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

Position of control
Latest advances in servo actuators

Let's mingle
How radio telemetry will soon merge different types of data

Wind power
Design and development details of SubSeaSail's Gen6 wingsail-propelled USSV

UST 33 : AUG/SEPT 2020
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UK £15, USA $30, EUROPE €22


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Safety factors

The coronavirus pandemic is accelerating engineering trends in unmanned systems. Driverless car programmes are moving on apace, both in testing and in partnerships. Autonomous vehicles are being tested on the streets of Munich, while Fiat has chosen Waymo as its exclusive partner for driverless technology.

These developments are being spurred by the increasing need to keep people safe in cities and rural areas. UAVs have been used to deliver vital supplies across Scotland, for example, eliminating the need for delivery drivers, while European trials of UAV delivery technology have increased fivefold in the past three months.

Keeping people safe is the key theme for developments in driverless vehicle technology as well. Reduced capacity on public transport has led to higher demand for buses. This is also accelerating plans for ride-hailing services, minimising the risk of cross-contamination without increasing the number of cars on the road.

Technology suppliers are responding with higher volume production and cost reductions. Also, the testing of radio systems and safety features is being brought forward, and will allow many types of autonomous vehicles on city streets much sooner than originally expected.

The Unmanned Systems Engineering Network (see pages 16 & 17) can assist with engineering queries for autonomous projects, cutting development times. Our team of industry experts can help find the right solutions by working with to understand the challenge. Just email thenetwork@unmannedsystemsengieering.com to start the process.

Nick Flaherty | Technology Editor

UST-34 (Oct/Nov) and 2021 advertising

UST magazine is a proven platform for companies wishing to promote their products or services to engineers tasked with building unmanned vehicles and the systems that support them. We still have limited ad space available in the next issue, *UST* 34 (Oct/Nov), and if a copy of our 2021 media kit isn't inserted with your copy please email simon@ust-media.com who will be happy to send you one

hpm high power media

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ALSO FROM HPM

Elistair has boosted the power system to increase the height of its tethered UAV system

Tether adds weight factor

Airborne vehicles

Elistair has redesigned its tethering system for UAVs to increase the weight of unmanned aircraft and their payloads it can support (writes Nick Flaherty).

The Safe-T 2 extends up to 125 m and weighs 10.5 g/m. The redesign boosts the power supply to a UAV to 2200 W continuous and 2800 W peak, and adds IP54 protection for use in harsh environments.

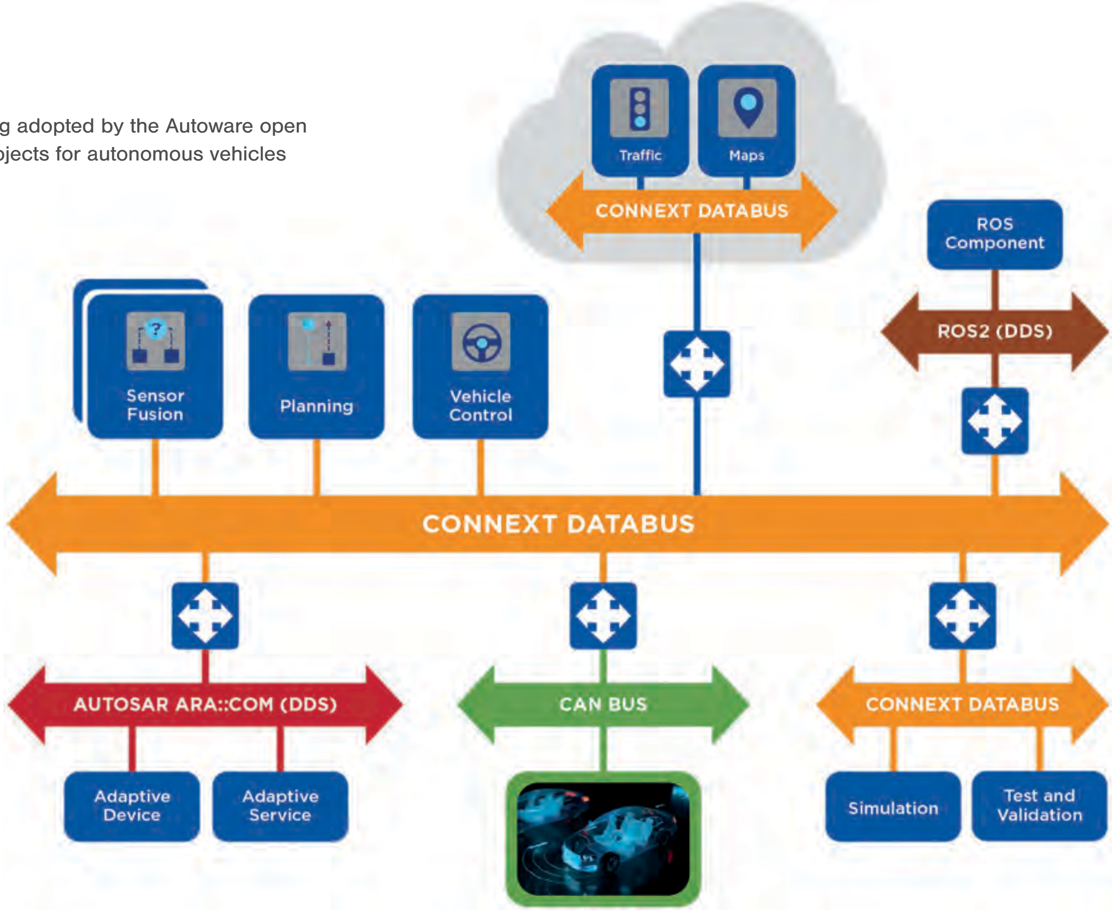
This higher power supports faster motor speeds to carry the additional weight of the longer tether and fly higher without reducing the payload.

More than 600 of Elistair's tethered UAV systems have been deployed to help monitor events, secure sites and protect assets. The new system is compatible with 50 commercial UAVs.

The secure, dual comms system uses a fibre optic cable and broadband-over-powerline to provide either a redundant tethered data link or the choice of link best suited to the aircraft or payload.

Elistair's brake system (described in *UST* 21, August/September 2018) allows the user to adapt the maximal tether length according to the safety zone needed, such as in urban or crowded environments, and to wind it in manually if necessary. Like its predecessor, the Safe-T 2 integrates Elistair's live flight management system.

Alongside physical mounting plates, the Safe-T 2 has an optional software development kit for seamless integration into vehicle systems and fixed structures while also being agile enough for use by a single operator. The interchangeable micro-tethers and adaptive winch control algorithms allow the operator to reconfigure the station and use the best tether weight/power range for the different UAVs that may be used.



The DDS is being adopted by the Autoware open source stack projects for autonomous vehicles

DDS tools picked for project

Autonomous vehicles

A group developing an open source stack for autonomous platforms is adopting the latest tools based around the Data Distribution Service (DDS) standard (writes Nick Flaherty).

DDS uses a technique called publish-subscribe to connect different hardware and software blocks without the traditional primary-secondary bus technologies.

The DDS implementation from Real Time Innovations (RTI) is being added to the stack development of the Autoware Foundation. The DDS technology will be used with autonomous vehicles as well as simulation projects.

Autoware was set up by machine learning specialist Apex.ai, board maker Linaro and systems integrator Tier IV. The main focus for DDS will be Autoware.ai, the autonomous vehicle project, but RTI will also use its experience with ROS2, the open-source robotics project, for the other two projects in the foundation.

The first of those is Autoware.IO, an interface project that can be extended with proprietary software and third-party libraries for device drivers for sensors such as Lidar and radar. The second is Autoware.Auto, a rewrite of the original Autoware but now based on ROS2.

Autoware.ai will use the Connext 6 DDS software. This adds a data representation that significantly reduces latency and CPU usage for large and small data samples, which is critical for sensor fusion applications that need to minimise the time between when an event happens and when it is recognised by the sensor fusion, localisation and path planning algorithms.

Any delay reduces the fidelity of the real-world model, and makes an autonomous vehicle's understanding of what is happening around it less accurate. This is a key part of the Lidar, radar and image data processing subsystems.

Connext 6 also uses a shared memory transport to nearly eliminate end-to-end latency. This allows developers using Autoware.Auto to use the same interface to communicate between applications running on the same CPU and across networks, while still maintaining the performance they expect and need from software modules running on the same platform.

This reduces development costs by avoiding the use of another protocol, while DDS enables IP portability, using software on a common CPU and distributing it to other processors in a second architecture without having to redevelop the software.

DDS also includes security that can be safety-certified – a key requirement for the stack being developed for Autoware.ai.

RTI is working on 250 autonomous vehicle projects, and works with more than 50 commercial autonomous system developers including Aptiv, Baidu Apollo and Xpeng Motors.

Tiny flow meter unveiled

Fuel monitoring

Flusso, a semiconductor company spun out of the University of Cambridge, has developed a gas flow meter that is smaller and less expensive than others on the market (writes Nick Flaherty).

It uses a MEMS micromachined combination of heaters and sensors to measure the flow, and can be used in fuel cells and engines to monitor the flow of hydrogen.

It is packaged and assembled using a standard chip process that allows manufacturing in tens of millions of parts per month. Its small size, 3.5 mm, allows more flow meters to be installed across an unmanned system to provide more data.

The flow meter uses hot-film sensors that are fabricated using a 1 µm silicon-on-insulator (SOI) CMOS chip-making process in a commercial foundry.

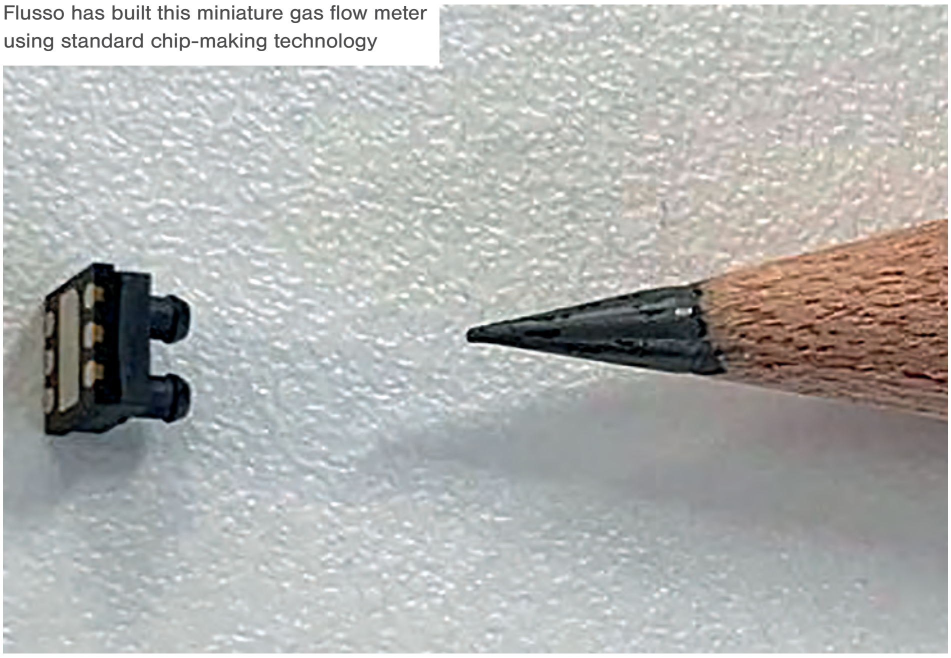
After the CMOS process, a Deep Reactive Ion Etching (DRIE) process is used to create cavities under a membrane to further increase the thermal isolation of the hot-film sensors. DRIE creates cavities with vertical side walls, as it does not depend on the lattice orientation of a silicon substrate. This creates more consistent heating for the measurements.

The SOI technology provides various advantages. The buried oxide insulator layer acts as an etch-stop layer for the DRIE process, controlling the etch depth. It provides a uniform thickness for all sensor membranes, and thermally isolates the sensing area to reduce the power losses to the silicon substrate.

It also electrically isolates the electronic circuitry, reducing crosstalk, and increases the device's operating temperature range.

"The energy efficiency of many products could be greatly improved if they incorporated gas and flow sensors, but companies cannot do that owing to cost, size or manufacturing constraints," said Andrea De Luca, founder and CEO of Flusso. "We want to bring flow and gas sensing technologies to these products."

Flusso has built this miniature gas flow meter using standard chip-making technology



Owl offers dual vision

Imaging

Raptor Photonics has launched an InGaAs-based SWIR camera with a 640 x 512 resolution that detects visible light as well as short-wave infrared by using a 10 x 10 µm pixel pitch (writes Nick Flaherty).

The Owl 640T has less than 50 electrons of readout noise and an intra-scene dynamic range of 69 dB. This enables simultaneous capture of bright and dark portions of a scene across 0.6 to 1.7 µm, and allows frame rates of up to 120 Hz.

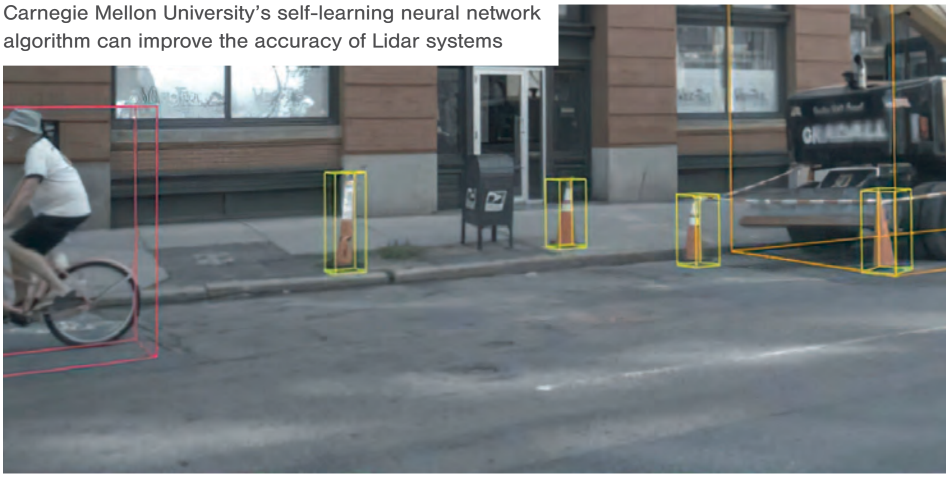
"The key to the camera's technology is essentially the sum of all its parts," said Mark Donaghy, a technical expert at Raptor. "This includes the low-noise electronics, the SWaP features, ruggedness and firmware features with auto-gain control.

"We also offer a range of OEM options such as a choice of camera interface, board layout, cooling and so on."

Raptor's Owl 640T has a readout noise of less than 50 electrons

Scene system trains itself

Image recognition



Carnegie Mellon University's self-learning neural network algorithm can improve the accuracy of Lidar systems

Researchers at Carnegie Mellon University (CMU) have developed a more efficient technique for training image recognition systems for driverless cars (writes Nick Flaherty).

The technique uses unlabelled data from Lidar sensors with error correction for self-supervised training of neural networks.

"Our method is much more robust than previous methods, because we can train on much larger datasets," said Himangi Mittal, a researcher working with David Held, assistant professor in CMU's Robotics Institute.

Most autonomous vehicles navigate primarily using Lidar sensors that generate a 3D point cloud. Scene flow involves calculating the speed and trajectory of each 3D point. Groups of points moving together are interpreted via scene flow as vehicles, pedestrians or other moving objects.

Neural network training for such a system currently uses labelled datasets, with each annotated 3D point tracked over time. Manually labelling these datasets from real-world sensor systems is laborious and expensive though, so little such data exists.

As a result, scene flow training is often carried out using simulated data that can automatically label the points. This is less effective than real-world data, however, even when fine-tuned with the small amount of labelled real-world data that does exist.

Instead the technique uses unlabelled data straight from the sensor to perform scene flow training coupled with error-correction algorithms.

The key is the technique's ability to detect its own errors in scene flow. At each instant, the system tries to predict where each 3D point is going and how fast it's moving. In the next instant, it measures the distance between the point's predicted location and the actual location of the point nearest that predicted location. This distance forms one type of error to be minimised.

The system then reverses the process, starting with the predicted point location and working backwards to map to where the point originated. At this point, it measures the distance between the predicted position and the actual origination point; the resulting distance forms the second type of error.

The system then works to correct those errors.

"It turns out that to eliminate both of those errors, the system actually needs to learn to do the right thing – without ever being told what the right thing is," Prof Held said.

The researchers calculated that scene flow accuracy using a training set of synthetic data from a simulator was only 25%. When the synthetic data was fine-tuned with a small amount of real-world labelled data, the accuracy rose to 31%. When they added a large amount of unlabelled data to train the system using their approach, scene flow accuracy jumped to 46%.

IMU sensor architecture cuts cost in half

Navigation

Memsense has used a combination of sensor architectures, characterisation, and proprietary correction algorithms to cut the cost of a MEMS high-performance IMU in half (writes Nick Flaherty).

The 25 g MS-IMU3025 uses COTS sensors with 28 x 28 x 11.4 mm (1.1 x 1.1 x 0.45 in) footprint. Its gyro bias instability of 0.6°/hour and accelerometer bias instability of 2.6 μg support applications from inertial navigation and control to precision platform stabilisation for half the cost of equivalent IMUs.

This is achieved using hardware sensor architectures and advanced algorithms running on a floating-point processor with individual sensor characterisations. That allows low-cost sensors to be tuned more accurately in the IMU. Self-testing built into the architecture also improves the IMU's reliability for critical applications.

The accelerometer's dynamic range configurability spans a range from ±2 *g* up to ±40 *g*.

Attollo rises with Phoenix

Imaging

Attollo Engineering has launched a 640 x 512 shortwave infrared (SWIR) camera using a VGA sensor with a 5 µm pixel pitch (writes Nick Flaherty).

The Phoenix InGaAs uncooled SWIR camera is suited to being integrated into small gimbals and other low-SWaP devices, for example for precision agriculture.

The camera's spectral response ranges from 1.0 to 1.65 µm, with more than 99.5% operability and greater than 70% quantum efficiency. Selectable frame rates include 30, 60, 120 and 220 Hz, with windowing available.

The Phoenix has a global shutter imaging mode, and presets and a user-defined integration time of 0.1 µs (minimum).

The Phoenix SWIR camera is suited to integration into low-SWaP devices

UAV bundle blends OSs

Airborne vehicles

Lynx Software Technologies has launched a preconfigured software bundle for UAV designs (writes Nick Flaherty).

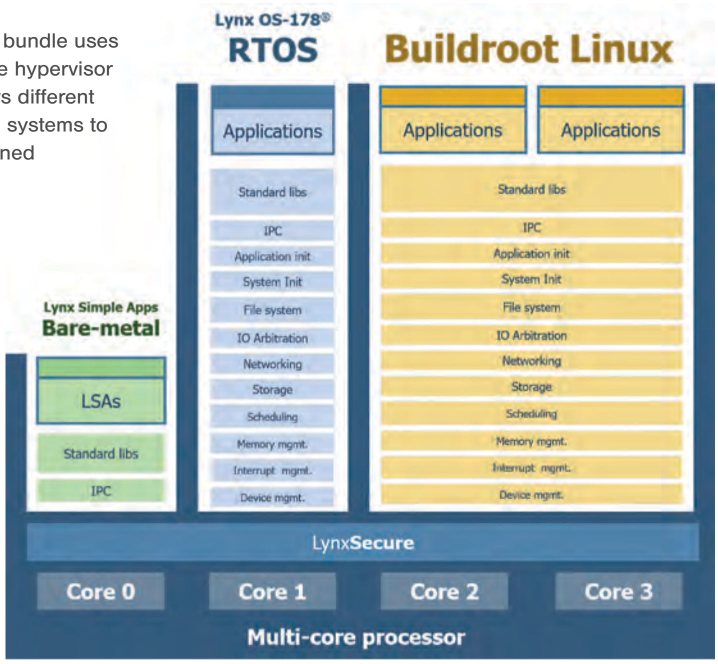
LYNX MOSA.ic for UAVs/Satellites uses a software hypervisor that allows developers to combine real-time operating systems with those from third parties. The hypervisor supports both ARM and x86 processor architectures to run LynxOS-178, Lynx's proven DO-178 certified OS, the LynxSecure separation kernel hypervisor and Linux.

The bundle includes tools such as Lynx Simple Applications (LSAs). These are true bare-metal applications, meaning they run directly on hardware without the need for any underlying operating system components.

For developers who need to meet the strict timing requirements of complex and safety-critical systems, Lynx Advanced Scheduling can be used to precisely control the execution and timing of the LSA components in the system. Comms interconnects are enforced by security policies with fast and low-latency comms between critical functions hosted on LSAs and guest operating systems.

Any LSA or guest OS can be securely connected with any other LSA or guest to move data efficiently through the processing pipeline. A key example of this is a cryptography module called LSA-store for security.

The bundle also includes the software tools for building applications. The Luminosity, SpyKer and TraceCompass tools are Eclipse-based environments that allow intuitive build and debug of applications and drivers, event tracing and visualisation for LynxOS-178 and Linux guests.



The Lynx bundle uses a software hypervisor that allows different operating systems to be combined

Rugged server/sensor unit

Data storage

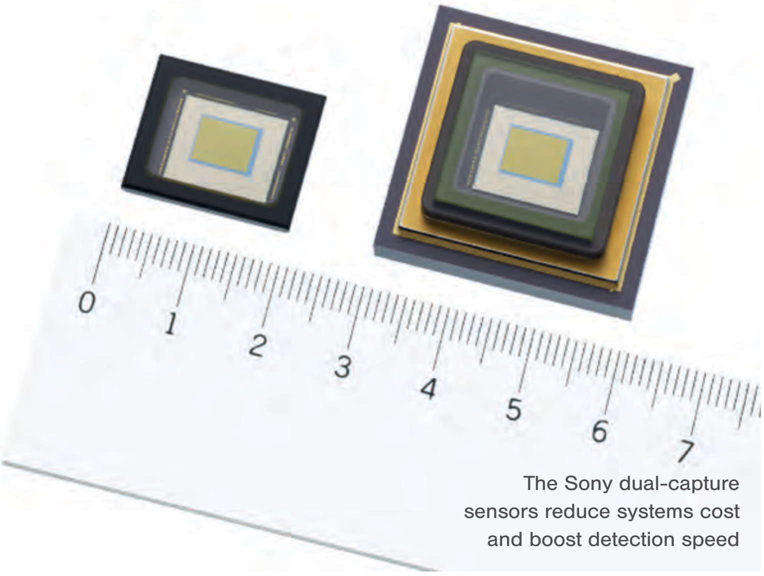
Crystal Group has developed a 5U server and sensor fusion unit for autonomous vehicles (writes Nick Flaherty).

The EIA-310 compliant AVC0161 Rugged Intelligence and Autonomy (RIA) sensor fusion system is designed to securely fuse massive amounts of sensor data and survive physical and cyber threats. It combines high-performance computer boards, data processing, storage and the critical thermal management capabilities necessary for autonomous and optionally manned vehicle operations.

The sensor fusion system is supported by the AVC5904 5U rugged server. It uses dual Intel Xeon Scalable processors and up to 384 Gbytes of DDR4 memory. Modular input/output panels provide integration with various connectors and sensors. An integral 1500 W 10-32 V DC power supply eliminates the need for high-power voltage inverters typically used with AC-powered servers.

This saves valuable space, time and energy by directly and internally sourcing the power needed for critical functions, and allows thermal issues to be addressed directly with liquid cooling for the boards and two fans for other components. The standard-fit, rack-mount server provides additional flexibility with either eight removable 15 mm/2.5 in drives or 12 removable 9.5 mm drives.

