the traditional video compression system. Field-programmable gate arrays (FPGAs) have been widely used to implement proprietary algorithms to improve the quality of the video and how it is transmitted. This can include proprietary forward error-correction implementations that add correction codes to the data stream to ensure the data is received

This S-band bidirectional power amplifier operates from 2200 to 2500 MHz and draws just 0.65 A at 28 V to provide 2 W of transmission power (Courtesy of Triad RF)

correctly, avoiding the need to re-send data packets.

All of this also has an influence on the choice of image sensor and the connection between the sensor and encoder. The resolution of the image sensor has not been a key factor in the past, as the unmanned platform could not send more than a high-resolution video stream, and a high-speed connection between the sensor and encoder was also not an issue. Now though, as more video can be carried, the sensor's resolution can be higher, opening up the use of sensors with a resolution of 1080p60, 4K or 8K.

Using ML in the video system also influences the sensor's specification. No longer does it have to be a standard camera sensor with an array of red, green and blue pixels. A multi-spectral or infrared sensor can pick up additional information in other parts of the spectrum, and this information can be used by the ML system to increase the accuracy of identifying an object of interest and avoid triggering false positives, or identifying spurious objects.

Ironically, that requires a faster connection to the encoder. Multi-spectral sensors deliver up to 10 times the data of a traditional camera sensor. There are several ways to handle this higher data rate, from a new standard from the MIPI consortium to 100 Gbit/s data links over fibre-optic links, and now even over a simple twisted copper pair cable.

More efficient encoders also mean smaller power systems. DC-DC converters can be made smaller, saving weight and power in airborne systems.

> AVC systems are being tweaked to fit HD video over smaller links and in smaller boards, to reduce size, weight and power demand

The current compression standard is the Advanced Video Codec (AVC), also called H.265 or the High Efficiency Video Codec (HEVC). This allows a 1080p30 video stream in a bandwidth of 1 Mbit/s down to 200 kbit/s at 15 fps with sophisticated additional tweaking of the video stream.

That is half the bandwidth of the previous H.264 standard, and the progressive display provides a higher quality image for surveillance and analysis.

All of this involves considerable trade-offs and tweaking, as most commercial system-on-chip encoders are developed and optimised for broadcast applications.

The next generation of compression standard, now being developed, is called the Versatile Video Codec (VVC), H.266, which aims to support 8K ultra-high definition (UHD) video or 1080p60. The draft of potential technology for H.266 has been issued, and the final version is expected next year. Chip makers can then start working on a final version of video encoders for then and into 2021.

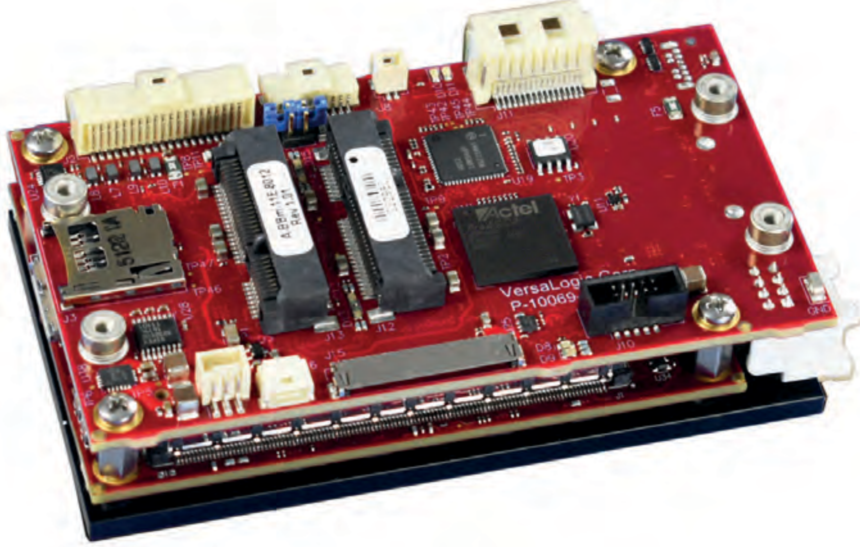
In the meantime, AVC systems are constantly being tweaked to fit HD video over smaller links and in smaller boards with lower power consumption, to reduce the size, weight and power demand.

These are being updated to HEVC, although that requires a slightly larger board, typically 4 mm longer than that for AVC. This similar footprint is an important factor, as it allows the higher compression rates to be added to a video system without increasing the size and weight of the components.

The latest generation of video encoders also operate at lower voltages, typically 1.8 or 3 V. This allows for smaller DC-DC converters and enables system developers to shrink the overall size of the encoder system, with better power efficiency and improved resistance to the noise (called the ripple performance).

However, these encoder chips have more complex power sequencing, as the power rails have to be activated in a specific order, so the design is more complex than previous boards.

The Harrier embedded processing board uses an Intel E39xx Atom processor with an integrated Intel HD Graphics 505 core that supports UHD 4K video with a 9 W power consumption (Courtesy of Versalogic)



A key consideration for the video is the metadata, to provide a frame's time and location, pulling the location data from the navigation system

UAVOS has developed a gyro-stabilized three-axis gimbal with an integrated RGB camera, full HD resolution and 30x optical zoom, and is looking at how to use machine learning to reduce the output's bandwidth (Courtesy of UAVOS)

Video compression card makers are now adding high-speed MIPI interfaces to support video at 4K resolutions. This is a result of the need for more signal lines with metadata, so all the parallel signals are combined in a few serial data lines in a serialiser. MIPI defines a serialiser/deserialiser for camera systems.