The RIA unit measures about 17 x 36 x 40 cm and combines dual Intel Xeon Scalable processors, 2 Tbytes of DDR4 memory, and PCI Express 16x high-speed data interfaces in a rugged, aluminium enclosure. It supports up to three graphics processors for running neural network algorithms for machine learning.



The Sony dual-capture sensors reduce systems cost and boost detection speed

First for visible/SWIR

Sensors

Sony has unveiled miniature single-chip megapixel sensors that for the first time can capture images in visible light and short-wave infrared (SWIR) at the same time (writes Nick Flaherty).

They use Sony's SenSWIR technology with a 5 µm pixel, the industry's smallest, for industrial applications. SenSWIR uses photodiodes formed on an indium gallium arsenide compound semiconductor layer and connected via a copper-to-copper connection with the silicon layer rather than a solder bump.

Using this approach for the readout circuit enables high sensitivity over wavelengths from 0.4 to 1.7 µm, as well as the smaller pixel size and a digital output.

Sony has used the technology in two compact sensors for cameras and test equipment for a range of industrial equipment such as materials selection, contaminant inspection and semiconductor inspection.

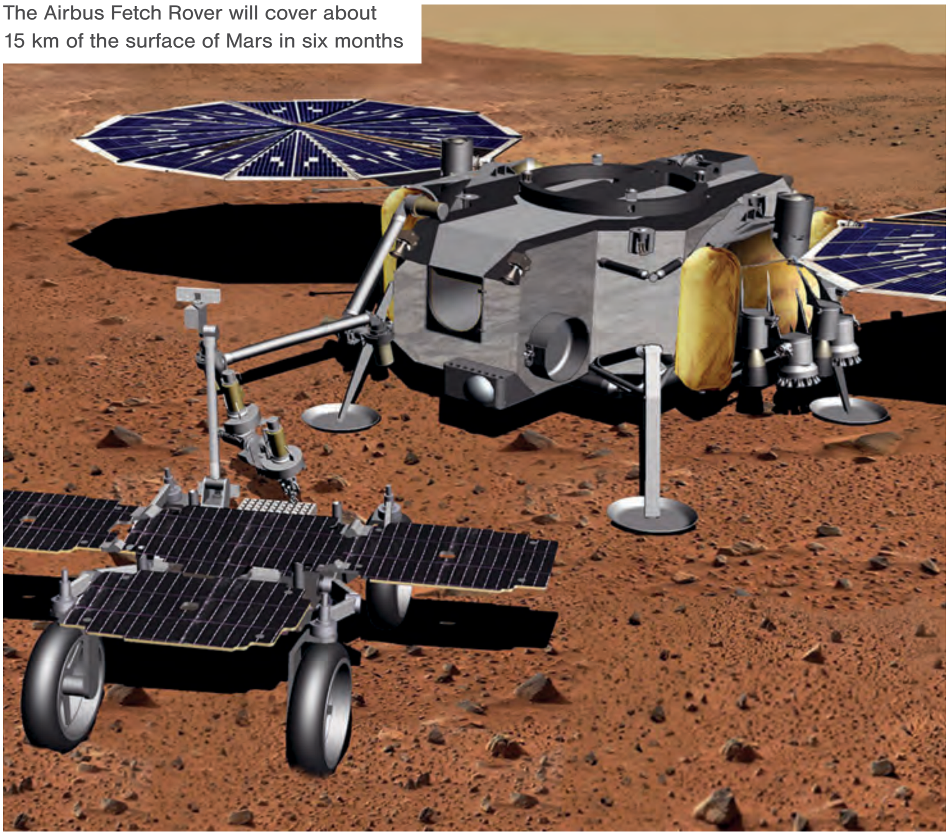
The combination of visible and SWIR imaging allows a wider range of materials to be detected from a single sensor rather than multiple units. This reduces the system cost and provides faster detection speeds thanks to the reduced image processing load, allowing for a dramatic expansion in testing range.

The first product to use this sensor, the IMX990, is a 1/2-type (8.2 mm diagonal) global shutter design with a 1.34 effective megapixel SWIR image sensor. It is packaged in a ceramic LGA and PGA package with a built-in thermoelectric cooling device.

An 8-bit output provides 130 fps, falling to 70 fps with a 12-bit resolution. The power rails are 2.2 V, 1.2 V (pixel); 3.3 V, 2.2 V (analogue); 1.2 V (digital); and 1.8 V (interface).

The second sensor, the IMX991 is a 1/4-type (4.1 mm diagonal) design with a 0.34 effective megapixel SWIR sensor in the same packages and with the same power rails and outputs.

However, the sensors initially cost upwards of $8000, which is typically the cost of a camera itself, so the smaller size will command a premium.



The Airbus Fetch Rover will cover about 15 km of the surface of Mars in six months

Fetch samples

Space vehicles

Airbus Defence and Space is developing an autonomous rover that will collect samples left by other rovers on Mars (writes Nick Flaherty).

The Fetch rover is different from the others on the planet in that it will travel much further and faster to collect samples. This requires far higher levels of autonomy.

The rover is part of the Mars Sample Return project with NASA and ESA. NASA's 2020 Mars rover mission Perseverance, which at the time of writing was due to launch shortly, will collect Martian soil and rock samples and leave them on the surface in small metal tubes. It will travel a total of 4 km over the length of the project.

In 2026, the ESA rover will travel to Mars to collect these tubes. Landing in 2028, it will then travel an average of 200 m a day over a period of six months and a total distance of 15 km to find and pick up 36 of the 43 sample tubes.

It will then carry them back to the lander and place them in a Mars Ascent Vehicle, which will launch them into orbit around Mars. Another spacecraft developed by ESA (with a NASA payload), the Earth Return Orbiter, will collect the samples from orbit and return them to Earth.

Image recognition algorithms for spotting the sample tubes on the Martian surface have already been developed by the Airbus-led team. A dedicated robotic arm with a grasping unit to pick up the tubes is being designed with a group of European companies.

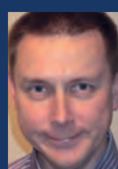
The 125 kg Fetch Rover will have four wheels, all larger than the six flexible wheels used on the ExoMars Rover to better cope with the range of terrain it will encounter. The rover has to move more quickly than ExoMars to meet the timings for returning the samples so that they can land back on Earth in 2031.

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.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UST diary *(Entries in italics denote shows being held virtually owing to the Covid-19 lockdown)*

TU-Automotive Detroit
Tuesday 18 August – Thursday 20 August
www.automotive.knect365.com/tu-auto-detroit

Military Robotics & Autonomous Systems
Wednesday 2 September – Thursday 3 September
www.smi-online.co.uk/defence/uk/conference/robotic-autonomous-systems

MOVE Asia
Wednesday 9 September – Thursday 10 September
www.terrapinn.com/exhibition/move-asia

Commercial UAV Expo Americas
Tuesday 15 September – Thursday 17 September
www.expouav.com

UAV Technology 2020
Monday 28 September – Tuesday 29 September
www.smi-online.co.uk/defence/uk/conference/UAV-Technology

Japan Drone
Tuesday 29 September – Wednesday 30 September
Chiba, Japan
www.japan-drone.com

TUS Expo
Wednesday 30 September – Thursday 1 October
Rotterdam, The Netherlands
www.tusexpo.com

AUVSI Xponential
Monday 5 October – Thursday 8 October
www.xponential.org

INEC 2020 – Disruptive Technologies
Tuesday 6 October – Thursday 8 October
www.imarest.org/events/inec-2020

Interaerial Solutions, Intergeo & European Drone Summit
Tuesday 13 October – Thursday 15 September
www.interaerial-solutions.com

UAS Summit & Expo
Tuesday 13 October – Wednesday 14 October
Grand Forks, ND, USA
www.theuassummit.com

BSDA
Wednesday 14 October – Friday 16 October
Bucharest, Romania
www.bsda.ro

AutoSens Conference & Exhibition
Tuesday 17 November – Thursday 19 November
www.auto-sens.com

Global Robot Expo
Tuesday 20 October – Wednesday 21 October
www.globalrobotexpo.com

PMRExpo 2020
Tuesday 24 November – Thursday 26 November
www.pmrexpo.de/en/pmr20

Unmanned Maritime Systems Technology
Wednesday 25 November – Thursday 26 November
London, UK
www.smi-online.co.uk/defence/uk/conference/Unmanned-Maritime-Systems

Oceanology International
Tuesday 1 December – Thursday 3 December
London, UK
www.oceanologyinternational.com

Undersea Defence Technology
Tuesday 8 December – Thursday 10 December
Rotterdam, The Netherlands
www.udt-global.com

ASME's Robotics for Inspection & Maintenance
Wednesday 9 December – Thursday 10 December
TX, USA
www.event.asme.org/Robotics

InterDrone
Tuesday 15 December - Thursday 17 December
Dallas, Texas, USA
www.interdrone.com

CES Tech
Wednesday 6 January - Saturday 9 January 2021
Las Vegas, USA
www.ces.tech

Oceanology International Americas
Monday 15 February – Wednesday 17 February 2021
San Diego, CA, USA
www.oceanologyinternationalamericas.com

Saudi International Airshow
Tuesday 16 February – Thursday 18 February 2021
Riyadh, Saudi Arabia
www.saudiairshow.aero

IDEX
Sunday 21 February – Thursday 25 February 2021
Abu Dhabi, UAE
www.idexuae.ae

BAPCO
Tuesday 9 March – Wednesday 10 March 2021
Coventry, UK
www.bapco-show.co.uk

DroneX
Wednesday 10 March – Thursday 11 March 2021
London, UK
www.dronexpo.co.uk

Unmanned Systems Asia
Tuesday 30 March – 1 April 2021
Changi, Singapore
www.unmannedsystems-asia.com

Ocean Business
Tuesday 13 April – Thursday 15 April 2021
Southampton, UK
www.oceanbusiness.com

Adriatic Sea Defense & Aerospace
Wednesday 21 April – Friday 23 April 2021
Split, Crotia
www.adriaticseadefense.com

Connected & Autonomous Vehicles
Monday 26 April – Thursday 29 April 2021
San Jose, CA, USA
www./tmt.knect365.com/connected-vehicles

Autonomous Vehicle Technology Expo
Tuesday 8 June – Thursday 10 June 2021
Stuttgart, Germany
www.autonomousvehicletechnologyexpo.com

Critical Communications World
Tuesday 8 June – Thursday 10 June 2021
Madrid, Spain
www.critical-communications-world.com

Australian Association for Unmanned Systems (AAUS) conference (Rotortech)
Wednesday 15 June – Friday 17 June 2021
Brisbane, Australia
www.rotortech.com.au

Autonomous Ship Technology Symposium
Tuesday 22 June – Thursday 24 June 2021
Amsterdam, The Netherlands
www.autonomousshipsymposium.com

iVT Expo – Autonomous Hardware, Software, Testing and Validation
Tuesday 29 June – Wednesday 30 June 2021
Cologne, Germany
www.ivtexpo.com

Global Drone Conference
June 2021, dates TBC
MITEC, Kuala Lumpur, Malaysia
www.globaldroneconference.com

DSEI
Tuesday 14 September – Friday 17 September 2021
London, UK
www.dsei.co.uk

UAV Show
Tuesday 19 October – Thursday 21 October 2021
Bordeaux, France
www.uavshow.com

BIDEC
Monday 25 October – Wednesday 27 October 2021
Bahrain
www.bahraindefence.com

Volansi's CTO tells **Rory Jackson** how his passions for mapping and aviation inspired his work on developing UAVs

Career map

Buchmueller has overseen the launch of the Voly M20, Volansi's fastest and heaviest UAV, which has a 5 kg payload capacity (Courtesy of Volansi)

Born and raised in the Zurich highlands, Daniel Buchmueller's early childhood was rich with experiences that would stimulate a lifelong interest in aviation. In the earliest of these, he witnessed a helicopter from aerial search & rescue organisation Swiss Air-Rescue (or Rega) land at an event celebrating the reopening of a hospital.

"Rega is one of Switzerland's most iconic brands, so seeing that red-and-white helicopter – this machine that to my eyes could miraculously set down and lift off vertically – was a real moment of awe, and remains one of my earliest aviation memories," he remarks.

Now the CTO of UAV developer Volansi, Buchmueller says, "Growing up in a small countryside town, I spent a lot of time outdoors, and when I wasn't playing sports I was flying and tinkering with RC aircraft. I was heavily into them, and I flew just about every type that was available in the late 1980s and early '90s.

"In parallel, I had a growing interest in computing. Although I'd originally enrolled at the University of Zurich to study physics, I transferred to computer science because that was where my passions were leading me. I started writing software, and building small websites – this was around the time of the dotcom boom, when everyone needed a website – using increasingly complex programming technologies."

On the basis of his studies and work experience, he founded another small software development company, iContent, aimed at programming custom software solutions for businesses. That company served as a springboard for creating Geocentrale and GeoCloud, two of the earliest cloud-based

Buchmueller co-founded Amazon Prime's delivery UAV initiative, and led the r&d from its development centre in Cambridge, UK (Courtesy of Amazon Prime Air)

geospatial data service providers, which still operate in Switzerland.

As he recounts, "I'd long had a fascination with mapping. It is kind of an intersection between aviation and computer science – how you get to the right altitudes and places, how you orient yourself and make sure the imagery stitches together to actually create high-quality maps through photogrammetry."

Mapping for Microsoft

After summer internships at Microsoft in Washington state in 2006 and 2007, he accepted an offer to work full-time there and moved to the US. He began working on Microsoft's Virtual Earth mapping initiative project (which would later become Bing Maps), programming software for both the back end and the customer-facing side of the product.

"I'm still friends with many of the people from those days," he says. "Gur Kimchi, for example, who was one of the three people who started Virtual Earth and would later go on to co-found Amazon Air, has been a consistent influence and frequent collaborator with me on several projects."

Over time, Buchmueller transitioned to working on augmented reality projects. That culminated in the Microsoft HoloLens and its associated services, such as matching query pictures of landmarks to a database of billions of pictures, to answer questions on the pictures.

Pioneering UAV photogrammetry

In late 2012 he was recruited by Amazon, which wanted him to create a product recognition solution for the Amazon Go stores (where customers would walk in, grab the products they wanted, and walk out while being automatically charged). For this he applied the lessons he had learned developing computer vision at Microsoft.

"Before that though, in the fortnight before joining Amazon, I'd gone with a friend to Hawaii for a personal project with a quadcopter drone kit from Team Blacksheep, to experiment with mapping using a point-and-shoot camera."

The pair aimed to disprove the widely held myth at the time that Lidar was always necessary to generate aerial 3D models. "I felt Lidar was excessively heavy and energy-inefficient for airborne operations," he says. "My hunch was that even consumer-grade cameras could create matches using the overlaps and common features between photographs, basically creating a self-adjusting and highly accurate model of the world."

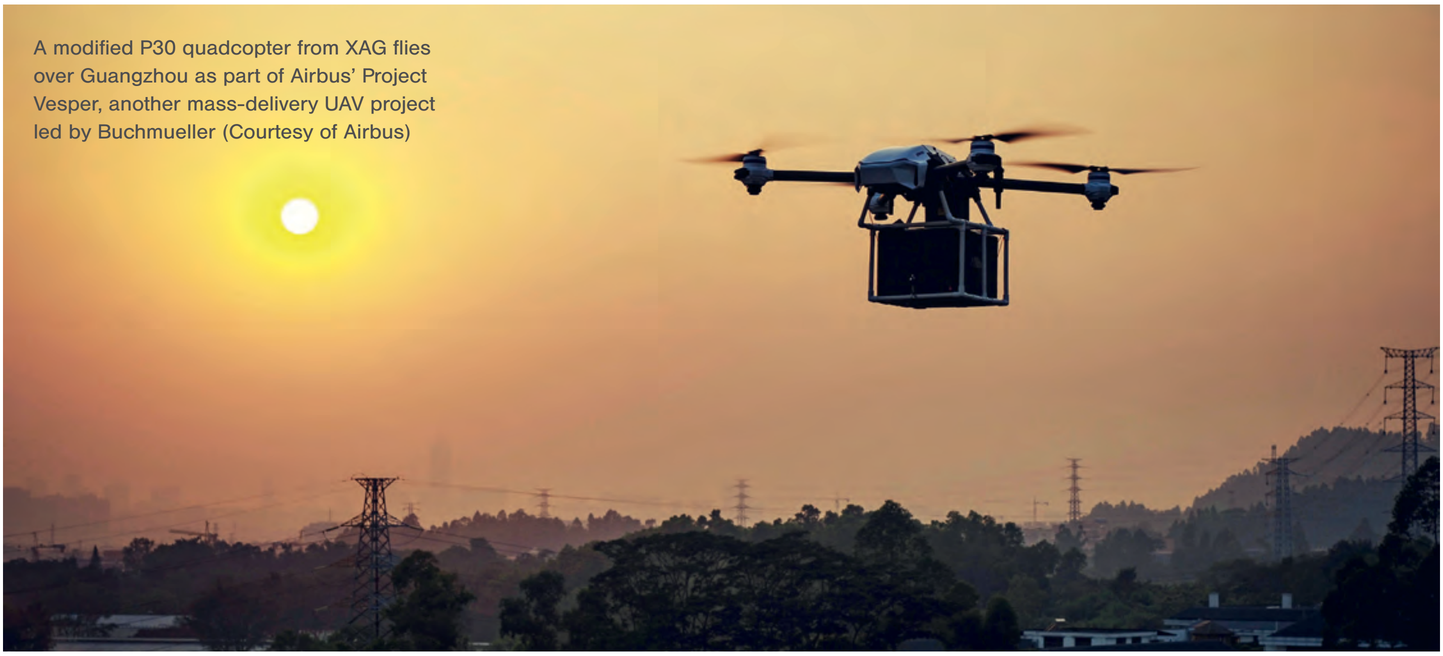
Having put markers on the ground all around the Iolani Palace in Honolulu at known distances between them, and uploading custom firmware to control the camera's shutter, they were able to program-in these distances to build their 3D model of the area.

The result had a margin of error just below 0.5% (equating to about 2 cm), definitively meeting the standards for commercial geo-surveying requirements in most places at the time.

Founding Amazon Prime Air

In early 2013, after relating this trip to Kimchi – particularly the tremendous stability afforded by the quadcopter's distributed lift architecture – Buchmueller posited that one day, UAVs would be used to save people or deliver medicines and other life-saving goods, just like the Rega helicopters that had captured his fascination as a child.

"And indeed, Rega uses UAVs for search & rescue missions today," Buchmueller notes. "So after our conversation, Kimchi and I were motivated to write a proposal to Jeff [Bezos] – as is standard for suggesting new



A modified P30 quadcopter from XAG flies over Guangzhou as part of Airbus' Project Vesper, another mass-delivery UAV project led by Buchmueller (Courtesy of Airbus)

business ventures at Amazon – to deliver Amazon packages by UAV to customers' backyards. And then we just started ordering COTS UAV parts with our own credit cards, excited to start building multi-copter aircraft that could accomplish this."

After assembling a team of technicians and coders to work nights and weekends, Bezos greenlit the project later that year, and in 2015 Buchmueller moved to Cambridge, UK, to build up Amazon's new UAV development centre there.

"In the US at that time there wasn't a clear path for flight testing and developing UAVs, which was a huge risk to these sorts of programmes," he says. "In the UK though, we were welcomed with open arms by the Civil Aviation Authority's UAS team, and they provided immense ongoing feedback and support for our engineering, flight trials and operations.

"Because it was England, it was often windy, which was great for proving out the limits of the UAV's stability, and often cold, which meant we didn't have to worry about motors or electronics overheating. By the end of 2016, one of my teams was able to accomplish the first real UAV-couriered delivery of a package to an Amazon customer – and of course, there's ongoing development and testing in England to this day."

Project Vesper

Following a roughly two-year sojourn from UAVs (spent as director of engineering at Flatiron Health, producing software to help accelerate cancer research), Buchmueller was approached by Dirk Hoke, CEO of Airbus Defence and Space, and Jana Rosenmann, head of Airbus' UAS programmes.

"Jana and Dirk wanted to develop commercial UAV programmes that could perform the same operations as helicopters across mapping, surveying and cargo operations but with far lower running costs. I was asked to start up and realise the cargo aspect," he explains.

"We did that in secret for about a year, and found a great partner in XAG, based in Guangzhou, which is one of the oldest UAV manufacturers in the world."

XAG and Buchmueller's Airbus team built modified versions of the former's P30 agricultural spraying quadcopter. In late November 2019, they launched Project Vesper in Guangzhou, a full delivery trial of cargo-carrying UAVs, to enable quick feedback cycles for critical updates on the UAVs.

"The UAVs were equipped with parachutes and other safety systems, and approved for flight by the CAAC [Civil Aviation Administration of China], enabling us to fly these vehicles safely in an urban environment," Buchmueller says. "UAVs aren't always built safely; they could crash and hurt a lot of people. But XAG's vehicles had millions of flight hours logged, and it all went fine."

Volansi's Voly M20

Earlier this year, Hannan Parvizian, CEO of Volansi, asked Buchmueller to join as CTO.

"Leading projects in a relatively small firm allows so much more engineering flexibility and focus than in large, comparatively unwieldy multinational corporations, and better incentivises efficiency too," Buchmueller says. "In the latter, you're required to double- and triple-check everything before you do it, and you risk losing your department's budget if you don't use it all.

"On top of that, Volansi has attracted some world-class engineers, such as Steve Morris as vice-president of aircraft engineering, who created Martin UAV's V-Bat [detailed in *UST* 15, August/September 2017]."

Although almost all his past UAS experience had been focused on last-mile delivery applications, Volansi's Voly family of aircraft are being designed and built for 'middle-mile' operations, working over dozens of miles rather than ten or less.

"In mining, for example, when a machine breaks down it can cost tens of thousands of dollars per hour," Buchmueller says. "You have to rectify the problem – and fast – and it takes less time to fly a spare part straight to the mine than transport it by road."

All Voly-series UAVs are designed as twin-boom VTOL-transition aircraft, which combine fixed-wing and quadrotor propulsion architectures. As CTO, Buchmueller has overseen the unveiling of Volansi's newest Voly, the M20.

He says, "The M20 can carry up to 20 lb [9 kg] of cargo, in a shoebox-sized container as standard beneath the centre of gravity. You'd be surprised by how many things people want to be able to deliver over medium distances at short notice that fit that volume.

"More than 80% of spare parts that are needed for broken-down equipment fit within this UAV's capacity. It's not dissimilar to what motivated us at Amazon – back then, 70-90% of Amazon shipments weighed less than 5 lb."

On top of this versatility in carrying capacity, the M20 has been designed with a multi-role capability for missions over water as well as flying over land – the 'M' prefix is intended to indicate that the craft has been designed for use in maritime environments.

That has involved significant structural and surface engineering to protect its internal and propulsion systems against ingress and corrosion from sea spray, and developing the control software to tolerate sea-level gusts and crosswinds during take-off, hover and landing.

The M20 also has a payload bay under its nose (unlike Volansi's other UAVs) to house 10 lb (4.5 kg) EO/IR gimbals for intelligence, surveillance and reconnaissance missions at the same time as the 20 lb of cargo.

These payload options are part of a 230 lb (104 kg) MTOW, and the M20 has a cruising speed of 70 mph, making it Volansi's heaviest and fastest UAV to date. Propulsion comes from a new (unnamed) boxer engine, available in gasoline and heavy-fuel variants, the latter being a vital requirement for maritime integration, given that the higher flashpoint of heavy fuels makes them less of a fire hazard.

"Volansi's engineers have accumulated huge in-house experience of hybridising aircraft to use the engine for propulsion, and for recharging the batteries for electrically powered hover and VTOL, as well as timing them, minimising emissions and keeping them reliable in different environments.

"I've had to quickly come to grips with a lot of that. Until the gravimetric energy density of batteries gets way, way higher, the use of small UAV-type engines is going to be a massive differentiator in the success of UAVs. The M20 for instance can cover 300 miles on a full fuel tank, and today's industrial users want ever-longer ranges.

"Also, every UAV carries cellular and satellite data links as standard. We can reach them and trial them from anywhere in the world, and recover lost links for customers before handing control back to them."

In Buchmueller's view, this 'always-connected' functionality will need to become a common standard for UAVs the world over. "You never worry about whether your smartphone for example is connected – you know you can be reached safely, anytime, anywhere. Our UAVs are the same, and that's driven by applying commodified internet technologies such as cellular, cloud computing, edge computing and so on."

He says this intersection between UAVs and IoT technology will enable a sorely needed rise in functionality and reliability for the former, not only across the geo-mapping world where he first began but in logistics, humanitarian aid, maritime surveillance and beyond.

Daniel Buchmueller

Daniel Buchmueller is CTO of California-based Volansi, where he oversees the development of the company's VTOL-transitioning, medium altitude, medium endurance heavy-lift UAVs aimed at maritime and terrestrial industries as well as defence and security forces.

His early childhood in Switzerland was spent among helicopters and RC aircraft, and during his university years he gained academic and professional expertise in software programming and mapping, as well as doing his national service in the Swiss Army.

After four years at Microsoft, working mainly on Bing Maps (or Virtual Earth as it was then called), he went to work for Amazon in 2013 and co-founded Amazon Prime Air. Here he led development teams for the retail giant's UAVs through flight testing and the first airborne package delivery in England in 2016.

From 2018 to this year he led Airbus' Project Vesper, aimed at developing UAV courier services, launching full-scale flight trials in November last year in Guangzhou, China, before joining Volansi earlier this year.

He has also developed software aimed at business development services, augmented reality and supporting cancer research. He is also a board member at Silo, which produces safes that incorporate biometrics and other IoT-type security technologies.

The Gen6 showing its transparent sail at an angle to the direction of travel with four sets of three internally mounted solar panels (Images courtesy of SubSeaSail unless stated otherwise)

Solar power generation and wingsail propulsion give this semi-submersible practically unlimited endurance. **Peter Donaldson** reports on how it was conceived and developed

Sailing orders

SubSeaSail's sixth-generation unmanned sailing vessel has an unusual configuration that places most of it under the surface. This enables it to keep acoustic sensors clear of wave noise, leaving only the wingsail and a small section of the flotation module that supports it above the surface, where they provide space for comms components, small payloads and solar panels.

Described by the company as an unmanned semi-submersible vessel (USSV), it is now in service with its first customer and is also offered for missions in the realm of ocean science and defence, including weather and water monitoring, surveillance, intrusion detection and even cargo delivery. Some versions will have the option of submerging completely to avoid bad weather, collision or hostile interference.

The original concept came from a requirement issued by the US National Oceanographic and Atmospheric Administration for a way to move small 'daughter' UUVs long distances and release them for limited-life missions. The concept was subsequently greatly expanded, and the initial patent went from eight claims to more than 20 that conceived a series of sizes and forms for the USSV.

> You have friction and viscous drag but not wave-making drag, so you need much less power from the sail, reducing its complexity

The Gen6's main hull is a streamlined cylindrical body connected to the flotation body by two members that form a triangle with the float at the apex and the hull at the base. The forward member is the structural keel, while the post around which the rudder pivots forms the after-member.

"Pushing a streamlined body through the water produces less drag than the same volume would on the surface, because you don't have to generate a wave train," SubSeaSail's co-founder and lead technical partner Chris Todter explains. "You have friction and viscous drag, but not wave-making drag, so you can get away with substantially less power from the sail, in turn reducing its size and complexity."

The wingsail is supported on the flotation module (buoyancy section) by a static mast, at the top of which lightweight antennas, cameras and lights can be mounted. Pivoting freely around the mast, the sail is hollow, transparent and floodable, and needs no powered actuation.

Transparent materials are used for the wingsail because several potential customers envisaged applications in which low observability in terms of visual, radar and thermal signatures was important. The wingsail is open at the

The Gen6 main hull has an interchangeable payload module in the nose. Above it are the keel, rudder post and rudder

This exploded view shows the major components. Note the computer module in the centre and the sail regulation mechanism at the upper left

top and bottom, so it floods naturally as the boat submerges.

To keep the wingsail at the optimum angle with respect to the wind for efficient propulsion, SubSeaSail has developed and patented a passive automatic wing control mechanism. Eschewing the use of complicated and expensive electronics, pulleys and lines, the mechanism works by a combination of aerodynamic forces and a cam with a spring-loaded follower system.

The only electromechanical control device the vessel needs is a servo actuator for the rudder. A modified RC servo is used, and it is pressure-balanced, filled with oil and fitted with a spring mechanism to prevent any overloading – perhaps from accidental pressure on the rudder – while it is being handled during launch, recovery or maintenance. It accounts for most of the electrical load the boat imposes, amounting to less than 1 W 'house load' (every load other than propulsion).

The upper region of the buoyancy section houses an inertial measurement unit (IMU) and navigation electronics, including the GNSS receiver and the autopilot. A ballast tank and related pump system to control submerging and surfacing (in versions with this option) are installed in the lower region of the float module, which can also accommodate payloads.

The main hull under the water provides space for internal and external payloads, and contains ballast – which can be lead or bismuth alloy – and a nickel metal hydride (NiMH) battery pack. It can also be modified to accept payloads to suit various missions through the use of modular, interchangeable nose caps.

At the aft end of the hull there is a T200 electric auxiliary thruster from Blue Robotics that is used for maintaining position inside predetermined survey areas and when sailing close to the shore in light winds. Fitted with a proprietary propeller, the thruster typically generates between 5 and 10 N of thrust and draws 5-20 W of power. Also attached in this area is a passive stabiliser that is designed to minimise pitch in higher sea states.

Power generation and management

Electrical power is generated by custom polycrystalline solar panels with an average output of around 5 W and a peak of almost 25 W. They can be mounted on the deck of the float module, inside the transparent wing structure, or they can form the outer wing skin.

The power management system is based on a maximum power point tracking (MPPT) controller, and is configured to allow the solar panels

Bolted to the rear of the hull is the T200 electric thruster from Blue Robotics, which has a fully flooded brushless motor with encapsulated motor windings

Specifications

Height: 152 cm for the wingsail, 152 cm for the vessel, 304 cm total
Length: 150 cm
Width: 25 cm
Weight: 28 kg
Endurance: theoretically unlimited
Depth rating: 10 m
Propulsion: sail, primary; thruster, back-up and station-keeping
Speed: 0.5-3.0 knots
Battery pack: 450 W/h nickel metal hydride
Solar panels: 30 W peak on wingsail, 10 W peak on deck
System operating load: 0.6 W/h
Maximum system power: 5 A @ 13.2 V DC
Computer system: PIC CPU, XBEE wi-fi, 9603 Iridium, serial, Micro SD, IMU
IMU: MEMS three-axis accelerometers, gyros, magnetometers
GPS: 12-channel, accurate to 3 m horizontal dilution of precision
Station-keeping accuracy: 30 m radius in a 0.5 knot current
Auxiliary power and comms port: for external sensors and payloads
Maximum payload: 20 kg (neutrally buoyant)
Payload power: 20 W peak, 5 W maximum continuous
Ports: 12 V, RS-232, battery charge
Comms: Iridium 9603, wi-fi, cellular FreeWave option
User interface: chart-based GUI for pre-programmed missions, full manual control via PC or tablet
Options: Conductivity, temperature and depth, turbidity and salinity sensing, water speed measurement, AIS receiver, magnetometry, mast camera, AIS receiver, custom comms, sonar, hydrophones, swarming behaviours, Iridium RUDICS data service

Some key suppliers
Sonar arrays: Applied Ocean Sciences
Waterproof connectors: Blue Trail Engineering
Auxiliary thruster: Blue Robotics
Satellite comms: Iridium
Component and subsystem manufacture: Kroova
Water quality sensor package: Sontek/Xylem

to charge the batteries and power the electrical loads directly. The power transfer efficiency of solar cells varies with the light falling on them and the electrical characteristics of the load, so MPPT controllers sample the cells' output and apply the proper resistance to obtain the maximum power available in the conditions.

Todter notes that such controllers have been used in large solar power installations for years, but have only recently become available off the shelf in packages compact enough for small boats. "We just chose a 40 mm square circuit board that has everything we need on it," he says. "We actually made our own at one point, but it wasn't worth the effort."

The electrical harness is made up of polyurethane jacketed multicore wiring with waterproof connectors from Blue Trail Engineering.

The Gen6's battery pack capacity is around 450 W/h. NiMH chemistry was chosen because of the shipping limitations imposed on lithium-ion batteries and armed forces' dislike of them.

Operating speeds of between 1 and 2.5 knots are typical, Todter says, adding that theoretically the boat can remain at sea indefinitely, while the practical limits have yet to be found. Also yet to be determined are its operational and survival limits in terms of wind speed and wave height, but it has been calculated that it will be able to operate successfully in winds of up to 30 knots and waves at least 3 m high, and survive in waves up to 5 m. With its 1.3 m draft, the vessel needs a minimum of about 1.5 m of water to sail safely.

While the submersible option is intended principally to avoid detection and rough weather, the vessel can move slowly under water when propelled by its thruster, but the intent is simply to loiter until the threat has passed.

Buoyancy and righting moment

The Gen6's configuration presents a challenge when it comes to generating a righting moment, which is the force that resists the tendency of the wind acting on the sail and the action of waves to push the boat over. To create a righting moment, the vessel has to have positive buoyancy (rather than the neutral buoyancy that would be appropriate for a submerged craft) and the centre of buoyancy has to be above the centre of gravity.

"In our case, the centre of gravity is as far down as we can get it because we put all the heavy stuff in the streamlined hull at the bottom," Todter says. "But since you have to be able to support the wing just above the surface you've got to have something that pierces the surface, and you can't balance the weight and the flotation exactly, so there has to be a little residual flotation."

The challenge is to minimise that residual buoyancy. "To do that you have

The Gen6 sailing in rough conditions. Balancing buoyancy and weight is crucial – too much weight will sink it; too much buoyancy will make it heel too far in the wind

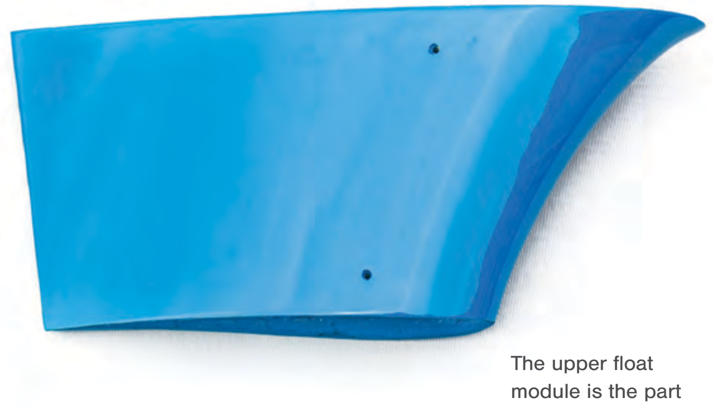
to do a fairly accurate assessment of the buoyancy and the weight, so our vessel is therefore somewhat sensitive to weight and the volume," he says.

He explains that carrying something that's even a little too heavy would turn the buoyancy negative, causing the boat to sink, while something that adds buoyancy would make it float too high so that the righting moment would be insufficient, with the result that the boat would heel over too much. "The physics says it will sail, and it does. It's not impossible; it's just a little weird," he says.

Designed using SolidWorks, the vessel has evolved from the original concept, becoming larger and faster and adding a submersible capability and a catamaran variant as options. Minor refinements and improvements have been made over time, arriving eventually at the current Gen6 form.

The first vessel built was a subscale proof-of-principle model about 400 mm long. "It was really only to demonstrate that the physics were valid, but it didn't have enough power to sail in anything other than a millpond," Todter says.

Other proof-of-principle models that focused on other aspects followed, gradually getting larger until one that was more than three times the size of



The upper float module is the part that pierces the surface. It is kept as small as practical to minimise wave-making drag

The 'perturb and test' autonomous sailing method is based on finding headings that maximise the 'velocity made good' towards the next waypoint without the need for direct wind measurement

the original attracted military interest as a means of transporting useful quantities of fuel and other materiel as cargo. It was for this role that the second generation represented the most substantial variation in the configuration of SubSeaSail USSVs – a catamaran.

In this role, the ability to bring the whole of the vessel to the surface for loading and unloading is essential. "You can't really do that with a monohull because it tips over when you bring it to the surface, so we built a catamaran version," Todter says. "It sailed mostly under water, but featured a ballast water pumping system so it would come up and sail on the surface as well."

After the Gen2 catamaran demonstration, SubSeaSail turned its attention back to monohull configurations, making the prototypes larger, faster and more powerful, and capable of longer missions. The next step was to develop an autopilot to enable it to sail by itself with minimal sensor input, which presented challenges of its own.

Submerging and surfacing

By this time, the company had what it considered to be a viable monohull vessel, but it also wanted to demonstrate the ability to submerge completely in order to shelter from bad weather or escape hostile attention. It therefore developed a version with a variable ballast system based on the one developed for the catamaran.

This pumps water into a set of three ballast tanks so that the vessel can submerge and hold the chosen depth before surfacing on command. In each tank is a bladder containing air that becomes compressed by the water pumped into the tank to make the boat submerge.

To force the water out, the control system opens a set of valves and the air pressure in the sealed bladders forces the water out again and brings the boat to the surface. The ballast pumping system has to be accurate and responsive because of the boat's sensitivity to small changes in buoyancy.

"It will sink as soon as it is neutral, but if it's 10 g over that weight it will just keep going, it will sink forever," Todter says. "So there is another control algorithm in the computer that uses input from a water pressure sensor to work out the depth and decide whether to pump more water in or let some out."

If ballast control is not sufficiently quick and accurate, the boat is likely to oscillate around its depth target dramatically, so the pumping system, water pressure sensing and control algorithm are critical to stable depth-keeping.

Unlike in a manned submarine, this is a closed system that does not require a snorkel to replenish the air supply or an air compressor and a system of high-pressure storage tanks.

One challenge with developing this buoyancy management system was sourcing the miniature submersible pumps, valves and tanks. While there are, for example, suitable tanks available off the shelf, they were never exactly the right combination of size, volume and pressure capability.

"There are some compromises in that, and I think the next place we will go in that regard is to develop our own tanks so that we can optimise them," Todter says.

Deducing the wind

The Gen6 vehicle has a basic level of autonomy in that it will accept a set of waypoints that can be uploaded to it via wi-fi or an Iridium satcom system, and follow them in the programmed order, loitering or submerging at any point as commanded. The software has been written in Embedded C, runs on a proprietary computer and sails the vessel between waypoints without any direct information on the direction or speed of the wind.

"If you are a sailor you understand very quickly that knowing the wind direction is important," Todter says. "You can't sail directly into the wind, but you can go almost anywhere else at different headings to the wind and at different performance levels."

Todter wanted to simplify the autonomous sailing system by eliminating the need for an anemometer and its associated cost and complexity. "Our aim from the outset has been simplicity and low cost, while trying to make the vessel almost disposable from the military's point of view," he says.

The only navigation sensors SubSeaSail uses are a GNSS receiver with an integral IMU and a digital magnetic compass. This combination enables the software to infer the direction and strength of the wind through a 'perturb and test' methodology, which Todter describes as new territory in control system operation.

"The simplest thing to do is to head straight for your next waypoint and see what happens," he says. "If you are making progress, the assumption is you are not sailing directly into the wind.

"Then you try to improve your performance by sailing either a bit left or a bit right of your current heading. The measure of performance is called the 'velocity made good' [VMG], which is the speed directly towards your goal."

Because velocity is a combination of speed and direction, if the vessel is heading directly towards the waypoint, the VMG and the speed are the same. If the boat is moving at the same speed but at some angle to the direct line between the boat and the waypoint, the VMG will be lower than the speed.

However, if the boat's heading allows the sail to generate more thrust than it could on a direct approach to the waypoint, and the boat's speed is higher, then the VMG is also likely to be higher.

Essentially, the perturb-and-test technique programmed into the autopilot's logic uses a kind of directed trial and error to maximise the VMG. Todter says, "In some cases you can't get anywhere near where you want to go, so you have to head off at quite wide angles and then figure out when it is appropriate to tack and head 90º from where you were going to put you on course for the waypoint."

A human sailor without an anemometer but with a cloth sail on the boat will be able to make efficient progress more quickly by steering progressively closer to the wind. They will watch the sail and steer away when it starts to flutter and lose its ideal curve, and generally

Crew deploying the Gen6 from a support boat gives an idea of scale. The spring-loaded cam follower arm is just visible between the float module deck and the base of the wingsail

feel what the boat is doing, Todter admits.

"In our case the response is quite slow, as you have to wait 30 s to a minute to find out whether the new heading is better or worse," he says. "So it's a bit ponderous, but it always gets where it's going."

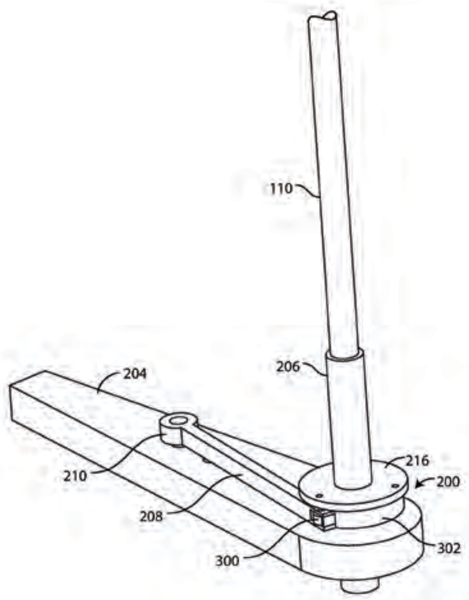
Control systems theory still applies though, and the software has to take into account the tendency to oversteer, for example. So it is important to measure the rate of turn with the IMU and/or the magnetic compass and use that information in programming the autopilot so that it can command rudder angles and rates that will allow it to turn smoothly and hold the vessel on course.

Self-regulating wingsail

The autopilot's job is made easier by the fact that the rudder is the only effector it has to control, thanks to the aforementioned patented mechanism that enables the sail to rotate and set itself at an angle of attack that powers the boat regardless of its heading – so long as that heading is not too close to the wind. "We don't have to control the wing, we just have to point the boat," Todter says.

The mechanism consists of a cam with a spring-loaded tensioner/follower that generates torque that exactly opposes the torque that wind pressure acting on the sail applies to the mast. Ensuring that these forces are balanced when the sail reaches the correct angle is a function of the cam profile, the spring rate and the length of the tensioner arm.

The wingsail is rigid and is mounted on a sleeve in the centre of the cam, and the whole assembly is free to rotate around the fixed mast. The cam has a dwell portion of constant radius that can be



The mechanism that automatically sets the sail to the best angle to the wind for thrust generation is based on a cam (302), which is subject to opposing torque forces from the wind and a spring-loaded arm (208), while 110 carries the mast

thought of as the cam's base circle, and a nose portion that can be considered as the cam's lobe, which is divided into symmetrical left and right profiles that meet at a point opposite the base.

When the tensioner is on the dwell portion of the cam, it generates no torque. That coincides with the wing being in a 'no-go' point of sail, which is a range of directions or angles with respect to the wind in which a sailing boat cannot sail. It is when the tensioner is on the nose portion of the cam that it generates a force that opposes the torque created by the wind on the wingsail. These positions coincide with the angles between the wind and the wingsail that allow the latter to generate thrust.

Control station and operating modes

While the 28 kg Gen6 vessel can be operated by one person, it is typically run by a team of two, and two are needed for launch & recovery. There is also a smaller, 14 kg Gen6 Mini that can be launched/recovered by one person.

The operator interface runs on a laptop or tablet, enabling complete mission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Weight 3.9 kg (8.6 lbs), size: 180 mm x 215 mm (7.1" x 8.5")
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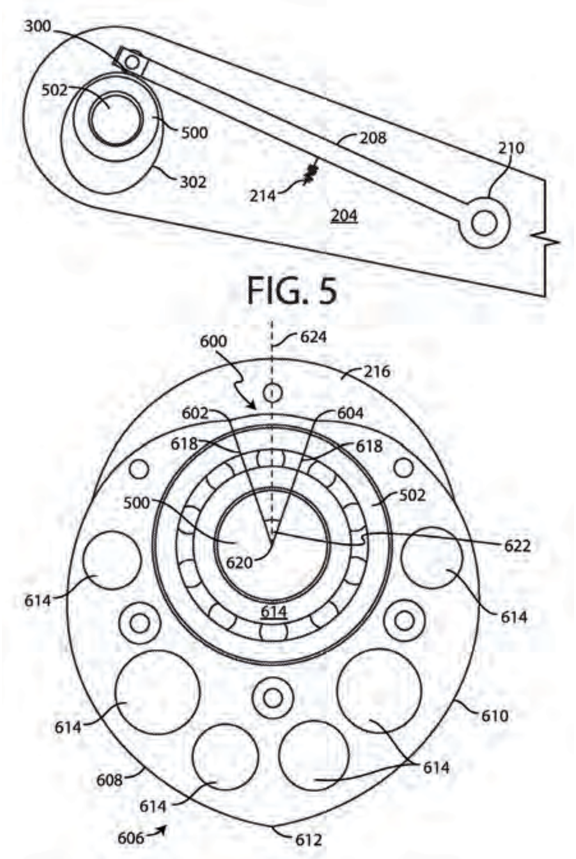


This drawing shows the relationship between the cam and the tensioner arm (top) and the symmetrical profile of the cam (above). With the arm on the dwell portion of the cam (600), the sail won't generate thrust. Holes (614) reduce weight

The white discs clipped to the Gen6's submerged hull are elements of the POCIS system used to monitor traces of explosives released from unexploded ordnance on the seabed (Courtesy of the US Army Corps of Engineers)

planning, loading, monitoring and remote operation using either wi-fi or Iridium comms. Once the mission has been uploaded and started, however, normal operation is completely hands-off.

The operator does not have to be a qualified mariner, although maritime experience is useful, especially in mission planning. No maritime 'rules of the road' are programmed into the mission system, nor are any active collision avoidance systems, as the Gen6 vessel's small size and low speed are sufficient to avoid causing damage to anything that it might hit or, more likely, hit it.

Capable of managing several vessels simultaneously, the control system software is based on a Windows-compatible GUI, enabling waypoint and course navigation, and allowing the operator to create inclusion zones, holds and loops, and set up station-keeping at a selected target waypoint. It also supports comms functions including text and visual status indicators, SMS and email alerts.

The wi-fi system is used for short-range, high-bandwidth comms directly between the operator's laptop/tablet and the vessel, while the Iridium system uses the satcom provider's Short Burst Data (SBD) service for anything beyond line of sight. Both are capable of supporting command & control (C2) functions and transmitting payload data.

A third option under development is a cellular comms system packaged with a masthead camera and integral computer. The camera's primary purpose is to capture high-resolution images of targets such as vessels fishing illegally, and the cellular comms will provide more bandwidth than Iridium SBD, and more range than wi-fi, while also supporting real-time C2 functions. It could also be used with the camera in a visual collision avoidance system under the control of the human operator.

Together with the cellular comms, the additional computer packaged with the camera will provide a means of separating the data-handling and comms for the payloads from those that serve the C2 functionality. Under the current arrangements, however, payload data can be stored locally on an SD card and sent via Iridium or wi-fi, but relies on the vessel's main computer.