The MIPI serial link requires careful design, with attention to the impact of electrical noise on the signal lines. Noise from other parts of the system such as motors can disrupt the signals and limit the data rate, in turn limiting the quality of the video that can be carried. Video from an infrared sensor is particularly sensitive to this noise, and this design requirement is relatively new to encoder board makers.

One of the problems facing designers is the complexity of such a link. A chipset simplifies the implantation of a high-speed serial link called MIPI CSI-2 to allow longer high-speed connections between a camera and encoder, up from 30 cm to 15 m.

The chip serialises up to four lanes of MIPI CSI-2 signals from a camera sensor and converts it into one or two lanes using a proprietary protocol that supports up to 4 Gbit/s per lane. That is sufficient to transmit 1080p60 2 MP uncompressed video over 15 m, allowing the encoder to be further away from the camera. A companion chip deserialises the lanes back to the original MIPI CSI-2 signal.

The USL sub-link aggregates bidirectional low-speed signals such as general-purpose I/O signals that might be carrying metadata from a navigation system. Separating out the high-speed lanes from the low-speed ones as general-purpose I/O makes it easier to build and test the system.

A chip allows a duplicate of the video signal to be sent to onboard storage to keep the original feed while the video for transmission is manipulated.

Metadata

A key consideration for the video is the metadata. This can be as important as the video, providing the time and location of a frame, pulling the location data from the navigation system.

For defence systems, this is defined by Stanag 4609 for the types of the data required. That allows the metadata to be used by a wide range of ground stations, rather than tying a video encoder to a particular one.

A lower bit rate for the video means there is more room for metadata, but it has to be carefully synchronised with the video feed.

The SMTPE 292 standard defines the format of the uncompressed video signal from an image sensor in a turret, and specifies the position in the metadata in the vertical synchronisation carrier of the video.

This metadata is extracted, the video compressed and the metadata is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Connection standards

There are a number of different ways of connecting an image sensor to a video compression system.

CameraLink

CameraLink is a legacy serial protocol that is widely used on machine vision systems. It supports up to three transceiver chips, using 28 bits to represent up to 24 bits of pixel data and 3 bits for the video sync signals. The data is serialised with seven parallel lines into one (7:1) and the four data streams and a dedicated clock are driven over five low-voltage differential swing (LVDS) pairs of signal lines.

Universal Serial Bus (USB)

The USB3 protocol provides a data rate of 5 Gbit/s using the USB Type-A or USB Type-C connectors.

The latest USB protocol, USB4, is currently being released and will support speeds from 10 to 40 Gbit/s to connect a camera to the encoder.

MIPI

Chips have been developed to extend the range of the latest standard from the MIPI Alliance. MIPI was originally set up to provide a serial interface for smartphones, but over the past few years it has evolved to address the needs of autonomous systems, particularly driverless cars.

MIPI CSI-2 (Camera Serial Interface-2) supports 1080p, 4K and 8K video from single or multiple cameras. Version 3 supports 24-bit colour from each pixel, which can decipher whether darkness on an image is a harmless shadow or a pothole in a roadway to be avoided.

The v3.0 standard also adds support for Smart Region of Interest (SROI) for handling data from specific areas of images and CNN algorithms. There is also a Unified Serial Link (USL) for encapsulating connections between an image sensor module and application processor to reduce the number of connecting wires.

MIPI CSI-2 can be implemented on either of two physical layers from the MIPI Alliance: MIPI C-PHY v2.0 or MIPI D-PHY v2.5. It supports speeds of up to 41.1 Gbit/s using a three-lane (nine-wire) MIPI C-PHY v2.0 interface, or 18 Gbit/s using a four-lane (10-wire) MIPI D-PHY v2.5 interface under MIPI CSI-2 v2.1.

RAW-16 and RAW-24 colour depth optimises intra-scene high dynamic range and signal-to-noise ratio (SNR) to bring 'advanced vision' capabilities to autonomous vehicles and systems.

Latency reduction and transport efficiency provides image sensor aggregation without adding to system cost. It facilitates real-time perception, processing and decision-making, and optimises transport to reduce the number of wires, toggle rate and power consumption.

Differential Pulse Code Modulation 12-10-12 compression reduces bandwidth while delivering superior SNR images devoid of compression artefacts for mission-critical vision applications.

Scrambling reduces power spectral density emissions, minimises radio interference and allows further reach for longer channels.

The capability of the Camera Command Interface (CCI) to work with the MIPI I3C v1.0 sensor interface supports advanced imaging performance requirements for autofocus and optical image

then added back to the compressed stream.

When a complete stream is being compressed, there are hooks within the encoders to ensure that synchronisation. However, the new techniques using ML raise significant challenges of ensuring the metadata is accurately synchronised with an edited video stream.

Onboard processing

System developers are using a number of techniques to identify areas of interest to send as video, rather than sending the whole video stream. These vary from convolutional neural networks (CNNs) that are trained to identify people, vehicles or other UAVs, to sophisticated edge-detection algorithms.

Once an area is identified, there are several ways to proceed. One is to send only that area, linking with the control of the gimbal to ensure that the object of interest is always in the centre of the frame. The frame can then be cropped to meet the bandwidth available.

Another is to use image processing algorithms to subtract the background from the video.

This can be challenging when a UAV is circling over a particular region, but by identifying the same stationary points in each frame, the background can be removed.

The background is then sent as a single still image, and the moving objects in the frame are superimposed on that image at the ground station. This allows hundreds of moving objects to be tracked, and reduces the bandwidth requirement dramatically.

Using ML for video analysis and compression over a satellite link is driving the need for multi-core processors. This is a combination of CNN networks and image processing algorithms from the OpenCV library of functions.