At the moment, the data interface for payloads follows the RS-232 standard, while the batteries supply 12 V DC power, stepped down to 5 V at the masthead, but others can be integrated as necessary.

Payloads integrated so far include a conductivity, temperature and depth sensor, a chemical 'sniffer' and both fixed and towed hydrophone arrays. Multiple payloads can be accommodated simultaneously, limited only by their size, drag penalties and power requirements.

Materials and manufacture

The principal materials used in the Gen6 vehicle are fibre-reinforced plastics, wood and monolithic plastics. They have been chosen for their combination of strength, low weight, durability, low visual and radar signatures, and cost, with marine paint applied for extra protection from the environment.

The wingsail is made from a combination of CFRP and polycarbonate, and the float module is formed from PVC foam covered with a combination of CFRP and Kevlar. The structural keel is aircraft plywood and CFRP, the stabiliser is also CFRP and the cylindrical hull is ABS, with multi-jet 3D-printed nylon for the modular nose section for payloads.

SubSeaSail does most of its manufacturing in-house at the moment, having built its prototypes on its own workshop equipment, which includes 3D-printing capabilities. It outsources printed circuit board assembly and CNC machining of the foam and wood components.

The company

Before setting up SubSeaSail, company principals Michael Jones and Mark Ott were co-founders of Ocean Aero. SubSeaSail's third co-founder, Chris Todter, joined Ocean Aero and co-authored Ocean Aero's patents for the folding wing mechanism and retractable thruster used by the Submaran S-10 (detailed in *UST* 9, September/October 2016). Ott and Todter have many years of experience in ocean-going yacht racing.

Todter is also the lead technical partner at SubSeaSail, and has been involved in every America's Cup since 1983, except the most recent one in 2017. He has been responsible for performance enhancement, and winning the cup in 2010 with the Oracle trimaran.

"That involved understanding what the guys do that makes the boat go faster and how to guide them," he says. "I have spent many years developing the analytical tools to understand the subtlety of acceleration and the forces, the aerodynamics and hydrodynamics, and how they interact with each other."

Testing and service entry

Most of the testing has taken place using real hardware, in the sea off San Diego, with some carried out off the coast of New Zealand. The company also used a PC-based virtual simulator for some tasks early and late in the autopilot development process.

"The simulator was very good at the beginning of the autopilot system's development and at the end, when we were working on remote command & control, when you don't need the boat to sail but just need to know it's doing the right thing," Todter says.

"In between, I think it is easier to use the real hardware on the water and observe it. To me that's a lot more fun anyway!"

At the time of writing, the project had resulted in one (non-submersible) Gen6 entering service with SubSeaSail's first customer, the US Army Corps of Engineers (USACE). The Engineer Research and Development Center (ERDC), a division of the USACE, successfully tested the vessel in the waters off Puerto Rico, ERDC reported in April.

The chosen location was Bahia Salina del Sur, a bay used by the US Navy for gunnery and aerial bombing practice from 1941 until 2003, and the vessel was fitted with sensors to detect and measure chemicals leaking from deteriorating unexploded ordnance.

The Gen6 was tested at three places in the bay, with between eight and 20 waypoints programmed into each search area. The principal sensor, which SubSeaSail integrated, was a polar organic compounds integrative sampler (POCIS) calibrated to look for traces of explosives including 2,4,6-trinitrotoluene and 1,3,5-trinitro-1,3,5-triazine. A set of five POCIS elements was strapped to the Gen6 vessel's submerged hull.

It also carried a multi-function water quality sensor package from Sontek/Xylem to measure temperature, salinity, depth and turbidity.

Future developments

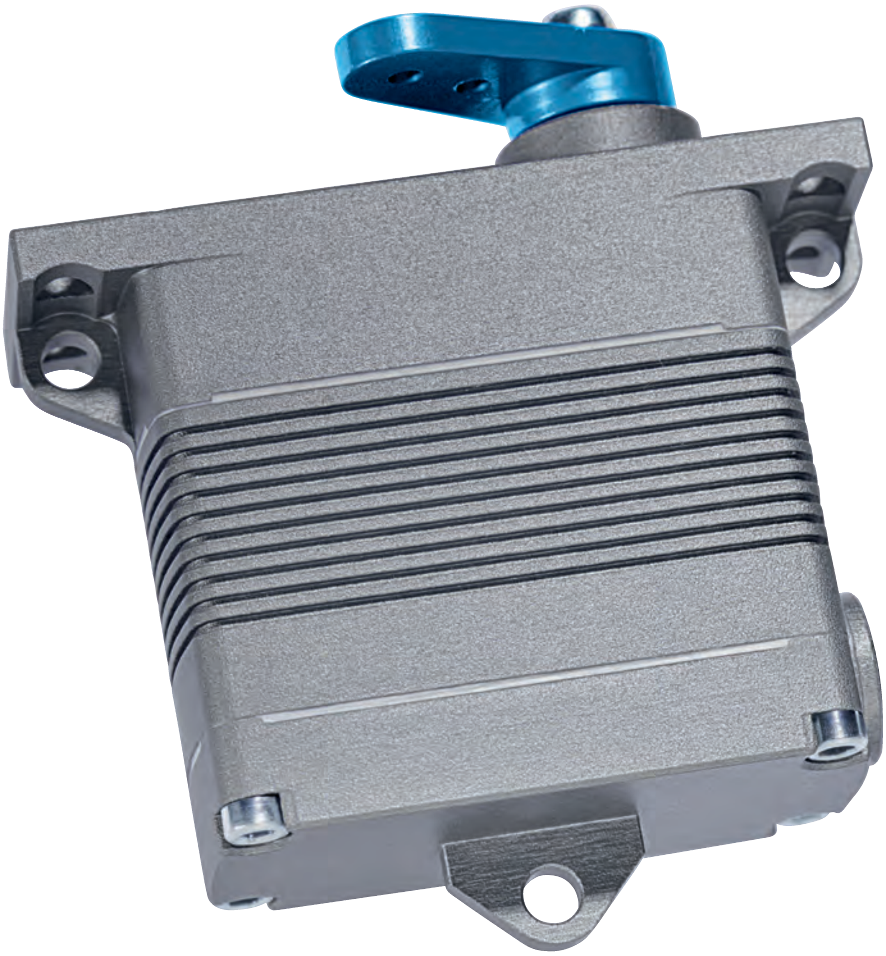
SubSeaSail is also developing unique sensors to take advantage of the platform's compactness and extreme quietness. For example, it and partner company Applied Ocean Sciences have applied for a provisional patent on a reconfigurable, rigid acoustic array.

This can be mounted on one or multiple Gen6 boats working together to produce a cooperative system with capabilities much greater than any single platform and sensor combination. While this raises the question of swarming technology, Todter believes that a virtual array capability can be achieved more simply by commanding the boats individually without requiring each to communicate with the others and automatically prioritise and apportion tasks among themselves.

Integrating sonar signals received by different boats to generate reliable locations for underwater targets requires each signal to have accurate time and location stamps. These can be provided by GPS, particularly with the aid of a real-time kinematic (RTK) system to boost accuracy.

"There are now RTK GPS systems that are almost chip size, and if one of the boats carries the base station, the others will know where they are relative to that to within a few centimetres," Todter says. "So the technology is there to do that; we just need to demonstrate it."

Plans for further tests are focused on missions of longer range, while future developments are to include an integrated payload bay, improved data-handling facilities, refining the submersible version and producing a catamaran variant for a sponsor. ◻



New aerospace-grade servos are packing more features into smaller packages, with some now weighing as little as 30 g while still using aluminium housings and steel gears (Courtesy of Volz)

Moving with the times

Advances in servo actuator technology continues apace, writes **Rory Jackson**, who explains some of the latest developments

Actuation encompasses the rotary or linear movement of control surfaces, widening and shutting throttle valves, opening and closing payload doors, deployment of landing gear, and a host of other functions on unmanned (and manned) vehicles.

Advances in this sector are critical. The UAV industry alone purchases hundreds of thousands of servos a year, and in-field replacements of them are one of the most time-consuming and labour-intensive maintenance tasks, requiring extensive testing to confirm that each one has been installed correctly.

While the term 'actuator' can encompass hydraulic and pneumatic systems, in the unmanned systems industry the overwhelming majority of (if not all) actuators are electromechanical, and are sometimes called 'servomotors' or simply 'servos'.

Servomotor technology has evolved considerably over the past several years. Materials, interfacing and data protocols, safety features and more are being optimised for different applications, leading to as diverse a range of actuator designs as unmanned vehicle configurations.

Key actuator components

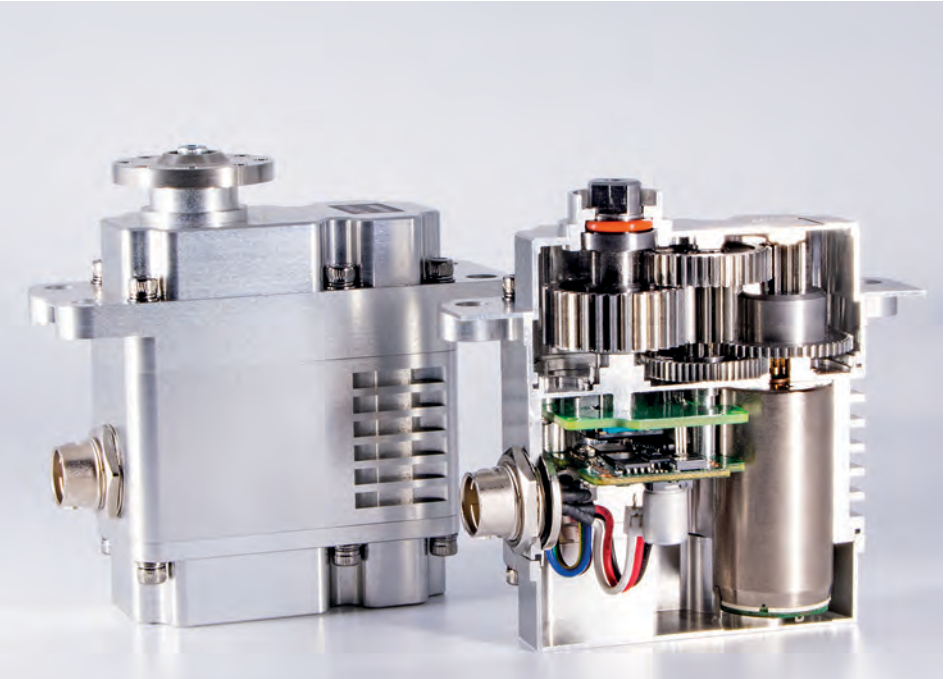
A handful of common components inside servo housings enable the chain of events that output actuations in all unmanned vehicles.

First, the circuits on the servo's PCB assembly receive control signals and power from the vehicle's autopilot. They are transmitted to an electric motor to allow it to produce the exact degree of rotation required.

The motor produces a differing effect depending on whether the servo is rotary or linear. In the former, the rotor turns a geartrain, typically reducing the rotational speed to produce a higher torque at the output shaft.

That end-point might have a servo arm and a pushrod for toggling a control surface, or a butterfly valve for opening and closing an engine's throttle.

For an electromechanical linear servo to extend or retract its output shaft, typically some form of screw train is used. Most often, a leadscrew is machine-cut with a helical thread, and a ball nut is mounted on the end



Servo actuators consist broadly of a power and signal input, a PCB assembly with control and power electronics, an electric motor, a geartrain and an output shaft (Courtesy of Futaba)

that interlocks with the output shaft.

When the motor's rotor turns, it spins the leadscrew but the ball nut remains still in its rotational axis, instead producing a linear motion – forwards or backwards, depending on the direction of rotation.

As the geartrain or screw train provides the critical mechanical output, it makes sense that they should be made of a strong material. Hobby-grade actuators are often made from plastic, which is lightweight, inexpensive and has low backlash – the error between the commanded input position and the resulting output position – but they often break down.

Vibration imparts a particular stress to gears, and as a result, plastic gear servos rarely last for much more than 20 hours of operation. They are even dangerously prone to failure within the first hour of operation.

Gears made from alloys of brass, aluminium and (sometimes, in small quantities) titanium are occasionally used as a compromise between strength and weight. These produce very low backlash but often degrade in performance after 50-100 hours.

Steel gears have the longest lifespan – from 2000 to 10,000 hours – so they have a much lower ratio of cost to service life

Steel gears are prone to higher backlash than the alternatives, and are more expensive as they need higher quality tooling and process controls. However, they can provide the longest lifespan – from 2000 to 10,000 hours as a matter of course – and as a result have a much lower ratio of cost to service life than alternative material gears.

The servo housing is the largest component and thus the heaviest, with aluminium 6061 being widely used for industrial and military-grade servos.

For UAVs needing extreme weight optimisation (such as HALE pseudo-satellites) some future servo designs will have carbon fibre structural parts to save weight where possible. For such systems, overall weight can be reduced by 30-40%.

Demands for low weight have also resulted in highly miniaturised actuators weighing less than 35 g that can be manufactured in bulk and designed with a minimum of internal wiring.

Wire harnesses being shaken loose is a perennial concern in UAVs of all sizes, but smaller UAVs incorporating smaller servos naturally have less inertia, so both the UAVs and servos can be more heavily subjected to shock and vibration from turbulence hitting aerofoils or from revving motors.

While a good PCB assembly will reduce the amount of wires needed, and is typically fastened securely to the housing, many components – such as temperature and position sensors – must be wired to the motor, adding potential points of failure.

Wire harnesses can be secured further by potting the connections with an epoxy, reducing the ability of wires to swing about within their internal free space as vehicles are shaken around.

Motion control and position sensing

In the unmanned systems market, the brushes on a brushed high-end DC motor often wear out after 500 hours of use, although they can be cycled on a test bench to determine with good predictability how long they will last. However, they also produce EMI through sparking, which can be detrimental to internal electronics and signal integrity, as new unmanned vehicle designs carry increasing quantities of sensors and processors dependent on secure connections.

Switching to a brushless DC (BLDC) motor not only removes a lot of friction and EMI from the servo's normal operation, it also greatly reduces the damaging effects of shock, vibration and ingress by environmental contaminants. With less physical contact between parts, such problematic factors are transmitted far less throughout a servo's internals.

It should also be noted that servos must be able to measure the position of their motors, to determine the next correct turning angle or linear movement (and therefore input power) or confirm that the actuation has been performed as required.

While the use of BLDC motors does a lot to improve servo lifespans, combining them with a potentiometer for position sensing still leaves the problem of persistent contact being needed for consistent actuation. Potentiometers incorporate resistors with sliding or rotating contacts that will degrade over time, far quicker than contactless sensors.

The service life of potentiometers in UAV actuators is often limited to around 100-300 hours, given how shock and vibration can damage such parts. For a UAV flying two to four missions per year, for example, that might be acceptable, but for MALE-class UAVs flying 8-hour missions multiple times per week – let alone HALE-class UAVs flying 365 days a year – having to replace servos so often is unacceptable.

Contactless position sensors give far more accurate feedback than potentiometers, through methods such as the Hall effect sensing approach.

Switching to contactless sensors is also useful for manufacturing. With no direct coupling between the sensor and the output shaft, there is no risk of misalignment, as there is when trying to mate a potentiometer with the shaft.

Lastly, contactless sensors increasingly come with built-in diagnostics, further reducing the risk of failure modes compared with potentiometers.

New kinds of contactless position sensors are reducing servo weight and complexity while greatly enhancing their accuracy and reliability (Courtesy of Ultra Motion)

By switching to BLDC motors and contactless position sensors, the geartrain becomes the primary bottleneck in the lifespan of the actuator. If steel gears are used it takes the mean time between failures (MTBF) from about 100 hours to upwards of 2000 hours.

It should also be noted that, as well as the first control loop for servo position, BLDC motors can incorporate a second loop for controlling temperature, to enable them to heat themselves when the temperature sensor detects that the actuator is nearing a configurable negative temperature threshold (such as -40 C). This is a common problem with smaller servos, which lack significant air gaps for innate insulation and start to suffer slower dynamic responses below that kind of temperature.

Programming considerations

Increasing sophistication in actuator firmware is critical for more rugged applications. For example, servos used to actuate engine throttle valves must have sub-degree accuracy to rotate to the correct angle for every performance level, from wide-open throttle to idling.

Once the angles and air quantities have been mapped, a UAV manufacturer or operator can change their throttle bodies in the field, upload the maps and find that their new throttle body behaves precisely as the previous one did in normal operations.

It has been traditional to set commands and protocols for actuators (in engines and on wings, fins and tails alike) using PWM (pulse width modulation), but the vulnerability of this form of interface is well-established. Between a servo and an autopilot, PWM signals can be exposed to high levels of EMI (or magnetic interference), to which they are highly vulnerable, compared with other available signal standards.

CAN, for example, typically incorporates a 15-bit cyclic redundancy check (CRC) that detects accidental changes to the raw data before performing corrections, to prevent corruption. With the CRC providing a safety layer around CAN-transmitted information, servos can far more easily ignore inaccurate comms.

As such, more and more UAV servos are adopting CAN bus as their interface standard for electronic speed controllers and data comms.

CAN microcontrollers, drivers and other components from the automotive world have served as a broad but vital design basis, and some UAV servo manufacturers have adopted specialised versions such as UAVCAN, CANopen or custom protocols on top of CAN.

Different standards and formats of CAN require different degrees of work on integrating and implementing them in associated components. Some servo companies now work directly with autopilot and engine manufacturers for example to ensure common interface standards.

Larger servos for urban air taxis and heavy-lift UAVs are being designed for higher continuous and peak torque (Courtesy of MKS Servos)

Adoption of CAN bus (and variants such as UAVCAN and CANopen) in actuator designs is widespread, thanks to the greater security and breadth of useful information the protocol enables (Courtesy of Hitec)

CAN enables multiple data inputs to be carried to multiple end-points on a single bus, with all the required arbitration performed by a CAN chip. That makes sure signals are transmitted correctly and consistently in their order of priority, as was needed by the automotive industry when it first produced CAN in the late 20th century.

For example, aileron servos might be programmed with the highest priority to ensure that attitude control is activated persistently and accurately, whereas a payload servo is less safety-critical and could therefore be given a lower priority.

CAN also enables the integration of multiple sensors per servo, on position feedback, temperature, voltage, power consumption and other factors that can contribute to accurate diagnostics for the motor, processors and other internals.

For servos being designed to work for months at a time (such as – again – on HALE pseudo-satellites), self-testing diagnostic features can be added. These allow the onboard computer to perform, for example, tests of every motor winding, stepping it through different positions to check that the motor's sensors and windings are all working correctly while still months away from the vehicle's next ground maintenance check.

Naturally, such functionality could also automate and speed up maintenance for UAVs that fly on a daily basis, to ascertain in better time that the servos' motors, memory, comms, power supply and so on are working.

Redundant systems

In addition to equipping CAN and other software functions with useful redundancy features, designing actuators with built-in hardware redundancies is also key for improving their inherent safety and reliability.

This is likely to become a prerequisite for delivery UAVs and urban air transports operating over cities and industrial assets.

It is also important for experimental or highly dynamic vehicles. For example, supersonic target UAVs used by military forces could cause severe collateral damage if a servo seizes up and they lose a degree of freedom.

To enable dual redundancy, many servo manufacturers have therefore developed versions of their existing actuators that incorporate a second channel of their internal components.

Having a second motor, gearbox, driver chip, microcontroller and so on can considerably increase a servo's MTBF (as projected by tests performed according to standards such as Mil-Std 217), as the probability of a single component failure causing a total breakdown of the actuator will have greatly decreased.

OPV actuators

As more OEMs develop urban air taxis (or refit light aircraft for autonomous flight), servos for optionally-piloted vehicles (OPVs) are growing in demand. These are actuated by the autopilot when engaged; when disengaged, their link to the autopilot is cut and the pilot's yoke becomes the sole source of control.

Such servos are also useful for testing new autopilot hardware and software, for example when using manned aircraft or ground testing stations to trial autonomy before flight tests.

An established approach is to incorporate a toothless, electromagnetic clutch. These typically mount a disc to the output shaft, with a spring-loaded magnet under the disc. When electrical power is applied, the clutch closes, and when electricity is no longer supplied, the magnet and disc spring apart.

However, the position of the output shaft cannot be sensed by the servo's processors when the clutch is disengaged. That means an external position sensor is needed at the disc end of the shaft, along with some method of feeding the signal to the servo's PCB.

Adding external position sensors will mean enhanced safety, but it will also mean more wiring harnesses and potential points of failure in the actuator. That will make alternative interconnection technologies highly desirable in this area (although which approaches the industry will adopt remains to be seen).

UUV actuators

UUVs have to endure far higher pressures than UAVs, and their servos must incorporate more rigorous sealing while still allowing free output shaft movement. This is of course to prevent saltwater ingress that would rapidly corrode the geartrain – rendering the actuator inoperable – and destroying the motor, processors and sensors.

For UUVs operating down to 2000 m (where pressures exceed 200 bar) or deeper, some actuator companies now use oil-filling systems to pressurise their enclosures, compensating for the pressure outside.

This typically requires major modifications to the housing to enable free flow of the oil, as well as a connection to a pressure compensator pump that will add or subtract oil from the servos as needed to keep the oil pressure slightly above the external water pressure.

> OPV servos are useful for testing new autopilot hardware and software, such as when using manned aircraft to trial autonomy

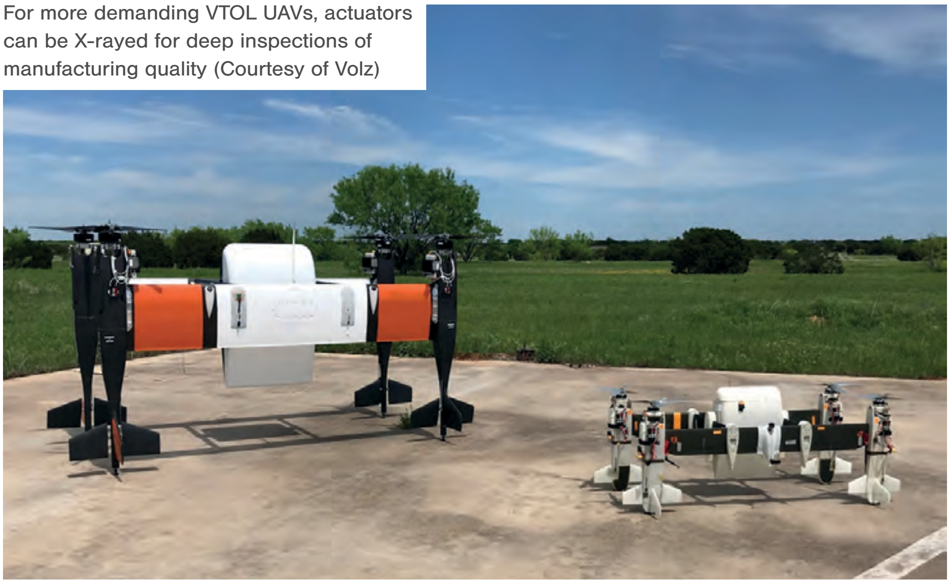
Customising these servos for different UUVs is prevalent, to cater for the different pressures at different operating depths, as well as variations in UUV architectures. For example, some customers want oil to flow from one servo to other servos and systems.

Such engineering is now being put to the test even further, as the past two years have seen new UUVs being built for civil and military operations down to depths of 6000 m.

While the gearbox, motors and ball bearings are comparatively unaffected by the quantities of oil such depths require, chips and processors can suffer major problems. If the plastic enclosure of a servo's CPU for example is too exposed to the pressure of the oil (and its viscosity at 6000 m or so), the chip can become damaged.

Oscillators made from piezoelectric crystal are especially vulnerable to oil ingress. While they are often housed in their own metal enclosure – and

For more demanding VTOL UAVs, actuators can be X-rayed for deep inspections of manufacturing quality (Courtesy of Volz)



continue working even if, for example, a car is driven over them – at depths of 6000 m, the resulting 604 bar of pressure is enough to collapse their housings.

As a result, it is useful to be able to replace crystal oscillators with semiconductor clocks in UUV actuators. The latter are not quite as precise as the former, but they can still enable reliable operation while withstanding the oil-compensation needed for work at 6000 m.

Such servos do require added maintenance though. For example, the oil will still pick up particles from the PCB assembly and gears, so an oil change will be needed at service intervals. So far though, oil-filling is the only proven way to design vehicle servos that can operate at such depths.

Quality control

It has been remarked by some in the industry that actuators are the most likely component on a UAV to fail. That is not an unfair assessment, given that they can be intermittently (or in some cases routinely) subjected to shear loads that stress their arms, gears, motors and other parts.

Designing and testing them for environmental and physical robustness is therefore vital to ensuring their viability for commercial and military use. Testing is particularly important for throttle servos, as they must be especially robust against extreme vibrations and heat.

> Standards such as DO-160 provide clear and proven guidelines for trialling servos towards long-term reliability

Given the wide range of altitudes and climates that UAVs must endure in their flights, however, it is not unusual for every servo to undergo precisely the same kinds of testing and equipment to ensure a common and high bar for survivability.

These include freezers and heat chambers to prove that their components can withstand extreme heat and cold, from -45 to +80 C, rate tables to vibrate them at 4 *g* for a given time (30 minutes being one standard), and cycling tests to operate them at different loads for extended periods.

When loaded, further tests can be conducted to verify a servo's performance in terms of backlash, force constant, axial or radial stiffness, and other parameters. Unloaded tests can also identify the motor size constant, running friction and other critical specifications.

It follows that load cycling can also be conducted under different vibrations and temperatures to gauge their performance in extreme conditions. Aerospace standards such as DO-160 provide clear and proven guidelines for trialling servos towards long-term reliability.

Further certification standards such as ISO 9001 and CE guidelines can be vital for ensuring that production and testing are carried out to the quality, precision and cleanliness needed for UAV servos.

As aircraft configurations become more complex, however, more in-depth proving of actuator design and operating integrity becomes desirable.

For example, the servos used in some helicopter UAVs are X-rayed. In operation, they are typically used with direct couplings to the UAV's rotor head to enable pitch, roll, and yaw, and are subjected to extremely high and fluctuating loads, as well as far higher than usual vibration.

Losing one servo would result in massive loss of control and a high probability of the helicopter's destruction. By comparison, non-supersonic fixed-wing aircraft can still glide to safety if a flap or aileron is lost.

X-ray images are thus inspected in order to visually examine every solder joint, every phase of every motor and so on. This unearths flaws in components that cannot be found using other standard tests and inspections.

While this level of testing is labour-intensive and time-consuming, it certifies beyond reasonable doubt that there are no insufficiently bonded electronics that might be shaken loose by vibrations or by shock loads to the helicopter's rotor head.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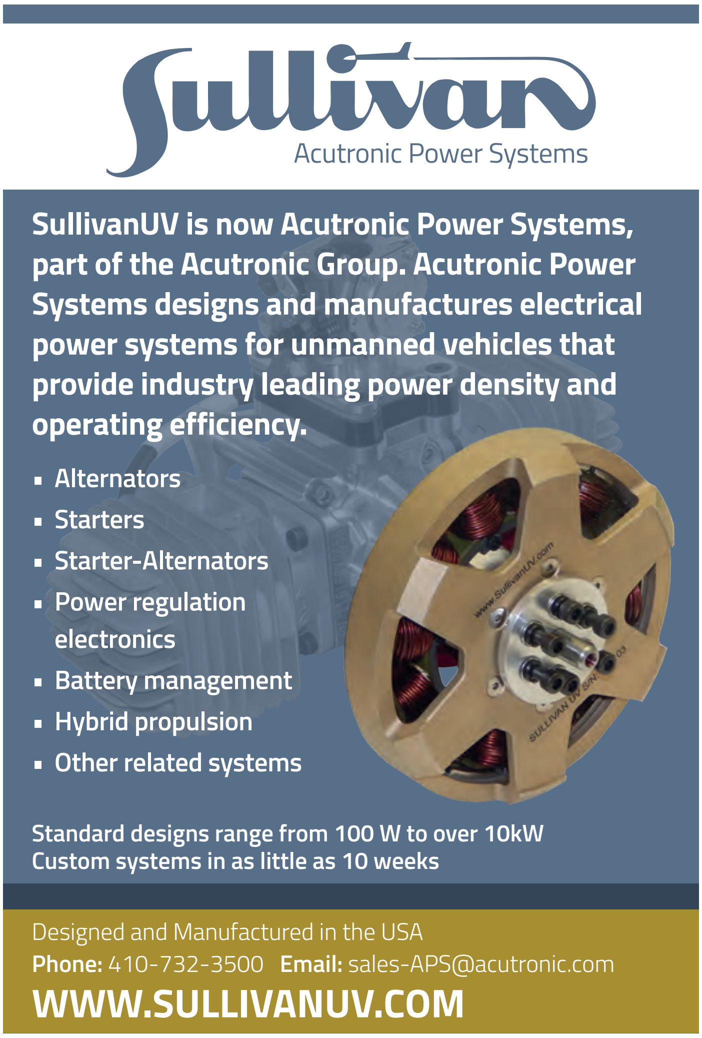
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Along with the imagery, the helicopter manufacturer can be supplied with pictures taken during production that show solder joints, potting and other parts and processes to assure that the servomotor has been manufactured to the highest precision and quality.

And even after servos have been shipped, the performance data amassed via CAN bus can be matched to product serial numbers to track and identify where long-run problems might be occurring with a given servo model. That would enable future improvements to actuators using real-world data, rather than being limited to simulated data and trials.

Conclusion

With a variety of critically useful new features being designed into unmanned vehicle servos, new innovations are anticipated that will satisfy vehicle manufacturers' new requirements, such as heavy electromechanical servos capable of more than 200 Nm of peak torque.

Large, safety-critical urban taxis in particular will need more in terms of sensors, safety features, power and MTBF than unmanned vehicles have previously demanded. That will doubtless spur entirely new designs and ranges of servo actuators to suit this new class of vehicle over the next five to 10 years.

Acknowledgements

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Weighty

Rory Jackson reports on how developers are meeting the surging demand for UAVs with greater weight-carrying capacities

Over the past few years, countless organisations around the world have realised just how much cost-effectiveness, safety and time efficiency can be gained by using UAVs for logistical tasks such as carrying cargo, hoisting inspection equipment or providing temporary telecoms services.

The enormous demand this has spurred has given rise to bigger, more powerful unmanned aircraft that are engineered to lift heavier weights than ever before – both in absolute terms, and relative to their airframe bodies. Such UAVs now come in a wide range of sizes and configurations, with a broad divergence in designs to suit end-users and their different needs.

Agriculture

The economy and geography of Ukraine are dominated by agriculture, with 25 million hectares of crop fields being planted and harvested every year. It is only natural then that the country would host a number of UAV developers aimed at aerial agriculture services.

UAVita's Discovery UAV is the latest platform aimed at this market, with crop dusting being its primary launch application. It has been tested extensively with local farmers, spraying pesticides at ultra-low volumes, and has also been used for monitoring crop health using various cameras, according to the company's CTO Yuri Pederiy.

"Most recently, we partnered with Israel-

UAVita's Discovery UAV for agricultural spray and monitoring has been slightly redesigned for series production (Courtesy of UAVita) based Taranis, who specialise in payload development and back-end analysis for agricultural photogrammetry," he says. "We integrated their payload, flew many hours and took many pictures with it. They analysed those photos, and determined the prevalence of diseases, insects, weeds and other problems to give the farmers a good idea of how and where they should be treating their crops."

Deep, field-wide photogrammetry is crucial for boosting agricultural yields, Pederiy adds, as most agriculture specialists – at least in Ukraine – will not travel far into the fields. They will stop at the edges and make projections based on the samples of data taken there.

The Discovery measures 3.7 m in length with a 6 m wingspan, and is capable of up to 6 hours of endurance per fuel tank at a cruising speed of 100 kph. It runs on gasoline, using Italian company Polini Motori's Thor 250 engine (a 244 cc single-cylinder two-stroke) with 1 kW of electric power generated using an alternator from British racing technology firm Brise.

Its data link enables up to 300 km of autonomous flight, and with an MTOW of 170 kg it can carry up to 80 kg of payload weight, such as tanks of pesticides or fertilisers inside the fuselage, or gimbals with inspection sensors typically mounted on the strut between its landing wheels.

Over the past six months, UAVita has partnered with Aeros, a local ultralight aircraft manufacturer, for series production of the Discovery. It has reworked its digital model of the UAV to better suit mass production of its structural components – including the fuselage, struts, spars and chemical spray lines – using Aeros' machinery and processes.

"Aeros will supply the resulting 'kit sets' to us, up to four units per month, so that we can assemble the aircraft in our workshops, integrate the electronics and the end-user's desired payloads, before we then ship the vehicle," Pederiy says.

"In the future, we'd like to look into producing a series-hybrid version of this UAV. We're confident about which generator we'll pick, but we're hoping for a big increase in battery energy density before we go down that route."

matters

Parallel Flight Technologies' UAV has been trialled for its ability to remain airborne and stable throughout various potential failure modes (Courtesy of Parallel Flight Technologies)

Firefighting

Parallel Flight Technologies is continuing to develop its quad-engine platform, thanks to funding from NASA and the National Science Foundation via SBIR grants from the US government, to produce a highly redundant (and therefore very safe) power architecture. The UAV was originally developed to provide an unmanned platform capable of carrying hoses, retardant or other critical logistics items for firefighters.

"Each of the parallel-hybrid modules on the multi-copter's four arms incorporates an internal combustion component and an electric motor component," explains CEO Joshua Resnick. "That gives great potential for redundancy in and of itself, but a lot of data and programming rigour is needed to develop the right algorithms and hardware to leverage that.

"So we developed some proprietary software for doing just that, which we trialled, with particular regard to the aircraft's ability to remain stable and continue its flight path throughout a ton of different failure modes, and all at different altitudes."

As an example, through an interface with the flight computer, the operations team repeatedly inserted simulations of an engine flameout. They tested different ways a flameout could occur, such as by losing one cylinder, losing two, suffering oxygen deprivation or fuel starvation, and so on. They then tested the software's ability to detect the flameout and respond to it by switching to the electric motor for thrust on the affected arm.

"The aircraft was on a three-axis gimbal, and we recorded data from the flight controller on the degree of drift that the attitude, velocity and control experienced relative to their respective navigation targets, for the duration of the flameout and of the software dealing with it," Resnick says. "Our test results found that, to all intents and purposes, an observer would not have been able to tell that the UAV was suffering a failure mode at all."

The company has also upgraded the UAV's engines with electronic fuel injection systems from HFE International, following a number of customer requests to replace the engines' carburettors and needle valves with ECU-timed injectors.

"We're keeping a close eye on the features and technologies our customers want, because we're looking to move quickly towards flight trials of our beta-test prototype later this year," Resnick adds.

"The prototype used Desert Aircraft's DA70 engines, but the beta-test version will use either DA100s or DA120s, depending on the customer," he says. "Wildfires are an ongoing crisis in California, so we're catering to a lot of demand there. In any case, with the new engines everyone will get at least 100 lb [45 kg] of payload capacity."

Humanitarian aid

As featured in *UST* 30 (February/March 2020), Wings For Aid is a Netherlands-based foundation dedicated to developing autonomous swarm distribution of charity aid and disaster relief supplies.

Although its proof-of-concept flights so far have been conducted using a Pipistrel Sinus OPV, the flight team at Wings For Aid has recently taken delivery of its prototype UAV chassis (also manufactured by Pipistrel), which is to begin ground testing soon.

The UAV has a 9.5 m wingspan, measures 2.9 m tall and 6.4 m from nose to tail, and has an empty weight of 390 kg. It has been designated the MiniFreighter 8/500FW, has a MTOW of 610 kg, and an expected cargo-carrying capacity of 160 kg.

That capacity is enough for eight of the company's patented 20 kg (or 70 litre) aid boxes, which will be dropped from an altitude of around 100 m.

"We have also developed the flight control system with Pipistrel and one of its technology partners," comments general manager Barry Koperberg.

"In parallel with the introduction of this UAV, we're working on radar-based detect & avoid systems with the Technical University of Delft and some commercial partners," he says. "We're also running range extension projects to cater for extended radio line-of-sight and interconnectivity for the cargo UAVs. Taken together, these projects will enable future swarming of UAVs over a wide airspace."

Each UAV will be capable of cruising at around 125 kph, with a maximum airspeed of 150 kph, the power coming from a Rotax 582UL and a tractor propeller drive integrated at the front of the airframe. This two-cylinder two-stroke uses liquid cooling and a rotary intake valve to produce a continuous 65 hp (48.5 kW) while running on premium unleaded gasoline.

The maximum range is 500 km (or a 250 km return flight), and Koperberg estimates that with two UAVs his


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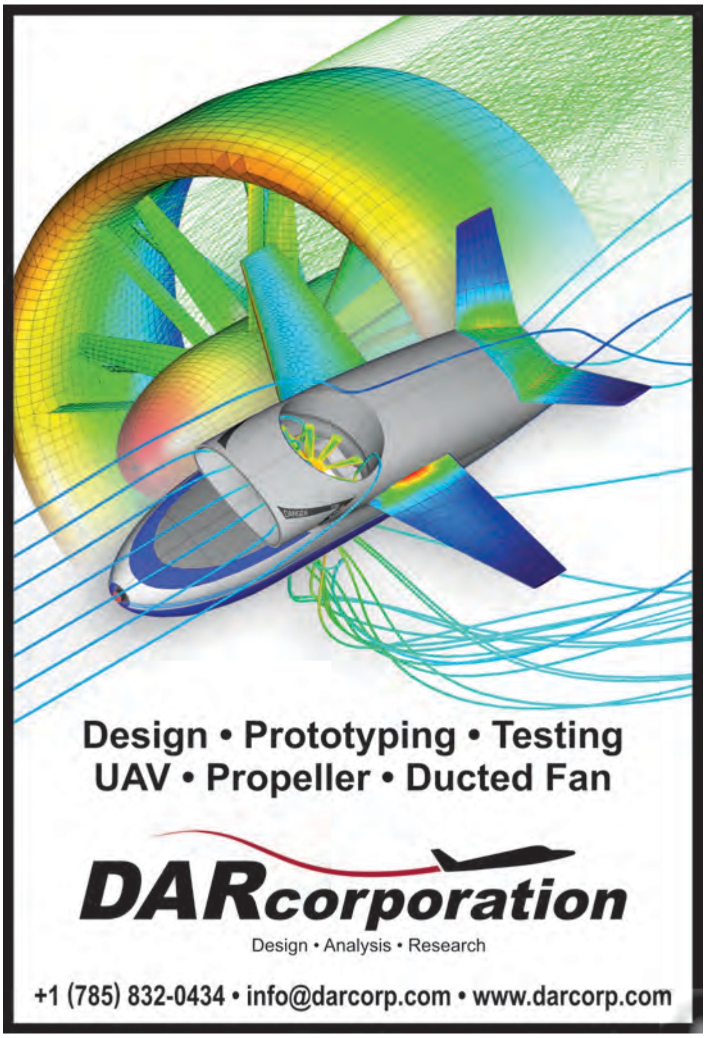
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Pipistrel has finished building the chassis of Wings For Aid's prototype MiniFreighter UAV, with assembly performed by the latter's technicians (Courtesy of Wings For Aid)

team could deliver a tonne of aid per day in disaster-struck areas. That is the equivalent of 50 standard UN shelter kits, 1000 litres of water or enough water purification kits for 20 villages, he adds.

Flight tests of the cargo deployment system have been conducted in the Dominican Republic and are expected to be performed there again with the UAV. Kenya and Senegal are also among the countries where Wings For Aid's prospective end-users (such as the Red Cross) are aiming to trial and operate the system.

Defence

UK-based Animal Dynamics is continuing the development of its Stork series of UAVs, which are designed – uniquely for the UAV world – as paraglider aircraft, to be used primarily in logistics applications for the defence sector.

As the company's CEO Alex Caccia explains, "The craft came about from [the UK government's] DSTL's Joint Tactical Autonomous Resupply and Replenishment programme, which is aimed at sourcing industry proposals for dealing with last-mile defence logistics problems, such as delivering essential items to the front line. In regions where the ground is contested as a result of military conflicts, or struck by disaster, getting supplies to soldiers or civilians in need without putting logistics personnel in harm's way is a really big problem."

The company noticed that most of the entries in the competition were putting forward quadcopters, which Caccia's team noted was rarely an optimal solution for heavy-lift applications.

"There are many reasons for that, from how the motors are controlled to the weight and energy density of batteries, and so on," Caccia says. "If you really want to maximise your payload capacity and minimise your cost, you should marry as little fuselage as possible to the largest wing possible."

The company calculates the Stork UAV to cost one to two orders of magnitude less than the typical military resupply vehicle. Part of this cost saving comes from using parafoil wings, which Caccia says use the minimum density and weight of material to give the maximum area of lift. With a cloth wing, ram-air expands it outwards, but between uses the wing can be rolled into a small carry case for easy transportation to the point of use.

The decision to build the system as a parafoil also came about as a result of the company's co-founder Professor Adrian Thomas' extensive experience with the technology. Being a champion paraglider, he had been designing and constructing wings for paragliding for more than 10 years, and knew how the aerodynamics and weight tolerances of such an aircraft would work.

This knowledge was further aided through Prof Thomas' specialisation in biomechanics, which helped guide the shaping of the wing for aerodynamic efficiency – even though the Stork does not outwardly seem to resemble any bird or other animal.

Animal Dynamics has also conducted extensive trials and iterations to optimise the craft's ability to withstand crosswinds, and to absorb ground impacts through its landing gears and structural spars, while keeping its electronics, engine and cargo unaffected.

A few different Storks are in development, but the company's efforts are focused particularly on certifying and commercialising the 25 kg ST25 (which can fly for 50 km or more depending on how much of the 10 kg payload is used) and the STM, which can carry payloads of up to 150 kg.

Both craft will be embedded with AI redundancy software in the event that BVLOS landing and recovery locations suddenly become unavailable, and new, safe landing zones need to be found. While navigation currently rests on GNSS-INS, future iterations will test visual and other approaches to intelligent landing capabilities.

Power infrastructure

FulcrumAir has begun applying its E7500 UAV in powerline operations in its home state of Alberta, Canada.

The company specialises in helicopter-type aircraft with coaxial rotor-lift systems. Several proprietary and patented technologies have gone into these architectures, including steel and aluminium rotor head parts designed for high tensile strength, as well as a hinge design that allows the rotor blades to flap up and down with the rotation of the rotor discs.

This freedom of movement reduces the bending stress on the rotor blades, allowing for a higher rpm and correspondingly higher disc loading than conventional helicopter-based UAVs. It also improves the pitch and roll response as well as top speed, which is currently 60 kph.

The E7500 has two vertically oriented dual-bladed main rotors (each measuring 2.3 m in diameter), driven by two 15 kW BLDC motors, as well as a masthead above the lift rotors that mounts four horizontally disposed electric motors for both horizontal propulsion and pitch and roll control.

As FulcrumAir's vice-president of engineering Daniel Clarke explains, "Because of the four small e-motors generating lateral thrust, the 'copter doesn't really have to tilt nose-down as much for forward motion, which saves power owing to increased translational lift. That means, when you calculate power consumption in this versus a conventional helicopter, we are basically carrying those additional electric motors for free.

"This control architecture also keeps the E7500 really stable. It can be hit by gusts of up to 5 m/s and the payload tethered underneath will still be hanging dead still in the air."

While its empty weight is rated at 40 kg, the system can lift up to 60 kg. Running on battery power, it can carry its payload for up to 18 minutes, and has a maximum endurance of 32 minutes when flying without a payload.

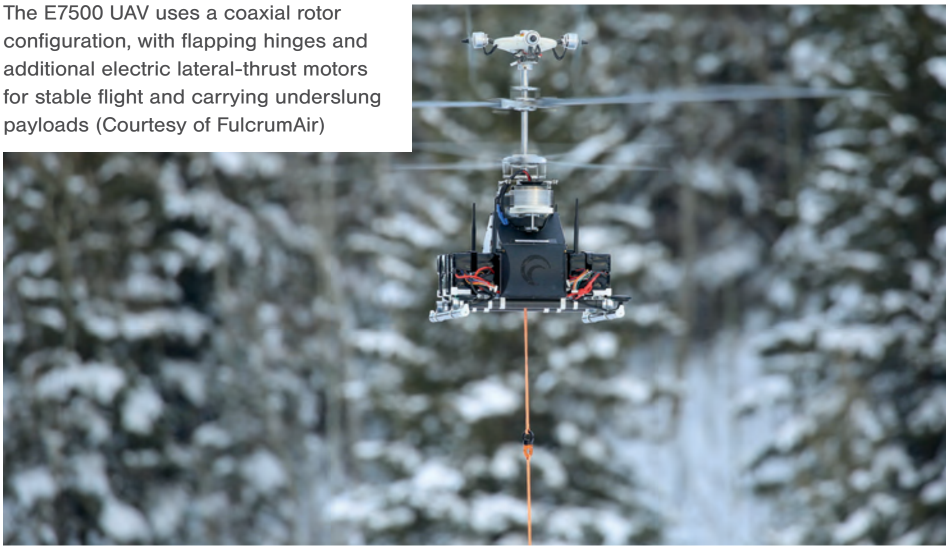
In its most recent missions, the UAV has been tasked with installing 'bird diverters' onto powerlines, hanging the reflective markers to prevent birds from colliding with the electrical cables.

The diverters themselves are installed using a heavy and bulky robotic device called the Line Fly (also manufactured by FulcrumAir). "This separate robot, suspended beneath the E7500, has its own flight control computer, batteries, GPS, powered wheels, video system and yaw control thrusters," Clarke adds. "It is controlled independently from the ground using a Herelink ground station and air unit, and has several operational modes.

"In Manual mode, the operator drives it back and forth, triggering the installs. In Auto mode, the Line Fly automatically 'drives' along the wire, mechanically installing diverters at preset intervals, based on distance data from its own BLDC wheel motors' sensors.

"Lastly there is Follow mode, which is the same as Auto except we also send GPS data a few times per second from the Line Fly to the E7500 to use as waypoints, so the UAV follows the robot automatically. This autonomy greatly reduces operator workload, but we're still beta-testing it."

Animal Dynamics' Stork UAV uses a parasail designed to maximise the craft's wing-to-body ratio (Courtesy of Animal Dynamics)



The E7500 UAV uses a coaxial rotor configuration, with flapping hinges and additional electric lateral-thrust motors for stable flight and carrying underslung payloads (Courtesy of FulcrumAir)

Government services

Periscope Aviation (a subsidiary of law enforcement systems supplier Chartis Federal) is engineering its MK4-R quadrotor UAV to carry mission-critical equipment weighing considerably more than the aircraft itself, for groups in the military, homeland security and the emergency services.