This combination can be used to

stabilisation, among other applications.

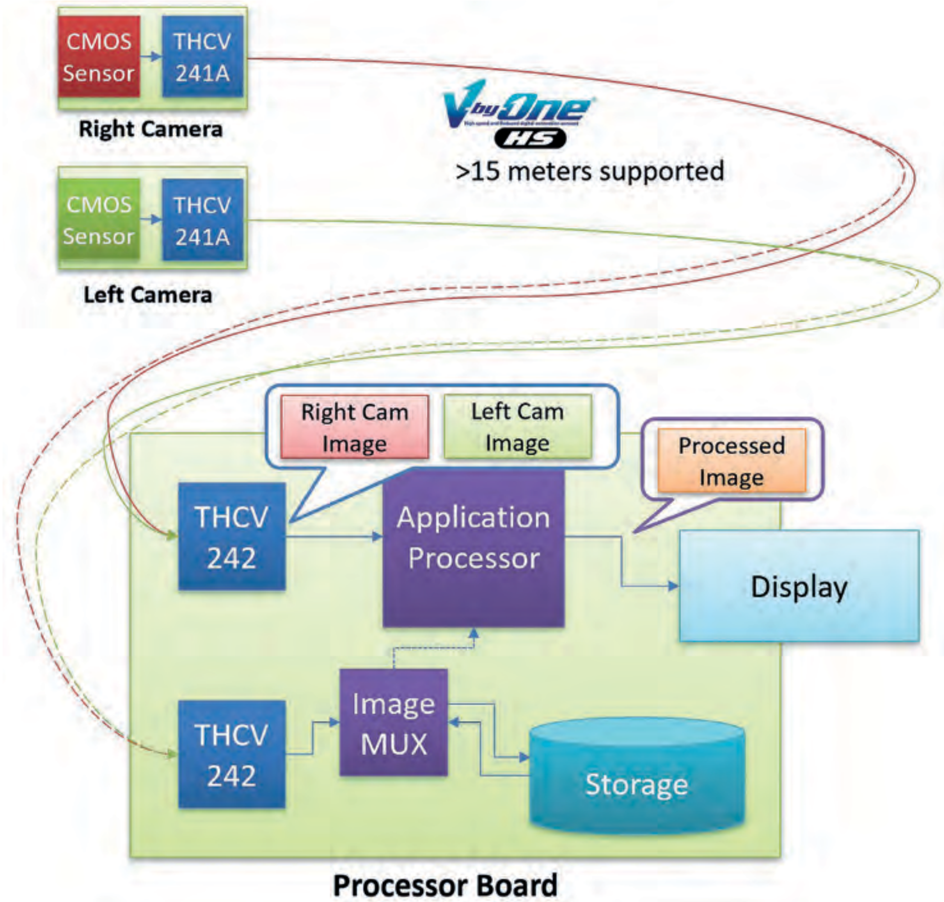
CCI is a bidirectional, two-wire interface that host processors can use to configure and control cameras before, during or after image streaming using the high-speed MIPI D-PHY or MIPI C-PHY interfaces.

CCI implementations can use I2C Fast Mode+, which supports up to 1 Mbit/s. When used with MIPI I3C v1.0 single data rate mode, the interface delivers data at 12.5 Mbit/s. It delivers 25 Mbit/s when used with MIPI v1.0 high data rate double data rate mode.

The USL avoids the need for additional signal lines by encapsulating the CCI control data within CSI-2 transport.

MIPI has developed a new physical layer specification to support speeds of 12 to 24 Gbit/s. MIPI A-PHY v1.0 is expected to be available to developers later this year. The specification will reduce the wiring, cost and weight requirements, as it allows high-speed data, control data and optional power share the same physical wiring.

The first vehicles using components with the A-PHY technology are expected to be in production in 2024.



The MIPI CSI-2 specification provides a high-speed connection from multiple cameras to a video compression board (Courtesy of Thine)

control the gyroscopes on a gimbal to keep the gimbal aligned with an area of interest selected by the operator. That gives a huge improvement in the stability of the system, and the operator can use the payload in real time with a full online video stream.

For example, when the operator picks up an interesting point on screen at the ground station, the processing on the UAV can look back in the memory to find the object and extrapolate to find the object in real time, avoiding the problems of the 1.2 s of latency over a satellite link.

One example is a surveillance mission to scan an area for a specific object such as a house or person. A traditional video system in a UAV gimbal with good optics would provide a compressed video stream to the ground station, allowing the operator to look for the target. However, that can be complicated for the operator, as there is noise and distortion on the screen.

Instead, the system sends a series of still images to the ground station every 200 or 300 ms, and the operator can identify an object of interest to track. This can be specified before the mission even starts, so that a UAV can fly to an area, identify a specific target and send back the track of that target.

This can be achieved using off-the-shelf software components that are then trained. Simulation software can be used to train the networks.

This moves the design challenge from the video compression and the data link to the onboard processing hardware. The current assessment is that the processing required for this will be available in the next 12-18 months.

This also changes the design of the hardware system. Between the image sensor and the video processing board is an FPGA that can process the raw data from the sensor to prepare the data stream for video processing, with functions such as scaling and image stabilisation. This pre-processing simplifies the processing on the main board and improves the accuracy of the CNN algorithms.

Small and custom UAV manufacturers are split between using a closed, often proprietary video system and a radio transmitter/receiver with a relatively simple, built-in video encoder. Unfortunately these often have problems with delivering a stable video link to a ground station.