The company has recently unveiled a range of precision-engineered tactical UAVs, the newest of which is the MK4-R. As Nick McCarter, president of Periscope and founder and CEO of Chartis, explains, "We wanted to develop the MK4 as a multi-purpose tool for high-risk operations that can behave as a radio tower

Periscope Aviation's MK4-R UAV being presented to the US Marine Corps in early 2020 (Courtesy of Chartis Federal)

in the sky, or for reliable logistics, with a flexible payload and a long flight time for the weight being carried.

"If you want to put a heavy Lidar on it, that's fine too. We also recently tested a long-range acoustic device, which can be used for crowd control or for disseminating lifesaving information to large groups of people on the ground."

To achieve this payload flexibility, the MK4-R has been designed to maximise its payload capacity versus its empty weight. To that end, Periscope has made design choices in terms of its propeller design, batteries, ESCs and several other factors that remain proprietary, to produce an aircraft that can carry more than double its own weight.

"In January we competed in a heavy-lift tactical resupply competition for the US Marine Corps," McCarter recounts. "We turned up to that competition with a small carry-case, compared to the giant trucks everyone else's UAVs needed, and we assembled the MK4 and had it ready to launch in five minutes."

The MK4-R is the largest of Periscope's UAVs, measuring roughly 175 x 169 cm, and weighing 8.6 kg without payload. When carrying 6 lb (2.72 kg) it can fly for up to 30 minutes, and has flown for 12 minutes with 41 lb (18.6 kg); its maximum rated payload is 55 lb. It has a top speed of nearly 129 kph, cruises at just over 56 kph and can operate in winds of up to 64 kph.

In addition to various government and military work, the company is looking at other critical services such as firefighting, where it envisions the MK4 providing critical comms relay and situational awareness capabilities to provide dynamic assistance in coordinating wildfire suppression and evacuation efforts.

Periscope is also in talks to work with filmmakers and cinematographers to start mounting IMAX cameras on the MK4-R. These cameras, usually costing upwards of $500,000, have typically only been entrusted to fixed-wing or helicopter-type aircraft, owing to their past dominance in payload-carrying capability.

Cinematography

Film production cameras remain one of the most expensive varieties of video-capture equipment, and very few UAVs are trusted to carry them safely.

The Freefly Alta X quadcopter ranks among the leaders in this field. It can carry 35 lb (15.88 kg) for 11 minutes, and its rotor booms are stiffened with foldable struts that reduce vibration from the motors to the hub and payload.

To customise the autonomy and navigation according to the required angles, speeds and routes needed, Freefly has begun integrating the PX4 autopilot stack from Auterion into the UAV.

"The Alta X has a unique motor design," says Kevin Sartori, co-founder of Auterion. "It is almost like a swashplate, and it helps to reduce vibration, improving cinematic picture quality and the longevity of onboard systems.

"To help in that regard, the Auterion Enterprise PX4 stack includes the UAV-CAN protocol for motor control response, as well as the newly created open Pixhawk Payload Bus standard to enable Freefly and other users to integrate and hot-swap a wide array of cameras. At the same time, component manufacturers can easily build payloads that are compatible with multiple vehicles.

"We have other partners in the US who are developing new heavy-lift UAVs to work in search & rescue, infrastructure inspection, mapping and other applications requiring heavy, high-power camera payloads – and incorporating our new Skynode autopilot and companion computer system to be unveiled later this year."

Summary

Designing for heavy lift is a problem that has many different solutions, and there is no single 'best' one. UAV manufacturers can cut hull weight, improve hull aerodynamics, install new motors, design a more suitable propeller, and mix in a host of other tried methods and new design theories and technologies.

With so many engineering techniques to try out, multi-copters, helicopters and fixed-wing UAVs alike are all diversifying into countless shapes, to better optimise them for carrying more weight for their intended missions, rather than standardising around a handful of hull and powertrain architectures.

As end-users guide UAVs in these different directions, component suppliers can be expected to follow suit. They will offer wider ranges of systems and features for navigation, propulsion and connectivity, as well as other products to suit the different breeds of unmanned aircraft that will emerge.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Flight plans

Rory Jackson catches up with some of the UAV technology suppliers who would have been exhibiting at this airshow had it been able to go ahead

With the Farnborough International Airshow having transitioned to a virtual format for 2020 amid the ongoing lockdown-related travel restrictions, we interviewed a selection of aerospace technology companies to learn about their newest UAV-related updates and innovations that would otherwise have been showcased at the world's foremost aircraft exhibition.

Leonardo shared the latest details about its Falco Xplorer S/N0001 UAV, which has a payload capacity of 350 kg, more than 24 hours' endurance, and satcom for BVLOS operations, all within a 1.3 t MTOW.

"Our regular engagement with customers using our original Falco [as featured in *UST* 5, December 2015/January 2016], and its successor the Falco Evo, prompted the development of the Xplorer," said Fabrizio Boggiani. "Some customers required a higher capacity for payloads and longer endurance.

"It is undergoing certification for flight in non-segregated airspace, and is not subject to ITAR restrictions."

The platform will come with a Gabbiano T-80 surveillance radar, as well as an EO turret, a Sage electronic intelligence system and an automatic identification system (AIS) for maritime use.

Boggiani added, "There will be further flights over the next few months to assess the aircraft's full range of capabilities, including its integrated sensors, and to certify the Xplorer to NATO Stanag 4671, dramatically expanding the territory over which it can operate."

Leonardo also discussed the latest on its AWHero rotary UAS. It is currently going through a military certification process, the only helicopter in its weight class to be doing so. With ongoing flight trials for Italy's military authorities, the AWHero's official type certification is expected later this year.

Its capabilities and features were demonstrated during the first live exercise for Ocean2020, a project funded by the European Union's Preparatory Action on Defence Research and implemented by the European Defence Agency.

The AWHero was equipped with a 10 in (25.4 cm) EO/IR and an AIS transceiver, and it successfully detected, identified and tracked intruder vessels, operating from an Italian Navy FREMM-class frigate in the Mediterranean. Real-time video and other data from the UAV were transmitted to the ship's tactical table and disseminated to maritime operational centres in Rome, Brussels and elsewhere via satellite.

During the demonstration, the AWHero was teamed with other unmanned assets (including Leonardo's SW-4 Solo optionally piloted helicopter) to support the persistent maritime surveillance coverage by

integrating data from multiple sources.

The 200 kg AWHero has two separate payload bays and a useful load of 85 kg for carrying mission sensors such as maritime radar, EO/IR, SIGINT, Lidar and comms relays, at a maximum continuous speed of 90 knots (or 50 knots for cruising) and with 55 nautical mile range on its encrypted data link.

UK-based rotary engine company Advanced Innovative Engineering (AIE), last featured with its 225CS in *UST* 7 (April/May 2016), spoke to us about its new 80S product, a multi-fuel Wankel engine displacing 80 cc.

"The 80S is a single-rotor 15 hp, liquid-cooled twin-spark plug system, and needs no rotor change when switching between gasolines and kerosene jet fuels," said Alex Vaughn. "With a compact size [120 x 191 x 250 mm] and a weight of 5.2 kg, this solution was developed for VTOL and fixed-wing platforms in direct drive or hybrid-electric configurations."

As well as high power density and low vibration being key targets (for missions oriented towards heavy payloads and long-range surveillance), the 80S uses AIE's patented self-pressurised air rotor cooling system, for improving gas sealing at the axial ends of the Wankel's apex seals. This results in greater engine operational efficiency and a lower workload for the rotor's seal pack.


The 80S multi-fuel Wankel from AIE

"This unique closed-loop cooling technology for rotary engines uses thermal balancing and eliminates wet oil loss, for cleaner operation and increasing the life of the engine," Vaughn added. "For hybridisation, the engine's lowest specific fuel consumption is at its higher revs: greater efficiency at maximum continuous output makes it effective at recharging batteries on the vehicle."

The 80S also incorporates ceramic rotor seals, for durability and lower oil consumption than its forerunners. Its power-to-weight ratio has been further improved by integrating the external oil tank onto the non-drive side of the engine, which also serves to reduce packaging complexity, size and overall weight.

SBG Systems' Ellipse inertial navigation units

SBG Systems has unveiled its third-generation series of Ellipse inertial navigation products, developed for increased reliability and size optimisation in GNSSs.

As Helene Leplomb told us, "A new 64-bit software architecture in the third-generation family allows for more precise algorithms, which will improve the overall performance of all the Ellipses in many situations, such as when coupled with RTK-aiding."

Further improvements include new dual-band, quad-constellation GNSS receivers in the Ellipse-N and Ellipse-D for outputting centimetre-accurate measurements with RTK processing.

The new Ellipse-D's enclosure has also been downsized to 46 x 45 x 32 mm while maintaining the same power, accuracy and dual-antenna


The Falco Xplorer is Leonardo's largest-ever UAV, with a MTOW of 1.3 tonnes. The aircraft is undergoing certification for flight in non-segregated airspace

Tecnalia's autonomous urban aerotaxi

capability as in its predecessor. And all third-generation Ellipse products will be made available in OEM form factors, for tighter integration where size and weight are at a higher premium. The Ellipse-D, for example, measures 29.5 x 25.5 x 16 mm, weighs 17 g without its enclosure and 65 g when covered.

"To qualify, test and calibrate our new INSs, we used our latest calibration algorithms and multi-axis rotary tables that we purpose-developed for producing higher performance sensors," Leplomb added.

Tecnalia spoke to us about its 'aerotaxi' for autonomous urban transport. The craft has been designed around carrying a single passenger, to reduce its footprint (with the hub measuring 2 x 2 x 1.8 m) and make integration easier in urban environments. It has a wide rear access port to enable the passenger to enter it while standing.

Antonio Bardasco Monge said, "The main technical difference compared to other similar urban air mobility designs is that it is an over-actuated aircraft – all its degrees of freedom can be commanded independently. This offers great advantages over other aircraft architectures when you fly in adverse conditions such as strong winds, or when you have to perform manoeuvres in which accuracy or stability is critical, such as take-off and landing in tight areas."

The Vector-400 from UAV Navigation

This propulsion architecture incorporates four quadrotor-like sets of rotors, meaning 16 propeller drives in total. They adjust relative to the hub using passive mechanical joints for flight stability, and will enable a top speed of 90 kph, or potentially up to 190 kph, at altitudes of 300 m or higher depending on legislation.

UAV Navigation has launched two new versions of its foremost UAV guidance products.

"The Vector-400 has been designed for the needs of our fixed-wing clients, such as unmanned aerial targets [UATs] and catapult-launched UAVs," David Pinta said.

It weighs 210 g, or 255 g when packaged with a built-in data link, measures 74.5 x 68 x 58 mm and consumes 2.5 W in standard operations. Measurements of pitch and yaw are output to 0.5º accuracy, and in GNSS outages the drift under dead reckoning is limited to 30 m/minute.

"Development of the Vector-400 started when we decided our AP04 autopilot for UATs needed updating," Pinta recounts. "Also, the system includes complex manoeuvres such as sea-skimming. These high-speed and low-altitude wave-level flights increase the difficulty of detecting the UATs, enabling special tests with radars and other systems."

Also newly launched is the Polar-500, an advanced version of the company's Polar-300 attitude and heading reference system. The Polar-500 incorporates a dual-GNSS compass for enabling precise heading in static and dynamic situations (even without a calibrated magnetometer), and can now communicate using the ARINC-429 protocol for antenna steering, based on requests for these features from the UAV community.

The Polar-500 consumes up to 2 W, weighs 170 g, and matches the Vector-400 for pitch and roll accuracy.

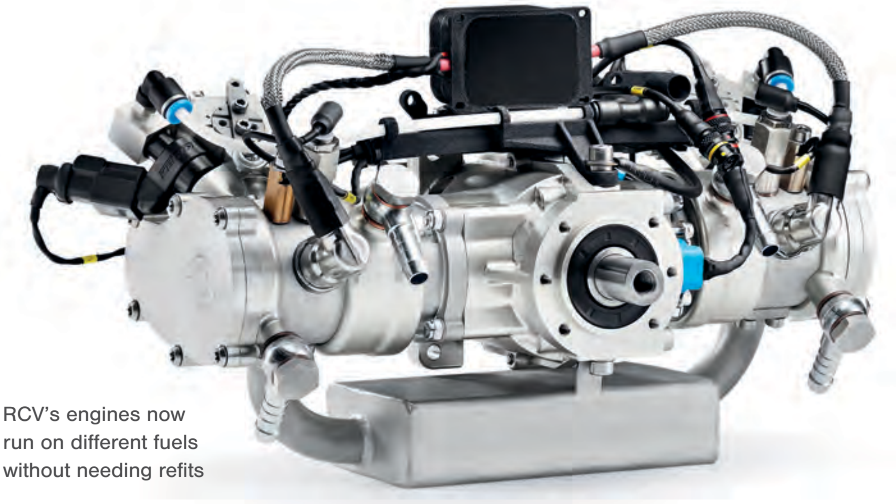
MicroLink Devices told us about its latest thin-film solar panels, development of which was supported by the US DoD's Rapid Reaction Technology Office (RRTO), explicitly for optimising MicroLink's flexible solar sheet array performance for pseudo-satellite-type UAVs.

"High specific power generation relative to mass is critical for enabling the multi-month endurances of HALE UAVs and operations at high altitudes and in the winter months," Ray Chan said.

Under the RRTO programme, MicroLink has further reduced the mass of its triple-junction (TJ) inverted metamorphic (IMM) epitaxial lift-off (ELO) PV cells. The latest demonstrated result was a flexible solar array panel with a specific power output of more than 1600 W/kg.

"The efficiency of our TJ IMM ELO solar cell technology now exceeds 30% AM0 [the solar spectrum in zero-atmospheric conditions] at 25 C, which is

IMUs on test at Silicon Sensing



RCV's engines now run on different fuels without needing refits

comparable to the best solar cells now used on space satellites," Chan said. "But we're also able to manufacture the cells in a thin-film, flexible format, enabling new applications and methods of integration."

The company added that this latest flexible solar array panel is at a technology readiness level of 7, having been tested in the stratosphere, and MicroLink is ready to begin initial production.

Silicon Sensing discussed its fifth-generation (and highest-performing) IMU, the DMU30.

"The DMU30 was developed to match the performance of a fibre optic gyro device but is more rugged, more affordable, and ideal for operating over extended periods in severe environments," Andy Hughes said.

"Independent trials have proved its performance, and it is now in production for a number of applications, including in the unmanned sector. For example, it has been selected for installation in the control system of the new iQPS small synthetic aperture radar satellite.

"Several of these satellites will be deployed to provide an Earth observation data service, with the DMU30 helping to monitor and control the satellite's angular velocity and attitude."

The DMU30's bias instability is limited to 0.1°/hour on its three gyroscopes and to 0.015 m*g* on its three accelerometers, with a maximum of 0.05°/s gyroscopic noise and 0.9 m*g* accelerometer noise.

RCV Engines has achieved the capability to run its engines using a range of different fuels – including gasolines, JP5, JP8 and diesels – without requiring any physical refits between fuel changes. Instead, only a toggle between the multi-fuel switchable maps (MFSM) stored in the ECU is required.

"The concept of an ECU that can switch between fuel maps is in itself not revolutionary, but given the correct fuel map, we can run our engines equally well on any fuel," Keith Lawes said.

"We can accomplish that because of our rotating valve engines' common combustion system. The rotation of the valve generates a high level of turbulence, which mixes the fuel and air thoroughly.

"Also, the combustion chamber within the rotating valve body is very compact, which ensures the burn spreads reliably and rapidly from the ignition point through the entire charge. It also ensures that as much heat as possible is retained within the charge to produce mechanical work."

With these design qualities enabling significant tolerance of changes in air-to-fuel ratio, ignition timing and other fuel-related considerations, all that remained was for RCV to write firmware for the ECU to allow the MFSM function.

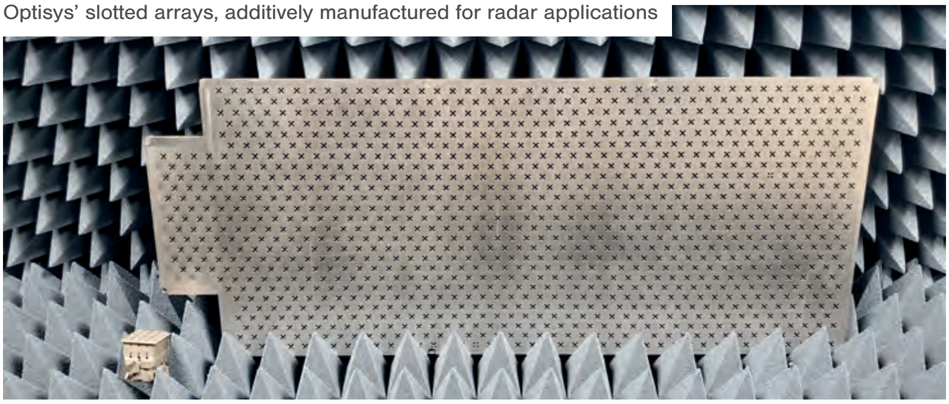
As Lawes explained, "It was decided to have four independent fuelling maps and associated calibration data. For example, cold-start enrichment tables will vary from fuel to fuel. The four tables enable gasoline, JP8, JP5 and diesel calibrations to be included in one ECU if required, and CAN bus was selected as the input method to select the fuelling map."

The calibration maps for each main fuel type have been based on a standard master calibration, individually adjusted for each engine to optimise operations. Standard-issue RCV engines will have a gasoline and JP8/Jet A1 calibration. A JP5 calibration can be supplied if requested, and while diesel is not currently a primary option, further optimisation to offer it as such is anticipated in the near future.

Curtiss-Wright informed us about two of its newest network comms products suited to the UAS industry. The first is the DuraMAR 6300, which the company described as the embedded comms industry's smallest and lightest rugged Cisco IP router.

"It comes with extensive Mil-Std qualification testing and cybersecurity offered by Cisco technologies for secure data in motion, which will be CSfC [Commercial Solutions for Classified]-approved by the autumn," said Mike Southworth.

The DuraMAR 6300 weighs 2.0 lb (0.91 kg) and integrates a Cisco ESR-6300 embedded services router card running Cisco IOS-XE software. Now available for use in network backbones on board


Optisys' slotted arrays, additively manufactured for radar applications

UAVs, it supports six Gigabit Ethernet ports, CNSA/IPSec encryption and advanced mobile ad hoc networking services.

The second technology discussed was the Data Transport System (DTS1) Network Attached Storage (NAS) device for storing, removing and transporting critically sensitive data. This was unveiled as the embedded industry's first COTS data-at-rest (DAR) storage solution to support two layers of full-disc encryption in a single device.

"Those two layers of encryption support leading encryption certification levels, including NSA-CSfC, NATO Information Assurance Product Catalogue and Common Criteria," Curtiss-Wright's Steven Petric said. "It's also qualified to operate from -45 C to +85 C, using conduction cooling in harsh environments."

Development of the DTS1 was spurred following demand for DAR protection on UAVs, in case of their loss or capture in the field. By supporting two distinct layers of AES 256-bit encryption in one device, it is evaluated to protect top-secret data more safely and cost-effectively than traditional NSA Type 1 devices.

The DTS1 NAS weighs 3.77 lb (1.71 kg) and measures 38 x 127 x 165 mm, while integrating a 4 Tbyte SSD with two layers of certified encryption.

It also supports the PXE protocol, enabling network clients to quickly boot from the encrypted files on the DTS1. This facilitates software updates for network clients and significantly reduces SWaP by eliminating the need for individual hard discs in each network client.

Optisys, which additively manufactures antenna elements in unmanned systems, spoke about some of its latest projects.

"We have been keeping up with demand for our electronically steered arrays [ESAs] for comms and slotted flat panels for radar applications," Janos Opra said. "Most notably, in the comms domain we have been developing technology for Satcom On The Move for large military UAV platforms. On the same types of platforms, we have also been using our slotted flat panels for very high-resolution, all-weather radar."

Optisys' additive manufacturing enables its engineers to combine RF horns into single-phase chips, sometimes packed as densely as 32 horns per chip. This can reduce the power consumption of its RF systems from multiple kilowatts to as low as 100 W in some cases, while still providing the data rates of kilowatt-level systems.

The ESA antennas consist of tens of thousands of elements with precise interconnections. To design, manufacture, and optimise these for reliable RF performance, Ansys and Rescale were used extensively by Optisys' engineers.

Structural and thermal models were also extensively simulated, as some of the company's ESAs also work as heat sinks and structural elements for the platforms they are integrated into, owing to their monolithic aluminium constructions.

"Also, our arrays are the only ones capable of Tx and Rx in the same aperture, making them small enough for UAVs but also able to cater for full Ku- to Ka-band coverage in the same product," Opra added.

"Equally, our lightweight slotted flat panels, which are narrowband in comparison to our arrays, are proving suitable for high-resolution synthetic aperture radar imagery for detecting vehicles, personnel and even weaponry in bad weather or through clouds."

Auterion followed up on its previous discussions with *UST* with more details about its new Skynode product.

"Skynode's OEM module measures 97 x 47 x 30 mm and weighs 83 g," Kevin Sartori said. "It therefore fits large VTOL-transition craft as well as small quadcopters."

As well as integrating open interface standards such as MAVLink and FMUx5x, the newly announced Pixhawk Payload Bus and Pixhawk Smart Battery Standard will enable UAV manufacturers to build scalable integrations with payloads, batteries and battery management systems that are compatible with their respective protocols.

Also, after a growing number of requests for expanded computing capabilities and a higher-level development environment for UAV software, Skynode has integrated a full Linux computer to run Auterion's software distribution and allow customers to write their own apps in Docker containers.

"This allows developers to build computer vision or deep-learning algorithms without having to go down into the low-level flight control software," Sartori said. "The connectivity module also enables developers to build workflows over a software development kit and connect UAVs to existing enterprise infrastructure; UAVs then basically become flying servers.

"And recently we announced our own ruggedised handheld GCS for government customers, Skynav Gov, to help them control UAVs with Skynode or Auterion software out of the box."

Transforma Robotics' engineers were able to work throughout the lockdown to produce the XDBOT

The Covid-19 pandemic has brought into sharp focus the value of using unmanned systems to disinfect buildings. **Rory Jackson** looks at one such system

Clean bill of health

While many people spent the Covid-19 lockdowns confined at home and in reasonable safety, a considerable portion of the world's population had to put themselves at significant risk every day, performing essential work in sanitation, healthcare and other critical sectors.

Amid labour shortages and dismay over essential workers facing excessive exposure to the coronavirus, many proposals have been made as to the ways unmanned systems could (theoretically) help fill the personnel gaps that the virus has left in the world's economies.

Singaporean company Transforma Robotics is among those few companies to have proven the pandemic-fighting potential of unmanned systems. It has developed a UGV that autonomously sprays disinfectant throughout buildings, minimising the risks to life from putting cleaning staff to such duties.

In a development cycle of three months that started last February, the company has designed and completed its eXtreme Disinfection roBOT (XDBOT), tested it in various locations (hospitals included) and iterated it to nearly full production readiness.

Designed to be compact and transportable, the battery-electric XDBOT measures 120 cm tall and 45 cm wide, weighs 50 kg (excluding its 10-litre disinfectant tank and battery pack), and mounts a self-aiming, self-adjusting sprayer for dispensing disinfectant at up to 160 ml/minute.

With a 4-hour endurance between charges, it can disinfect 1200 m^2 per session, which the company estimates as four times that of a human worker.

Timeline of the XDBOT

Transforma Robotics is a spin-out from the Nanyang Technological University (NTU) in Singapore, which over the past few years has focused primarily on developing robots for the construction sector.

The first XDBOT prototype was developed and trialled in six weeks, following an increased pandemic alert in Singapore

On February 7, however, Singapore's national coronavirus alert level was raised, from a 'yellow' to an 'orange' rating. That spurred the directors of the country's National Robotics Program to call together industry leaders and academics, to discuss what the robotics community could contribute to the fight against the pandemic.

"China had experienced rises in cases earlier than Singapore, and we knew it had used robots and UAVs for various tasks during the lockdown there," says I-Ming Chen, CEO of Transforma Robotics and a professor at NTU's School of Mechanical and Aerospace Engineering. "I discussed with some colleagues and staff how we could build a vehicle that would help.

"That discussion included several other NTU spin-outs, from areas such as medical robotics, AI for computer vision, AI for grasping and picking up objects, and teleoperations, as well as some industry partners."

The bulk of the project's development (including hardware and software design) and organisation was carried out by Transforma, with 'pick-and-place' logistics start-up Hand Plus Robotics providing the AI vision for the spray arm, and Maju Robotics providing the robot's interfacing and teleoperations systems.

Prof Chen and his team then drew up a six-week development roadmap for a robotic disinfection vehicle. That time frame was chosen to ensure that an effective system could be produced quickly enough to make a positive contribution to Singapore's efforts to curb the spread of the coronavirus.

"We knew there were other ways of designing a robot for fighting the coronavirus," Prof Chen says. "For example, there are some out there that emit UV light, and others that produce an ambient fog of disinfectant rather than spraying in a targeted cone, but we had designed another UGV for construction spraying, which gave us a head-start for development.

"Furthermore, information we gathered during talks with Singapore's hospitals showed that a lot of traffic in them comes from people constantly cleaning walls and furniture. That slows down the movement of medical staff, and means more potential disease-carriers moving in and out of the hospitals.

"There is huge potential for disinfection robots to cut down on both of these problems, and on top of that, robots can't get sick so they won't be affected by the ongoing shortages of PPE [personal protective equipment]. However, existing robots aren't designed to meet the required hospital protocols on cleaning equipment."

Transforma's UGV would therefore need to be capable of pointing and spraying in a wide arc, as well as concentrating its spraying efforts on what hospitals call 'high-frequency touch surfaces', such as doorknobs, elevator buttons and handrails.

Compared with human cleaners, existing robots achieve insufficient coverage, poor precision and therefore very little effective cleaning of such surfaces, with most of their droplets falling uselessly to the floor after being sprayed.

With these problems established, Transforma drew from its existing portfolio of projects for the XDBOT's

The current version of the XDBOT has been redesigned for differential steering, and has a narrower chassis, for easier navigation in rooms and corridors

technological foundations. These included a UGV being developed for autonomous mobile spray-painting (the Pictobot) and another UGV being developed to perform mobile quality inspections on finished walls and structures (the Quicabot).

Aspects of both systems were combined to complete the initial XDBOT prototype, in late March. This was the version that subsequently received so much attention in the local and international news media.

The company first tested the XDBOT at NTU, given its proximity to Transforma's facility, the fact that few staff were still on site there and that clean conditions were needed in which to work.

On April 8 though, the Singaporean government instituted its 'circuit breaker' measures. Most of the economy was locked down and people were ordered to stay indoors (except to procure essentials). Transforma's team therefore continued their programming, data analysis and CAD work at home, communicating with each other remotely.

"Singapore was locked down for two months, and in the middle of that, on May 1, we started work on the XDBOT's second [and current] prototype," Prof Chen says.

"This has a very slimmed-down chassis compared to the first version. It too took six weeks to develop, with actual construction starting on June 2 after the circuit breaker was lifted, and we trialled it in Singapore General Hospital on June 19."

At the time of writing, Transforma was developing its third version, which will be almost identical to the second prototype but with a few chassis alterations to protect it against moisture and dust, and some weight reduction. Series production of that version is expected to follow after sufficient testing has been carried out.

The chassis has largely been fabricated in-house, with key aspects of the electronics supplied by a mixture of local and international companies. With local manufacturers having returned to work by June, Transforma also had no problems with procuring the parts they needed from international suppliers.

Degrees of autonomy

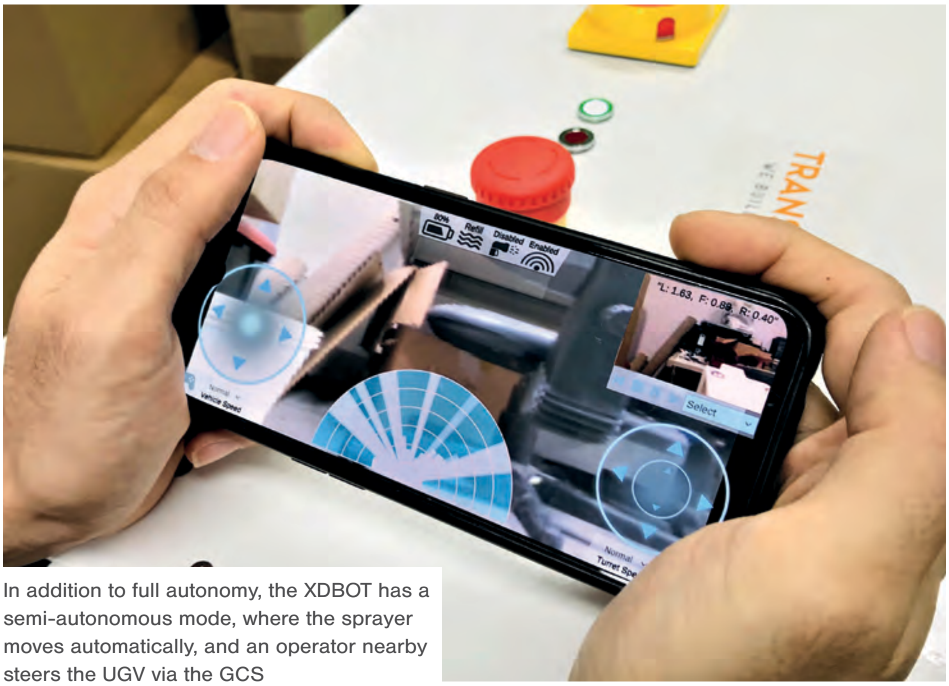
The company recognises that, depending on the regularity with which a location needs to be disinfected, the required mode of operation by the XDBOT's end-users will change. That has driven it to develop a spectrum of autonomy levels across which the UGV can be used, with ROS (Robotic Operating System) serving as the middleware for software installation and programming.

The first mode to be trialled and tested was semi-autonomous. Here, a remote operator controls the vehicle's traction speed and steering, typically from a handheld GCS connected by a 2.4 GHz wi-fi link.

Meanwhile, the spraying device acts with full autonomy, scanning ahead of the UGV's path and recognising high-frequency touch surfaces via an integrated camera, using embedded feature-recognition software from Transforma's partners working in AI.

It targets and prioritises these points for spraying, and its software manages the electromechanical actuations for height and angle to aim the nozzle as needed.

Semi-autonomous mode would be appropriate when a modicum of human situational awareness is needed – as in public spaces after large-scale gatherings where there are pedestrians – and where



In addition to full autonomy, the XDBOT has a semi-autonomous mode, where the sprayer moves automatically, and an operator nearby steers the UGV via the GCS

there are pockets of space where the XDBOT will need to linger in order to provide especially thorough spraying.

Teleoperation by the operator from a separate room is possible via the UGV's camera and wi-fi link, but it is preferable to have the operator standing and watching a short distance away for greater situational awareness in public spaces.

While trials of the UGV in this mode have been conducted with the operator following at some distance behind the UGV, the company is also developing a follow-me mode. In this, the vehicle would use its perception sensors to lock on to a cleaner working several paces ahead of it, and spray while following their path and approximate speed.

A full remote operation mode (where the operator controls both the arm and the wheels) is also available for rare cases where human judgement is needed. This is the most labour-intensive mode, however, and Transforma does not expect it to be widely used.

Lastly, full autonomy naturally entails traction, steering and spraying all being handled by the XDBOT's embedded software. While Transforma is putting the finishing touches to this mode, it anticipates full autonomy being the most productive and widely used mode, especially in unchanging daily routes, where there is fixed furniture or where corridors will not be blocked off.

An initial survey and programming round would be needed in order to embed an approximate map of the building in the UGV's internal storage. After that it can automatically cover its assigned floorspace up to three times a day.

Sensor architecture

For fully autonomous operations indoors (where GNSS is unreliable), two sets of perception sensors are integrated into the XDBOT.

The sprayer mounts a small rail with a pair of Intel Realsense D435i cameras (integrated for stereoscopic vision) above the nozzle for first-person view. Embedded machine vision is used to recognise those surfaces where people are most likely to have left infectious handprints.

To date, the feature recognition has been trained primarily for hospitals, but Transforma and Hand Plus anticipate that slight training updates will be needed for each mission location, as objects such as doorknobs and elevator buttons will be different in each building.

The Realsense D435i integrates an IMU for fusing time-stamped inertial data with its vision data. It has a vertical field of view (FoV) of roughly 58°, a horizontal FoV of about 87°, and a diagonal FoV of about 95°.

To sense and avoid furniture, people, and other objects, a Slamtec RPLidar-A3 is installed on the front. It has a detection distance of up to 25 m, a typical scan rate of 15 Hz, a sample rate of 16 kHz, and an angular resolution of 0.3375°.

Transforma has trained the software for it in order to improve its ability to recognise when objects and people pose potential obstructions.

As of the second prototype, another Realsense system has been installed next to the Lidar, to provide complementary obstacle detection data via the embedded sensor fusion, with superior range and colour information added as a result.

Spraying and sanitising

The sprayer assembly nozzle can be moved and pointed to dispense liquid disinfectant at up to 2.3 m above the ground in its vertical axis, down to floor level.

The typical horizontal reach of the aerosol droplets (which are typically 40 microns in size) extends up to 2 m from the nozzle, although 0.8 m is recommended for optimal coverage. The cone of the spray widens to 0.3 m in diameter at 1.2 m from the nozzle.

In the first prototype, the spray nozzle was installed and steered on a robotic arm from Universal Robotics – its UR5 model, which has three axes of rotation, a reach of 850 mm and a weight of 20.6 kg.

"In the second version though, we've designed and built the mechanics of the sprayer's aim and movement ourselves, and we've simplified it a lot," Prof Chen says. "We realised that three degrees of freedom was actually too many, so by making a simple pan-tilt gimbal ourselves we could make the XDBOT less expensive to produce and simpler to operate."

An Intel Realsense D435i depth camera is fitted on the nozzle, and embedded with AI from Hand Plus Robotics to recognise where to spray

The electrostatic sprayer enables wide dispersion and equal distribution of disinfectant droplets around surfaces and objects

Specifications

Dimensions: 120 x 45 x 45 cm
Empty weight: 50 kg
Operating speed: 1 m/s
Max speed: 4 m/s
Payload: 10 litres of disinfectant
Power: lithium-ion battery
Drive: differential wheel-hub motors

Some key suppliers

Lidar: Slamtec
Camera: Intel
Electric traction motors: Shen Zhen Zhongling Technology
Machine vision: Hand Plus Robotics
Mobile device interface: Maju Robotics

The sprayer's current gimbal mechanism can tilt from -45º to 45º vertically, and 270º horizontally. A gantry-like system mounts the sprayer gimbal and electromechanically elevates it to meet the range needed for spraying prioritised points for disinfection. This system has been deemed far more useful – and much simpler – than a *z*-axis rolling actuator.

"We are very familiar with a range of industrial robots, and the third degree of freedom would be useful for painting, so you don't visibly miss any spots," Prof Chen says.

"For disinfection though it isn't critical, because with the system we've set up the only important points of orientation are direction and distance."

He further explains that the XDBOT incorporates an electrostatic spraying capability to overcome the aforementioned problem of needing to cover and surround objects such as doorknobs and railings with disinfectant.

"It is not so much a robotics problem as a fluid mechanics problem," he remarks. "Luckily though, we have students and interns from NTU who specialise in this area.

"When the fluid particles leave the nozzle, they do so with a negative charge. As they diffuse through the air, they repel each other to ensure a wide area of effect, but as they encounter the object they've been propelled towards, they'll be attracted towards it, while still maintaining something of an equal distance from other droplets.

"That causes them to wrap around objects, so the robot ends up distributing droplets with a consistent and comprehensive coverage. Electrostatic technology is used in spray-painting as well, but it's perhaps even more useful here because disinfectant doesn't need to be sprayed as thickly or visibly as paint on walls."

Power and motion

Although exact operations will differ between locations, the XDBOT typically moves at 1 m/s (3.6 kph). Prof Chen notes however that it can travel much faster.

"1 m/s is the ISO standard for these kinds of robots in hospital environments. That speed still means we can disinfect a normal 20 m^2 hospital room in 5 to

10 minutes," he says. "Our motors allow us to move at up to 4 m/s, which is fine for traversing corridors that the robot doesn't need to linger in."

Two hub-wheel motors are installed to enable differential movement, thus the robot can rotate in place to minimise its turning radius in narrow corridors. Each motor is a single-shaft hub wheel motor producing up to 500 W of power from a 24 V supply, drawing up to 10 A in normal operations.

The XDBOT has a typical running time of 4 hours. Transforma has kept the charging system simple – a 100-200 V AC wall power outlet is enough to replenish the battery within an hour.

While many unmanned vehicles need to avoid downtime wherever possible, Transforma anticipates the XDBOT's operations being a matter of routine rather than urgency. A few daily cleans per UGV per floor of a hospital should be sufficient.

"In 4 hours, the robot can disinfect 1200 m^2," Prof Chen says. "A human cleaning team would do these rounds once in the morning, once in the afternoon and once at night, which leaves plenty of time for charging in between."

If, however, extra cleaning time is urgently needed, Transforma can provide a charging station in which fresh battery packs can be pre-charged for swapping into the robot, reducing downtime from an hour to 5 minutes.

"We are working on an automated battery swap system as well, just in case the end-user really can't be there to physically plug the XDBOT into a wall or swap the battery themselves," Prof Chen adds.

"And there are some other spin-out companies in our office building who develop wireless charging and power management systems, who we may well work with in the future to develop suitable convenient charging peripherals for the XDBOT."

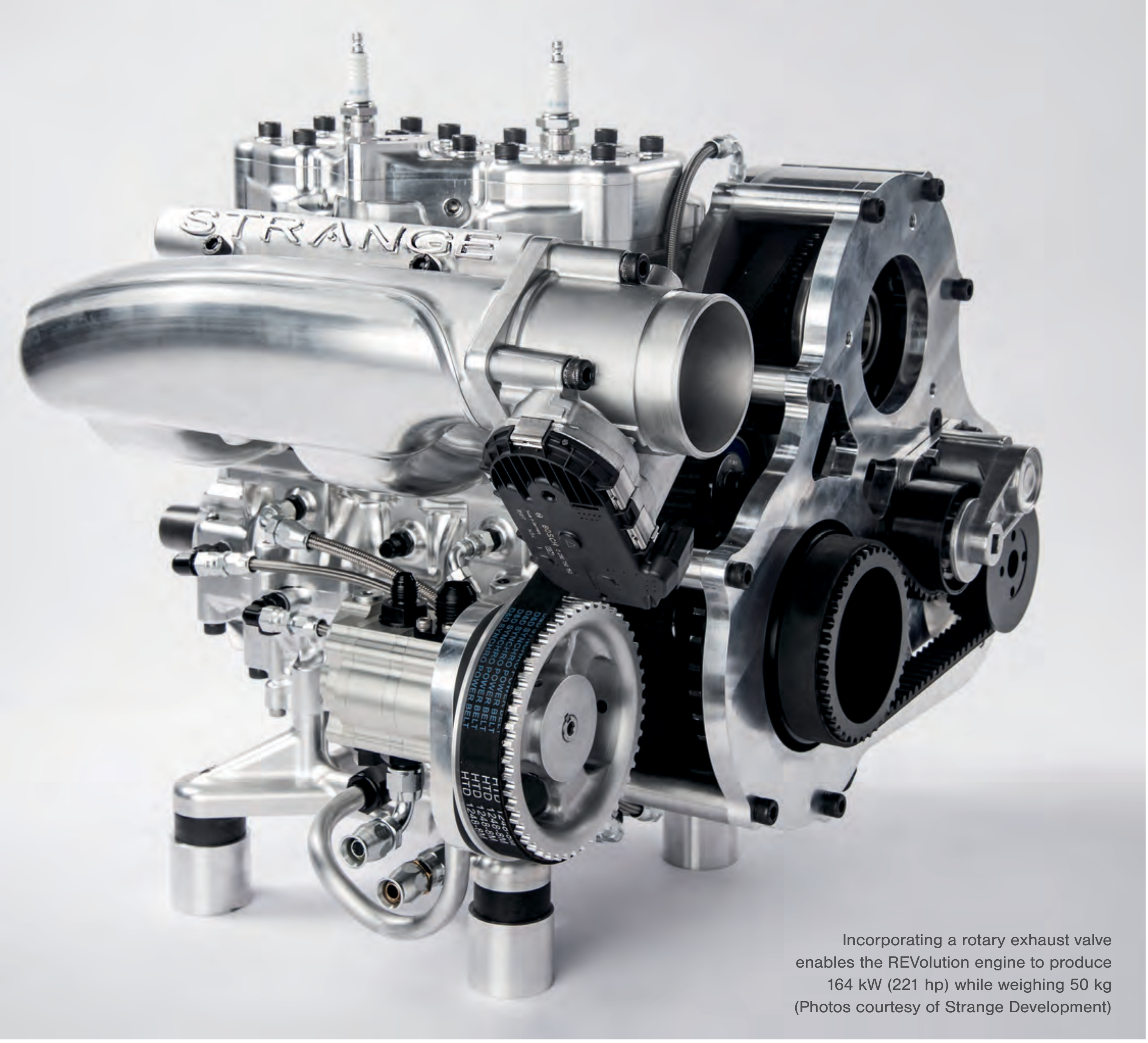
Conclusion

Prof Chen notes, "Full autonomy on industrial UGVs is challenging. You not only need to perceive, drive and steer autonomously, you have to do so in a way that gets your mobile manipulation system – in this case, a disinfectant spray system – where it needs to be.

"This latter system then needs to move and spray intelligently while taking the vehicle's dynamics, power and surroundings into account – all without human supervision."

That means having a complex network of systems compared with self-driving cars and factory AGVs.

However, given the widespread need for persistent and intelligent robots that can reasonably act as substitutes for human labour while people are under lockdown, Prof Chen anticipates that over the next 5-10 years there will be some major innovations in these kinds of unmanned vehicles.



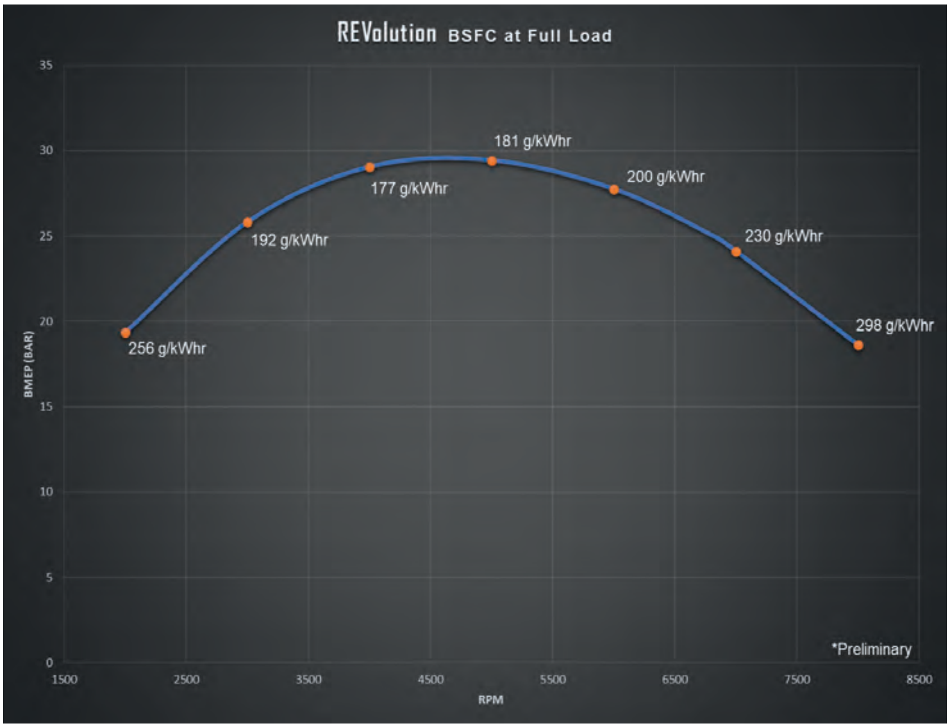
Incorporating a rotary exhaust valve enables the REVolution engine to produce 164 kW (221 hp) while weighing 50 kg (Photos courtesy of Strange Development)

Rotary foundation

Rory Jackson reports on how the concept of a rotary exhaust valve maximises the merits of this supercharged UAV two-stroke

The city of Fenton, Michigan, is home to Strange Development, an engineering company aptly named for its predisposition towards new and unconventional solutions for powering vehicles. Based not far from the 'Motor City' of Detroit, the company was founded by CEO John Krzeminski about 15 years ago as an r&d workshop focusing on the design, engineering and manufacturing of advanced vehicle power plants.

Krzeminski and his team's foremost ambition was to identify and resolve the most pressing needs of the UAV market, seeing it as the best outlet for their passion for developing new engine architectures. And indeed, Strange



The REVolution's BSFC depicted as a function of speed and BMEP

Development has produced a new engine entitled the REVolution, which is designed primarily for UAVs but can also be customised for marine, road and other vehicle applications.

The REVolution is a supercharged two-stroke inline two-cylinder measuring roughly 400 x 350 x 300 mm, with a maximum output of 220 hp (164 kW) – which it achieves at 6800 rpm – and a BSFC of 221 g/kWh when performing at these levels. It had been trialled at up to 7000 rpm at the time of writing, with 8000 rpm as the expected redline.

It runs on gasoline, has a BMEP of 25 bar, and weighs 49.89 kg (110 lb) including the oil pump, supercharger and a front-end accessory transmission system that drives both of them. The standard-issue electric fuel pump and dry oil sump are external to the main design (although a pan for collecting oil via gravity is bolted under the crankcase). Thermal management is provided largely by an internal water-cooling system, and integral oiling channels provide further cooling, along with lubrication.

> The client asked us about supercharging their design, so we built a test engine, put it on the dyno and it actually lost power

The REVolution's origins

Between 2008 and 2010, Krzeminski and his team were performing some work on a four-cylinder, four-stroke, carburetted engine to be used on a UAV – which left Krzeminski somewhat nonplussed.

"What surprised me was how heavy it was – and still is – relative to its actual power output," he says. "There are ways to improve it: it's a well-known model, and engineers slap turbochargers and fuel injection systems onto it all the time, but the base architecture is heavy and outdated.

"We determined that a much higher power-to-weight ratio would be necessary to draw users away from that comfortable, suboptimal-but-reliable type of engine to a newer, more innovative one."

That motivated Strange Development to start considering what such an engine would look like. Soon after, the team started working on software designs and CAD simulations for a poppet valve-controlled two-stroke. This design was inspired by Detroit Diesel's uniflow-scavenged configuration (referred to in the Apple Tree Innovation dossier, *UST* 28, October/November 2019) but in late 2012 the team decided against this approach.

"With poppet valves, you'd get all the mechanical complexity, cost and weight of a four-stroke valvetrain, and Detroit Diesel's engine was designed to run at maybe half the revs we were going to need," Krzeminski says. "The valvetrain dynamics would be great on a diesel, but not for the gasoline engine speeds we were looking to tackle. It also just wasn't going to get us the power-to-weight ratio we wanted, so we shelved that design temporarily and focused on our engineering services for a while."