A key trend is to use the extra

This gimbal acts as a video motion detection payload and 'server in the sky' for persistent surveillance (Courtesy of Controp)

processor cores that sit alongside the encoder core in a multi-core chip to boost the radio link to give more margin for the video.

Using the additional processing power to implement multiple in/multiple out (MIMO) systems that use up to four transmitters, receivers and antennas can give an extra 3 dB in the radio link margin – the equivalent of doubling the transmission power, allowing a higher video bandwidth without actually increasing power consumption.

Video standards

The Advanced Video Codec (AVC), also called H.264, is a widely established video compression technology, and is used across terrestrial broadcasting, DVD and many wireless video links.

It is based around the discrete cosine transform function, and uses a series of I-frames, and full frames with intermediate P and B frames. P frames use data from previous frames to decompress the image and are more compressible than I frames, while B frames use information from both previous and forward frames to get the highest amount of data compression.

AVC supports resolutions up to 8192 x 4320, including 8K UHD video, with each pixel's colour defined by an 8-bit value. This compresses HD video to 2 Mbit/s.

High Efficiency Video Coding (HEVC), also known as H.265, provides 25-50% better compression at the same level of video quality, or substantially improved video quality at the same bit rate. It supports resolutions up to 8192 x 4320, including 8K UHD, and adds support for more complex pixels with 10 bits of colour. HD video is compressed to around 1 Mbit/s.

Versatile Video Coding (VVC), also called H.266 or MPEG-I Part 3, aims to provide a 30-50% improvement in compression over HEVC and is looking at how to add AI capabilities to the compression. The first version of the standard is being developed for the end of this year, with a final standard by the end of next year and hardware encoders available by June 2021.

It should support resolutions from 4K to 16K as well as 360° videos that require higher data rates and 16-bit colour. It will also support variable and fractional frame rates from 0-120 Hz, and is expected to be 10 times more complex than HEVC.

A VVC test model has been built to make sure all the compression systems produce a standard output.

Several suppliers of radios with built-in encoders now have MIMO capability, and these need radio amplifiers that can handle two, three or four concurrent RF chains. Embedding processor power into the integrated units with the video encoder, radio subsystem and multiple amplifiers allows the input and output power of the amplifiers to be monitored in real time, including the MIMO chains.

The MGW Ace Encoder and Decoder use Vitec's HEVC GEN2+ codec with zero latency compression, allowing a 16 ms latency across the whole video link (Courtesy of Vitec)

That allows the gain of the amplifiers to be automatically adjusted in real time to match the data rate of the video, reducing the RF power when the video is a lower rate.

This approach also allows compensation of any drift in gain, power, signal-to-noise ratio or other variables that come from changes in temperature or frequency. It is a common reason why a video link does not always operate well.

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embedded in the amplifiers on the low-power input and high-power output stages. That bolsters the amplifiers' resistance to RF interference, and gives a highly accurate RF power output, reducing or eliminating the EMI caused by other onboard systems, which also reduces the bandwidth available for video. The filters also address any interference between radio channels and EMI from the power supply wires.

These filters and the embedded processing can often be done without increasing the size or weight of the integrated encoder or radio subsystem, providing a highly stable output with a reliable bandwidth for the video as well as lower power consumption.

Future system design

The move to ML has implications for the system architectures. More complex multi-processor systems with arrays of graphics processing units can be used for the ML, but can also handle the video encoding.

That can avoid the need for a separate hardware encoder board, saving power and weight, but in addition it means having to send the raw video over a longer distance to a central processing unit.

That is driving the need for even faster connections, provided by fibre optics or even twisted copper pairs running at up to 10 Gbit/s.

Software compression also consumes more power than the hardware version, but it is more flexible. If the video being transmitted to the ground station is dramatically smaller as a result of the ML pre-processing, that lower power efficiency still results in a lower overall power consumption.

Acknowledgements

The author would like to thank Aliaksei Stratsilatau at UAVOS, Patrick Sherlock at Triad RF, Mark Zanmiller at Sightline, Mike Southworth at Curtiss-Wright, George Nelson at Delta Digital Video, Bob Buxton at Versalogic, Raanan Shelach at Controp, Nicolas Pons at Vitec and Yasuhiro Takada at Thine for their help with researching this article.


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The HL4 Herculift originated from a commission for a lightweight heavy-lift UAV for trialling experimental payloads (pixellated by request) and missions (All images courtesy of Aerdron)

Test cases

For a heavy payload that needs testing, this UAV could be just the thing. **Rory Jackson** reports

Although companies across various industries are working on heavy-lift UAVs for different consumer applications and payload weight classes, one company based in Spain has developed an aircraft specifically to work as a multi-role testbed for heavy payloads (up to 11.9 kg). It is aimed particularly at aerospace companies, researchers and security agencies.

Notably the payloads are mounted on top of the vehicle, the HL4 Herculift, as opposed to underneath. This was done to provide an unobstructed view upwards for comms and inspection purposes, and to ease payload maintenance and exchanges.

The HL4 was originally commissioned by a company called SENER Group, which needed an aerial testbed capable of carrying up to 8 kg of experimental comms payloads. The UAV has a large, top-mounted payload area with a universal mounting system to enable experiments to be swapped out easily.

Origins

One of SENER's activities is to develop comms equipment for satellites and other aerospace and infrastructure projects. For that it needed an aerial testbed platform that could stay on station accurately at various altitudes.

"The problem was that there weren't any UAVs on the market that serve as a testbed for companies or scientists to use," says Marcos Fabian, founder and CEO of Aerdron. "Most UAVs are more focused on photography or carrying some type of gimballed camera payload.

"SENER wanted something that could fly any manner of experimental payload, with integration being a simple plug-and-play with a few screws. Also, it wanted a high-grade engineering solution rather than something designed and built to be mass-produced at the lowest possible cost.

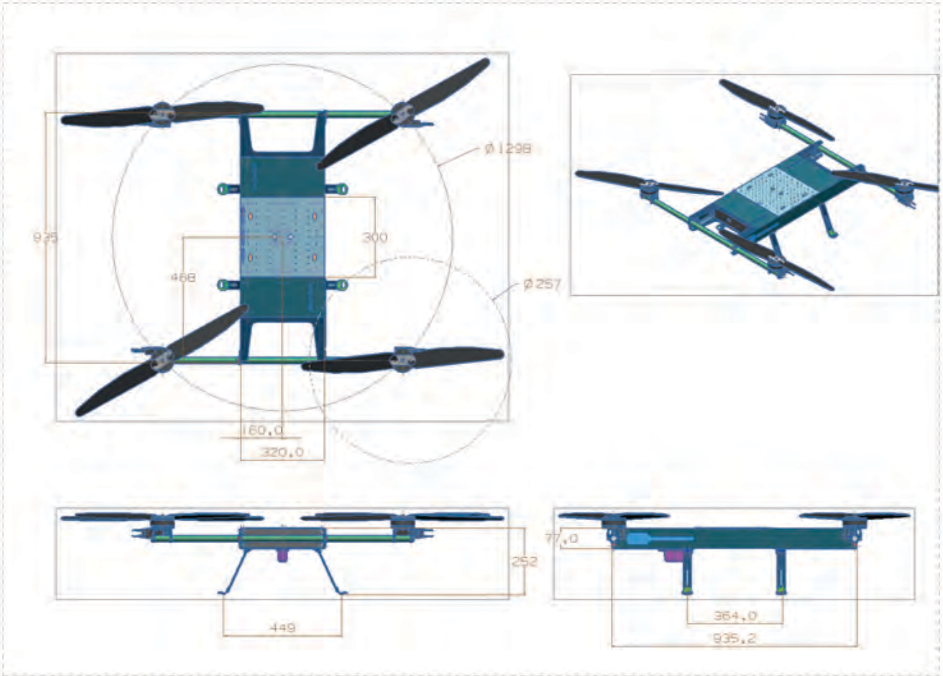
"I didn't feel comfortable modifying a mass-market consumer UAV to carry up to 12 kg of payload, because it could easily fail and someone could get hurt, so we started work on a bespoke solution from the outset."

The main idea behind the HL4's development cycle was therefore to design a structure that would have the lowest possible ratio of aircraft mass to payload capacity, in order to generate the highest payload-carrying capabilities in its class (less than 25 kg MTOW) to meet SENER's requirements without being distracted by concerns about the craft's aesthetics.

The chassis was designed to be structurally efficient and predictable in terms of operating loads, component attachments and the manufacturing methods used.

Importantly, the team had to come up with a design concept, perform the required engineering, complete the manufacturing of the aircraft, and turn that into a flying prototype within four months. That led to what Marcos Fabian has described as a "very lean" development process.

That process has resulted in a quadrotor aircraft weighing 13 kg (with batteries and equipment), that can carry up to 11.9 kg of payload capacity – a limit imposed by regulations requiring a MTOW of less than 25 kg for craft of this class; it measures about 130 x 130 cm (or 166 x 166 cm including propeller diameters) in size. At its maximum payload it can fly for up to 13 minutes, or up to 30 minutes with no payload.



Early design diagrams of the HL4's structure

> If you want to get reliable results from FEA it's easier to know if they're correct if you've done the classical engineering work

Airframe development

The 'H' shape of the aircraft arose from the drive to obtain the highest possible structural strength-to-weight ratio. With that basic shape, payload size and estimated weight as a guide, the dimensions of the spars and other components could be adjusted in height, width, thickness, and other variables as needed to meet the operating load requirements.

"It had to be a structure that was incredibly efficient, using structural elements such as C-beams, shear panels, and so on," Marcos Fabian explains. "Everything that could be calculated 'on paper' had to be worked out in full, taking account of all the bending moments, shear forces and so on, so that it would be very predictable, calculable and statically determinate."

The HL4's structure was worked out on paper using classical engineering calculations. V-M diagrams based on the operating requirements were used to determine the required dimensions, likely stresses, deflections and other features of the structural sections, long before going into FEA and other CAD tools.

"In my opinion, any design engineer should be going through load calculations and running the gamut of hand-mathematical modelling before jumping onto computer modelling," Marcos Fabian says. "If you want to get reliable results from FEA it's much easier to know if they're correct if you've done your classical engineering work ahead of time, and it's great when they correlate to within 5%.

"I wanted to use the carbon fibre legs as flat springs, so we looked into the energy absorption characteristics of the material and shape of the legs, and how to couple-out the reaction forces – landing, drag loads – at three attachment points, similar to what you'd do with an aircraft's landing gear. As an engineer, you're always after the most efficient and elegant load paths."

To design, build and fly a UAV that would fulfil SENER's requirements in less than four months, Aerdron first looked at what components were available in the market, placing significant priority on finding the largest energy-storage batteries available, since that was a key component along with the motors.

The UAV was then designed and built around the batteries, motors, propellers and payload bay.

"We calculated the mass-moments of inertia in all axes – including the weight of the motors, batteries, payload – and input them into a simulator from UAV

The HL4 uses two 22,000 mAh batteries fastened into dedicated compartments on either side of the airframe body, although future versions will have a tool-less quick-release system

The folding propellers originally used were found to vibrate during take-off, so they were swapped out for fixed versions

avionics company Drotek to fine-tune the gains of the autopilot's PID controller. That got us 90% of the way there in terms of fine-tuning the autopilot before the first flight," Marcos Fabian adds.

All the structural attachment components are CNC-machined from 6061-T6 aluminium alloy, for strength and durability.

In order to finish the project in the limited time span, the chassis was made from aerospace-grade prepreg carbon composite sheets and tubes, built in sub-assemblies, and a jig used for final assembly. Once on the jig, the parts were riveted together and bonded with Hysol structural adhesive.

Designing the HL4 relied particularly on the use of 3D CAD, with key objectives being to get the hull 'packaging' as tight as possible around the batteries and other internal electronics, to minimise chassis size and weight.

The CAD models for the structural components were taken to local CNC and water-cutter shops. Extruded carbon fibre preforms were used for the composite beams in order to fit the project budget – future HL4s will use a composite moulded sub-frame to optimise weight and minimise assembly time. Aerdron anticipates this will reduce the aircraft's empty structural weight by as much as 15%.

The motor mount flange's thickness was thinned out as much as possible to save weight, and that part was designed as dual load path structure. This means that if a crack is propagated in any critical area it will not develop into a structural failure: the cracked motor mount will still be able to take the full motor thrust load and assure a safe landing.

For the first complete HL4 prototype, the weight was within 7% of what the engineering team had estimated in its original hand calculations.

The company also designed the HL4's transportation case, which in addition to the aircraft holds two pairs of battery modules; it is also ruggedised.

Lifting power

The HL4 uses two Tattu 22000 battery packs connected in series. Each pack consists of four cells in series to produce a total of 14.8 V and 22,000 mAh (from which the name is derived), and weighs about 1.7 kg.

The batteries mount onto a carbon fibre tray and are fastened directly into the structure. Future versions of the HL4 will use a 'quick-release' system though, to enable tool-less battery swapping that would take less than a minute.

A battery management system from Drotek was selected for its power redundancy features as well as algorithms and filters for health monitoring, surge protection and other critical electrical functions.

Lift is provided by four P80 electric motors from T-Motor, each of which provides up to 17 kgf of thrust. They contain 36 permanent magnets and 42 manually wound stator poles.

It might seem curious that the craft uses four motors rather than eight, but early in the development process

Aerdron studied the benefits and drawbacks of that choice. It turned out that using eight motors would have been less cost-efficient and less energy-efficient, and would have yielded a lower ratio of payload capacity to empty craft weight.

"While eight motors is ideal for redundancy, using that many would have also meant needing four more motor mounts, four more sets of electronic speed controllers, propellers, more power cabling and hardware, giving more overall empty weight and less payload capacity," Marcos Fabian says.

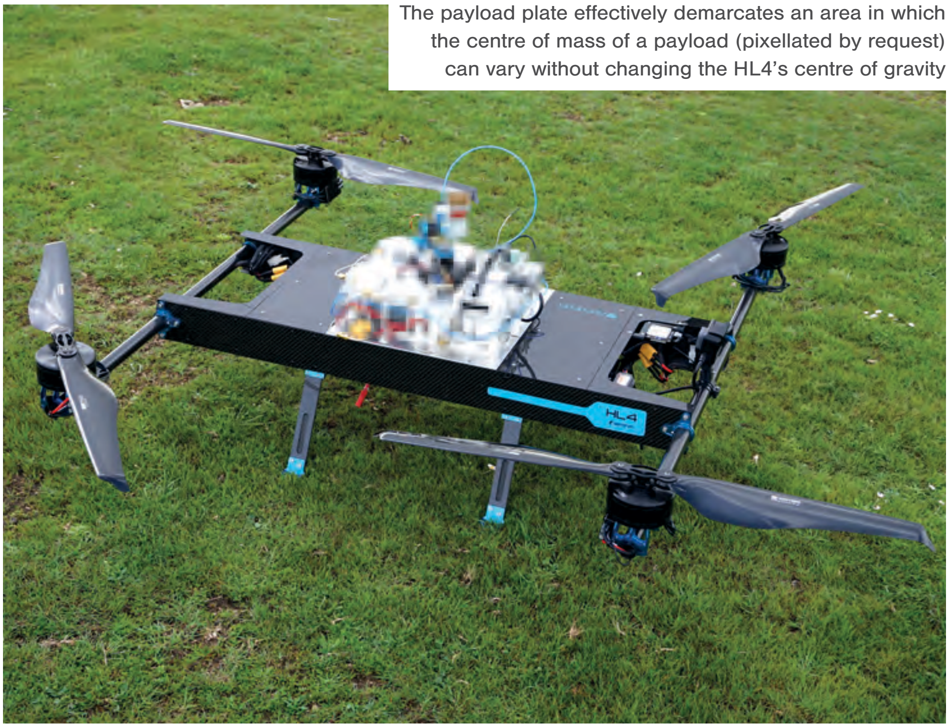
"If we could fly more than 25 kg MTOW legally then we might end up using more motors – as many heavy-lift UAVs do – but for this particular project's objectives, four proved to be more efficient."

The HL4 also currently uses T-Motor's G30x10.5 propellers. During early testing, the folding propellers previously selected were found to generate problematic vibrations during start-up. While it was initially suspected that they were folding during the motor start-up phase owing to the torque, video footage showed they were unfolding when the motor accelerated, then locked again when the centrifugal force increased.

The size of the propellers – 76.2 cm in diameter, 26.6 cm in pitch – combined with the fast acceleration, torque and applied power they underwent during take-off, caused the hub centre lines to 'break' from their hold. The propellers were therefore switched to a non-folding type, and thereafter the start-up was far smoother and the vibration levels much lower.

"T-Motor were hugely helpful after we sent them videos, data and technical explanations of what was happening," Marcos Fabian recounts. "They immediately asked us to send the props back to where we'd bought them, and shipped fixed non-folding replacement props to us that worked perfectly.

> If we could fly more than 25 kg MTOW legally we might use more motors, but four proved to be more efficient for this project


The payload plate effectively demarcates an area in which the centre of mass of a payload (pixellated by request) can vary without changing the HL4's centre of gravity

"After installing those the craft flew beautifully, and all those vibration issues were gone. We could certainly use similar folding propellers in the future with just a few design tweaks, but because of the short project time limits, the best option for the prototype was to replace them."

Autopilot

The autopilot is a Pixhawk 3 Pro from Drotek. Based on the open-source PX4 autopilot software architecture, the system met the client's requirements since it planned to use the sensor data from the autopilot with its payload, while its software's open-source nature made accessing and extracting that data a simple process.

Drotek also provided flight test consulting in order to fine-tune the autopilot gains to match the stability and control characteristics of the HL4 with different payload weights. It provided the data link that operates on the 433 MHz band as well, with a range capable of exceeding 5 km.

"We went through a huge amount of engineering calculations and parameters," Marcos Fabian says. "We moved the GNSS position around to mitigate magnetic EMI/EMF interference from the motors, then we made some changes to the autopilot suspension system to clean up some of the vibration and interference issues.

"Being open source, the autopilot architecture made it much easier to alter and view the parameters and behaviours to adaptively fit our various inertia profiles for different payload weights. All the third-party open-source ground station software and other modelling programs were compatible with it too.

"The Drotek autopilot and their other onboard electronics – two GNSS modules, a power management system and data comms modules – also performed as needed."

Two GNSS receivers are installed for redundancy (along with voting software for selecting the correct GNSS signal if two different sets of navigation data are being received), and a downward-facing laser altimeter with a 120 m range is also integrated to provide accurate and stable take-offs, landings and to stay on station for precise hovering.

"The laser altimeter gives a huge step in precision and redundancy over just relying on GNSS coordinates during hover, which was an important requirement for the customer's mission profile," Marcos Fabian notes.

Specifications

Battery-powered quadrotor aircraft
Size: 166 x 166 cm
MTOW: 25 kg
Payload capacity: 11.9 kg
Payload area: 320 x 300 mm
Battery capacity: 44,000 mAh
Maximum endurance (no payload): 30 minutes
Endurance at payload capacity: 13 minutes
Data link range: 1600 m

Some key suppliers

Composites:
GRM Composite Systems
Composites: Easy Composites
Electric motors: T-Motor
Propellers: T-Motor
Batteries: Tattu
BMS: Drotek
GNSS: Drotek
Autopilot: Drotek
Data link: Drotek
CNC machining: Controlmad

Payload integration

As per SENER's request, a 'universal' mounting plate is fastened atop the middle of the craft by eight M3 bolts. A carbon fibre or aluminium payload plate sits on the carbon fibre chassis, and allows payloads to be uninstalled and replaced in an easy plug-and-play form. Its size – 320 x 300 mm – also serves to encompass a zone within which the centre-of-mass envelope can vary without significantly altering the UAV's controllability.

"SENER have tons of different products and applications they want to test – not only comms equipment – so there's much more they plan to use on the HL4," Marcos Fabian says. "In one test they want us to perform a fast vertical lift-off to simulate a rocket taking off with 3 *g* of acceleration."

To make it easy to remove and integrate different experimental payloads, the payload bay has been designed to be isolated and independent from the UAV: the avionics and the payload bay are completely unconnected. This also ensures that if either the UAV or the payload fails for some reason, the other systems are not damaged or affected in any other way.

The electrical systems that provide power to the motors and the autopilot are also on different electrical buses for safety and redundancy. As a result, the payload has its own independent power and comms systems.

"This is the configuration we would recommend to anyone interested in our UAV," Marcos Fabian says. "If a customer wanted to use the large batteries to power their payload as well as the UAV, I would try to steer them away from that, unless they plan to put in other forms of protection."

The future

In addition to working on a fully moulded version of the HL4, which will have a greatly reduced structural weight and part count, the company has a few additional projects based on the IP it has developed.

One of these is the Aircarrus UAV, which would carry a heavier payload and payload exchange system than the HL4 in order to courier packages over long distances. It would integrate the Dbotix autopilot co-developed with Drotek, which comes with an integrated 4G LTE data modem and a dedicated companion computer for using 3D machine vision cameras to enable onboard sense-and-avoid and trajectory mapping.

"We've already completed some successful test flights, where a UAV with the Dbotix autopilot can be flown via the internet from different countries," Marcos Fabian says.

"We're around 40% into the tooling for the Aircarrus, but we want it to be a fully autonomous system for the EU's new U-Space ecosystem. The vision is to have UAVs that are fully operated over the internet with jump stations and automatic payload exchange platforms.

"The project won funding through the EU's Horizon 2020 programme, so we're working towards having the hardware and software fully developed within the next one or two years."

The company is also building a long-endurance solar-powered UAV, the Solvis, a 328 W solar charging system. It is designed to carry up to 2 kg of payload for over 24 h of flight time, with the first prototype due to be ready to fly around the middle of next year. ◻

"Now, here's a thing"

A fatal explosion involving what the Russian state nuclear corporation Rosatom calls an "isotope power source" but which western analysts believe is associated with a nuclear-propelled cruise missile is an indication that nuclear propulsion for space vehicles is back on the agenda, after decades in the wilderness (writes Peter Donaldson).

Another, less immediately threatening one is the US government's NASA-led revival of nuclear thermal propulsion (NTP) for spacecraft. NTP holds huge promise for exploring the Solar System and beyond in manned as well as unmanned applications. It will enable journeys to Mars in four months instead of six, for example, while reducing the amount of propellant required.

NTP's potential stems from its combination of high thrust capability with around twice the efficiency of the best chemical rockets. The thrust a rocket generates depends on the propellant's mass flow rate through the engine, the exit velocity of the exhaust and the pressure at the nozzle exit.

Rocket engine efficiency is measured in specific impulse (Isp), which is calculated by dividing the engine's thrust by the propellant mass flow rate. The most common unit used to express Isp is the second, as it can be defined as the number of seconds for which a propellant can accelerate its own initial mass with a force of 1 *g*.

The higher the Isp, the less propellant is needed for a given change in velocity. A high exhaust velocity is crucial to a high Isp, and the lighter the propellant molecules, the higher the exhaust velocity.

The Aerojet Rocketdyne RS25 Space Shuttle Main Engine for example achieves an Isp of about 450 s by burning liquid hydrogen in liquid oxygen. A nuclear thermal rocket, which simply heats pure hydrogen to temperatures of 3000 Kelvin or more by passing it through the core of a nuclear reactor, can achieve an Isp of about 900 s. Hydrogen is the lightest element, so it makes an efficient propellant by itself.

Electric thrusters, which accelerate charged propellant particles through electric or magnetic fields, can achieve Isp figures of about 1500-20,000 s, thanks to their extremely high exhaust velocities, but they tend to have very small mass flows and therefore low thrust.

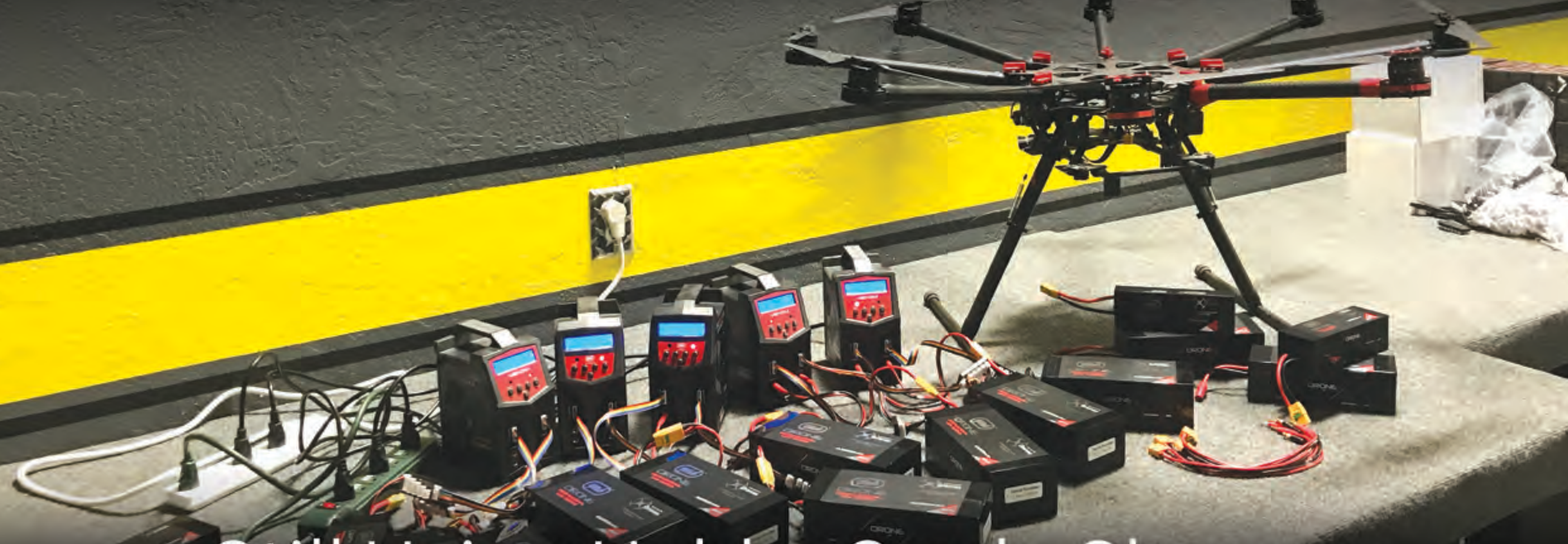
They can achieve large velocity changes in a very fuel-efficient manner, but it takes them a long time. They can of course use nuclear reactors as sources of electric power, a concept dubbed nuclear electric propulsion.

It is NTP though that offers the combination of speed and efficiency that seems more attractive to governments and industry at the moment, particularly if it can be realised with a safer fuel such as low-enriched uranium. This fuel has a concentration of less than 20% U235, which is much less radioactive than its highly enriched counterpart, and unsuitable for bombs.

President Trump's August signing of a presidential memorandum outlining new procedures to launch nuclear power systems into space directs the US Department of Transportation to publish guidelines within a year for companies who want a licence to launch spacecraft with nuclear systems aboard. It has given new impetus to technologies that have been almost dormant since the 1970s, and could help revitalise exploration of the Solar System.

However, the accident involving the Russian nuclear-powered cruise missile shows that the technology's dark side is still alive and kicking.

The President's memorandum has given new impetus to technologies that have been almost dormant since the 1970s



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