In 2014, the company was asked to provide r&d for a two-stroke that used turbocharging to compensate for altitude effects. This spurred an in-house discussion about forced induction, with a focus on how best to control the flow of gases through the two-stroke combustion chamber to boost power output.

"That four-stroke engine manufacturer I mentioned earlier, for example, will always put the turbo after the combustion chamber, because you'd want a measure of the wave dynamics to push the charge air back into the chamber," Krzeminski says.

"And then the client asked us about supercharging their design. So we built a test engine, put it on the dyno, and witnessed it actually losing power, because it wasn't getting any energy back from compressing the gas.

"Once the compressed gas was pushed into the engine, the piston would come down and the extra charge would just escape out through the exhaust. We drew all of this out on a whiteboard and laid it out for the client, and I remember pointing at their exhaust manifold and saying, 'You need a valve, right here, to stop or slow the airflow from leaving the engine'."

From these three observations – the need for high power-to-weight ratio, the excessive complexity of poppet valves, and the countervailing need for a valve to improve the scavenging and exhaust control to fully exploit the benefits of supercharging – the idea of the rotary exhaust valve (REV) was born.

The rotary exhaust valve

In 2015, Strange Development started running 1D simulations of a two-stroke with an axial-flow cylindrical rotary valve similar in principle to that developed by Bishop Innovation and Mercedes-Ilmor for the exhaust port in Formula One V10 engines. The company used the bottom half of its previous poppet-valve engine design but redesigned the top half to use a REV instead.

The team quickly noticed that not only could the exhaust valve increase the two-stroke's power density, and yield more from supercharged induction, but depending on how the valve was timed, it could also enable better control of greenhouse gas emissions.

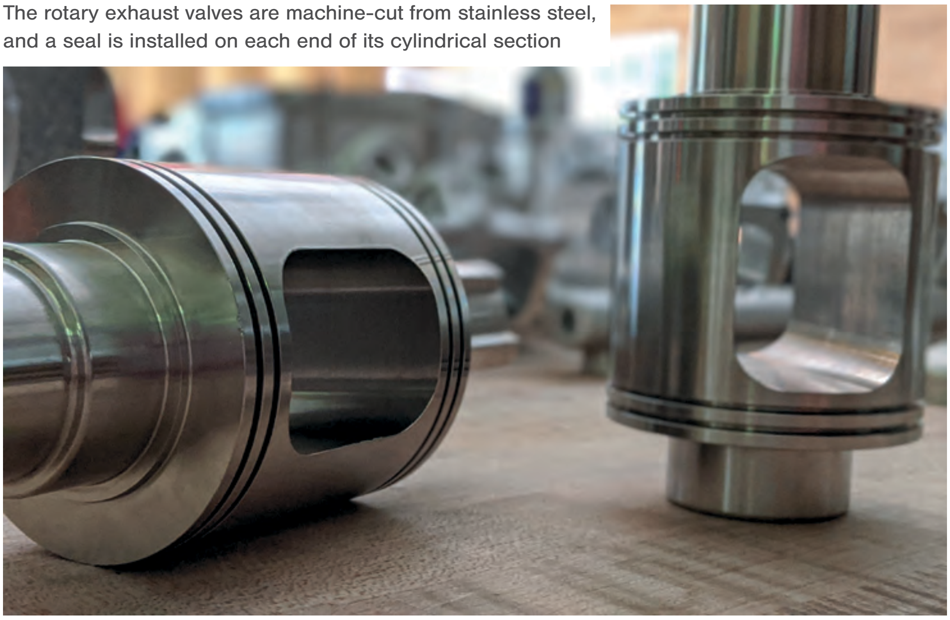
Considerable design work has gone into the timing of the rotary valve system and optimising it for the airflow in and out of each cylinder. As a result, the typical REV unit has a few key specifications.

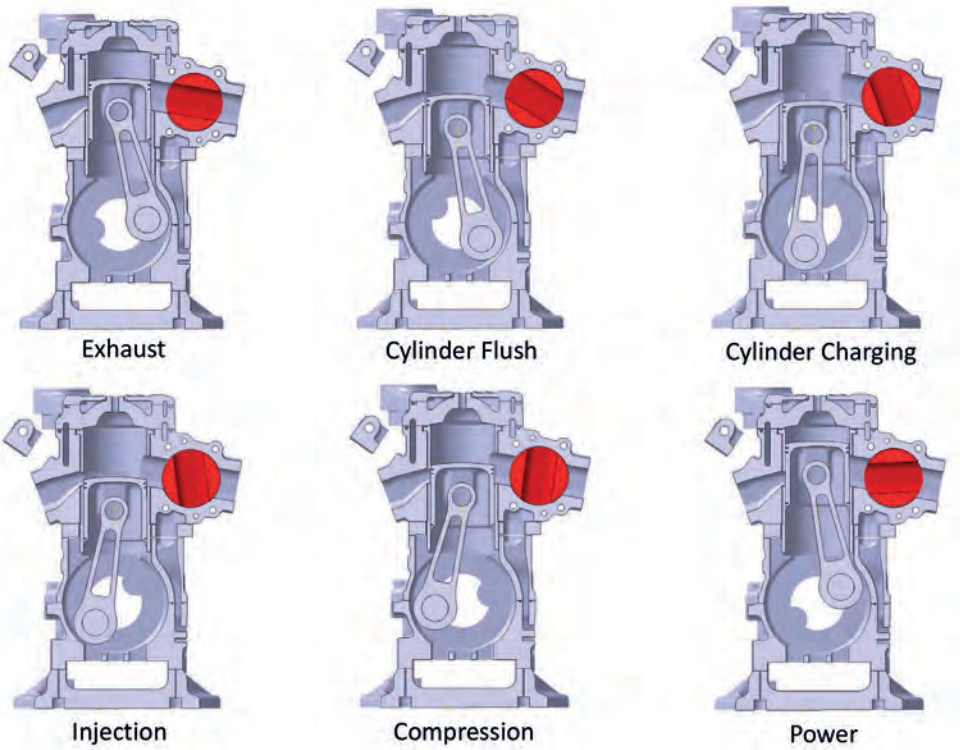
The valve is machine-cut from stainless steel (to prevent damage or thermal expansion from the exhaust gases, which can reach temperatures of up to 1200 F (649 C), and its port measures about 68 mm in diameter. "We might make it from titanium to save weight in the future, or from aluminium with a thermally resistive coating," Krzeminski adds.

"The way we cool the valve – with water circuits and oil injection – is absolutely critical to ensuring that it operates smoothly, as it fits with very close tolerances inside a chamber that runs across the two exhaust ports, and we can't have it or its bearings expanding and sticking from the heat.

"As for sealing, we don't look at the valve like a poppet valve, which has to provide 100% sealing; the valve is there to control flow dynamics, not to completely seal. Even so, whenever the piston crosses up past the exhaust port, sealing by the valve is no longer needed because the piston provides all the sealing necessary."

The rotary exhaust valves are machine-cut from stainless steel, and a seal is installed on each end of its cylindrical section





The changing movements and relative positions of the piston and exhaust valve effectively make for six stages in the REVolution's two-stroke cycle

So although each valve has two seals – one on each side of its cylindrical section – the valve is designed with the knowledge that it will experience some marginal level of leak. The company sees this as a valid trade-off; in exchange, the seals are subjected to a minimum of friction, which reduces their associated wear and parasitic losses, and allows the valve to spin freely.

The two valves rotate parallel with the crankshaft, with the timing factory-set by a belt drive on the engine's front and a quadrangular push-fit interlock connecting the two valves as a shaft at 90º to each other.

Six-cycle two-stroke

The way in which this engine operates and scavenges is not to be confused with a conventional two-stroke's crankcase compression.

The traditional two-stroke will forgo valving (aside from reeds or other systems on the throttle) because it relies on the piston as a pump to carry out internal pressure changes and dynamic fluid movements. Most often, the piston moves upwards (lowering crankcase pressure) to draw fuel and air into the crankcase, and when it thrusts downwards it pushes the fuel-air mixture out of the crankcase, through transfer ports up into the cylinder.

In the REVolution, however, the supercharger provides a persistent feed of high-pressure air directly into the cylinder, with a flow rate of 6188 litres/minute at peak power, eliminating the need for the piston to act as a pump. Instead, the piston acts solely as a valve for the intake air, shutting off the feed from the supercharger at key moments.

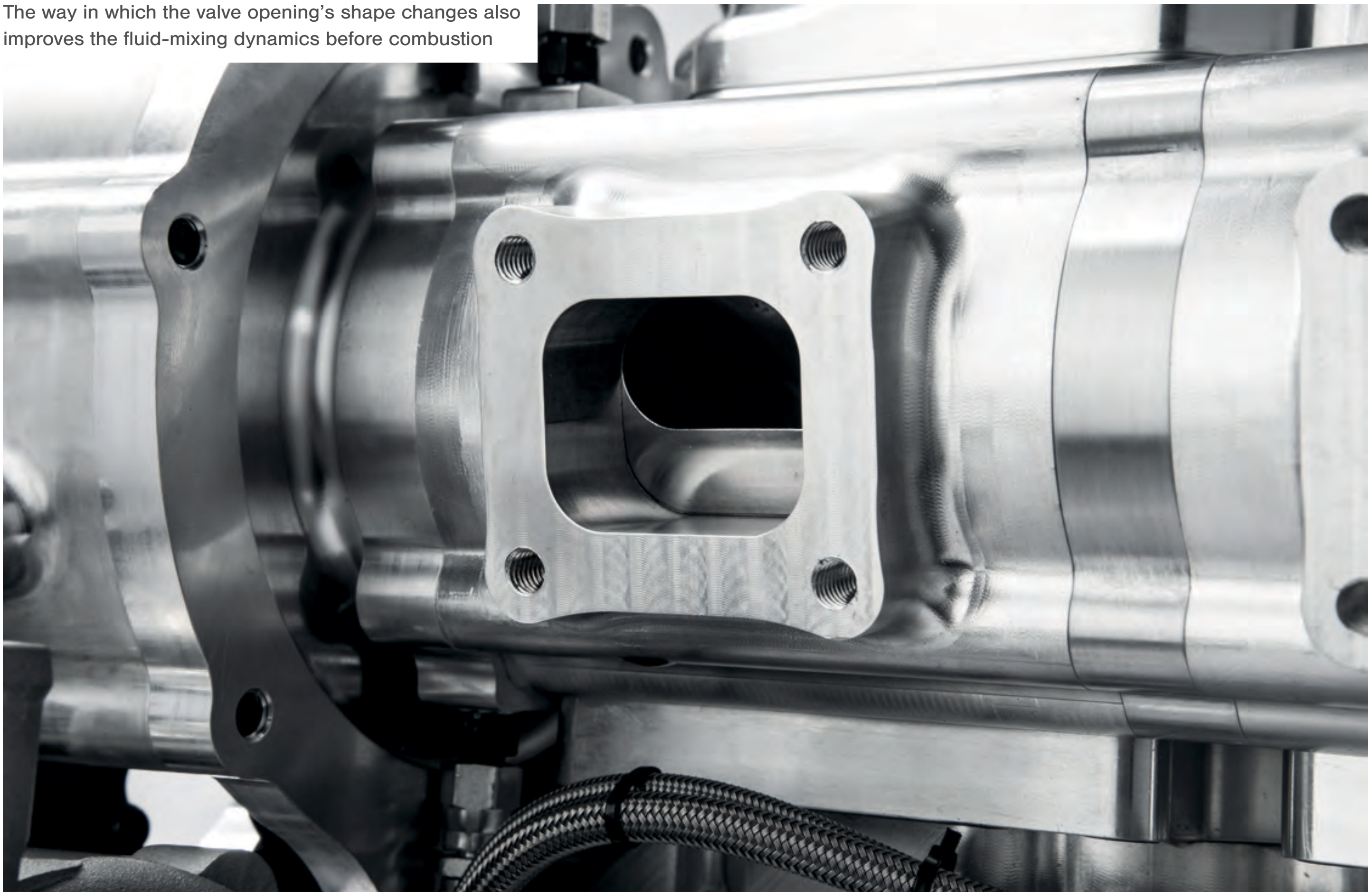
With the exhaust port positioned slightly higher than the intake port, the piston leaves the exhaust open for combustion gases to escape when needed. When it needs to be closed off, to catch and compress the intake air, the REV shuts off this passage, as per Krzeminski's earlier recommendation.

The added element of having a rotary valve in the exhaust port creates a 'six-cycle, two-stroke' operation, with six stages or events taking place during each revolution of the crankshaft: exhaust, cylinder flush, cylinder charging, injection, compression, and power.

These stages are defined by the relative positions of the piston and the REV, with the latter driven by a belt and gears on the front of the block (and initial start-up provided by a standard 12 V starter).

In the initial, exhaust, phase the piston thrusts from top dead centre (TDC), opening the exhaust port. At this stage the REV's passage is lined up with the exhaust passage, allowing combustion gas to exit freely, as it would in a conventional two-stroke.

However, the difference becomes noticeable as the crank angle goes



The way in which the valve opening's shape changes also improves the fluid-mixing dynamics before combustion

from about 90º to 120º, to begin cylinder flush. By the latter point, the piston crown is nearly at the bottom of the exhaust port, and the intake ports are partially opened, but the REV is continuing to revolve backwards, closing the exhaust port.

"Again, if intake air escapes out through the exhaust, it's a waste of the supercharger, and reducing the oxygen content in the exhaust allows for add-on technologies such as catalytic converters that you don't usually get to use with a two-stroke," he says.

"With the REV changing the exhaust port 'shape' by closing upwards helps draw the incoming scavenged air in an arc towards the cylinder head, which helps a lot with fuel mixing later."

As mentioned, the engine's unconventional scavenging design does not feed air into the crankcase. The intake air path is completely separate from the lower crankcase and the oiling system, with air fed directly into the cylinder via an intake piston port, and the piston behaving as the valve mechanism. As the piston uncovers the port, air flows in and is stopped when the port is covered again.

So long as the intake port is uncovered, the low position of the piston ensures in-cylinder pressure is lower than the pressure of the supercharger air. The latter is typically around 1.2 bar, although this changes depending on where the engine is performing in its map and operating range, ensuring air flows undisrupted into the cylinder. In-cylinder pressure will not rise above intake pressure until after the intake port is already covered.

When the REV has completely closed off the exhaust port, and the pistons have completely uncovered the intake ports, cylinder charging takes place.

This brings the biggest benefit of Strange Development's rotary valve – typically, when a piston is at bottom dead centre, a direct channel is opened between the intake and exhaust ports. With the company's custom valve shutting this off to control the scavenging, internal cylinder pressure can be raised above atmospheric.

"This is where we get our power density from," Krzeminski says. "A traditional two-stroke cannot effectively supercharge without something stopping exhaust flow. Companies can try altitude compensation, pipe tuning or other approaches, but our method will actually significantly raise cylinder pressure above atmosphere in a reliable and consistent way, to an extent we've not seen in any comparable engine. Our long-term target for pre-combustion pressure is about 15 psi above atmosphere."

Also, by having a supercharger and a valve for controlling it, the combustion pressure can be changed dynamically. This means that if any future version running on heavy fuel (or other fuel type prone to knock) began detecting knocking, the REV and supercharger speeds could be slowed down to limit its occurrence.

To achieve the optimal swirl of air for mixing with fuel in the injection stage, the cylinder liner has five scavenging air ports. Each is only half as tall as the exhaust port, so the intake stays cut off during exhaust. With the exhaust port, this gives a total of six ports.

"The liner actually looks a lot like a traditional two-stroke sleeve, but with a single larger exhaust port and without reed valve intake ports. We're controlling upper cylinder pressure purely with the REV's sealing," Krzeminski notes.

"The most important scavenging air ports are the ones immediately next to the exhaust port. If we had only the crossflow-type ports that sit across from the exhaust, our CFD showed that the air would travel straight across the cylinder, with nowhere near enough scavenging of this air out of the chamber.

"The air from those Schnuerle-like ports 'catches' the air from the crossflow ports in the middle of the chamber during the charging phase, so it mixes just how we want it to in the injection phase.

"Balancing the flow from intake ports is something Detroit Diesel always had problems with in their uniflow-scavenging system. Turbulence can be a bad thing for uniflow systems, because you want almost linear movement of the air as a monolithic 'slug', but for us, turbulence is actually quite useful."

Fuel is sprayed at 50 psi and an angle of 15º, after the REV is closed but before the intake port has shut, to avoid pushing fuel out with the exhaust.

The compression stage starts once the intake port is fully shut off. Krzeminski notes again that in most two-strokes the exhaust port would still be slightly open at this point, resulting in less pressure build-up.

"So this gets us about 87 cc of additional compression that you wouldn't normally have, hence more cylinder pressure than an average two-stroke, not just from better supercharging control but from starting the compression stroke earlier."

The cylinder liner is designed with five scavenging air ports and one (larger) exhaust port

Finally, the power phase starts as the piston nears TDC. The air inside the cylinder is compressed completely for ignition; outside the cylinder, although the exhaust port is now shut off by the piston, the REV has reopened almost fully. Once combustion occurs and the piston thrusts back down into the crankcase, the valve will again be wide open to enable the operating cycle to be repeated.

"The rotational momentum of the valve runs on fairly loose roller bearings, and receives ample lubrication. These keep losses and friction down to a minimum," Krzeminski says.

Iterative development

After successful 1D and 3D simulations of the new engine and valve concept, Strange Development began prototyping the system to begin testing and iterating its designs. Through its in-house cutting and casting machinery, the team was able to make quick adjustments to geometries and tolerances wherever it wished.

"We probably went through 10 iterations of the cylinder head geometry alone, for optimising the airflow and mixing dynamics inside the top of the cylinders," Krzeminski says.

"We've been running it on the dynamometer for six or seven months, and have accumulated nearly 400 hours of testing. We built a 300 hp dyno and customised pretty much everything on it, other than the head itself, to suit the engine's specialised design."

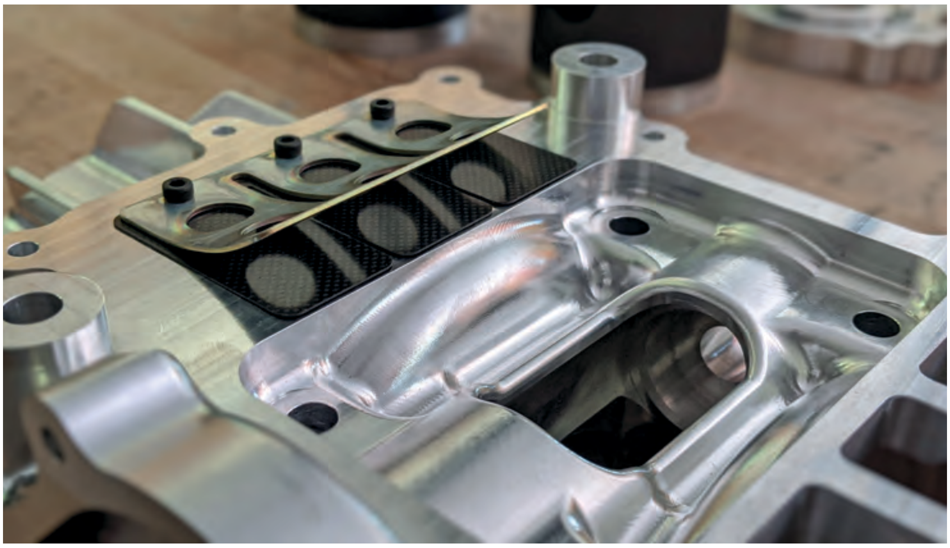
Most of its components have been machine-cut from 7075 aluminium alloy. This was selected for having the highest strength-to-weight ratio among the available metals, and for its track record in aircraft engineering.

"And because it's so strong, we're confident we can reduce our weight below 110 lb," Krzeminski says. "We're engineering on the safe side for now but we also have side projects aimed at weight optimisation, since that's crucial for UAVs.

"Complexity and time between overhauls [TBOs] are big bottlenecks for two-stroke performance as well. Many two-strokes have lubrication problems that mean their top ends have to be torn down every 50 hours or so, replacing pistons and rings and so on, which of course is time spent not flying.

"So we're aiming for a 1000-hour TBO on the REVolution, with just a minor oil change every 50 hours, and the engine can be stripped and rebuilt from scratch in less than 4 hours."

While the engine is oil-injected in a similar manner to a four-stroke, the



A system of reed valves is installed under the engine – not for intake but to push excess air and oil out from the crankcase, to recover the oil and prevent drag-induced losses

The aluminium cylinder head is designed as two plates that form an internal cooling jacket between them

company wanted to be able to use as little oil as possible, and eliminate even the marginal oil consumption levels that four-strokes are prone to.

As discussed, the REV forms one key part of the cylinder airflow management. The piston forms the other, and has thus received almost as much attention.

The crown is coated using a ceramic, to protect its exhaust side from being damaged by the high-velocity, superheated gases that rush out of the exhaust port as it opens. Krzeminski notes such damage is a perennial issue in the two-strokes he has observed over the years, and that Strange Development is also considering coating the valve in a ceramic to provide similar protection.

The piston skirts are coated in molybdenum disulphide (or 'moly') for long-term durability and low friction during their movements against the cylinder walls, as well as being able to survive the extreme heat of the cylinder.

Each piston pin has three trapezoidal piston rings, a shape that allows enough room for the rings to float stably in their grooves. The bottom ring sits at the end of the moly coating, preventing intake and exhaust gases from entering the crankcase, and keeping the crankcase's oil out of the cylinder's airstream.

"We want to stop excess oil flow from touching the moly, because that would contribute to emissions, smoke output and other problems," Krzeminski explains.

Two compression rings sit near the piston crown, with a holding pin in each one to prevent them from getting caught on either port as they float. Each pin rides on a needle bearing in its single-piece, non-split con rod's small end, with another needle bearing in the big end around the crank pin.

The crankshaft separates into three sections at the two crank pins. In addition to press-fitting the shaft pieces together, customised holding pins are routed through the crank throws and pins to stop rotational differentials occurring between the sections, otherwise they might start to spin at different speeds near maximum power output.

Each con rod sits between two counterweights, and in the centre of the crank is a gear for driving the water pump, which sits at the bottom of the crankcase, perpendicular to the crankshaft. That propels water up through the cylinder jackets, above and below the rotary valve seats, and up to the cylinder heads.

On either side of the water pump gear is a seal for separating the undersides of the cylinders. Keeping them airtight is key for preventing losses of charge air throughout the crankcase.

The crankshaft interfaces with the engine block via six steel ball roller bearings – one at the front, one at the back, and two on either side of each counterweight. Four more such bearings are installed on the two REVs, and four needle bearings are installed across the two con rods, for a total of 14 internal bearings.

The ECU controls the engine using a speed density strategy, mapping intake charge air pressure and temperature against engine rpm to determine fuel injection and ignition adjustments across varying speeds and altitudes.

Also, since airflow can be controlled via the exhaust valve end and the throttle, there is potential to layer a throttle control strategy atop the speed density to increase the accuracy and speed of adjustments in the REVolution's performance.

Self-vacuuming crankcase

To further assist in isolating the cylinder gases, six reed valves (arranged in two rows of three) sit under the crankshaft. Unlike with most two-stroke reed valves though, these six are not used for air intake.

Instead, as the piston comes down, the valves provide an evacuation route for pushing the air beneath the piston out of the crankcase. The force of this air also helps push oil collected in the oil pan back out to the external dry sump.

"We don't use a scavenging component on the pump, as you might in a traditional dry-sump arrangement where you mechanically pump out the oil; we're just using the engine as a pump," Krzeminski says.

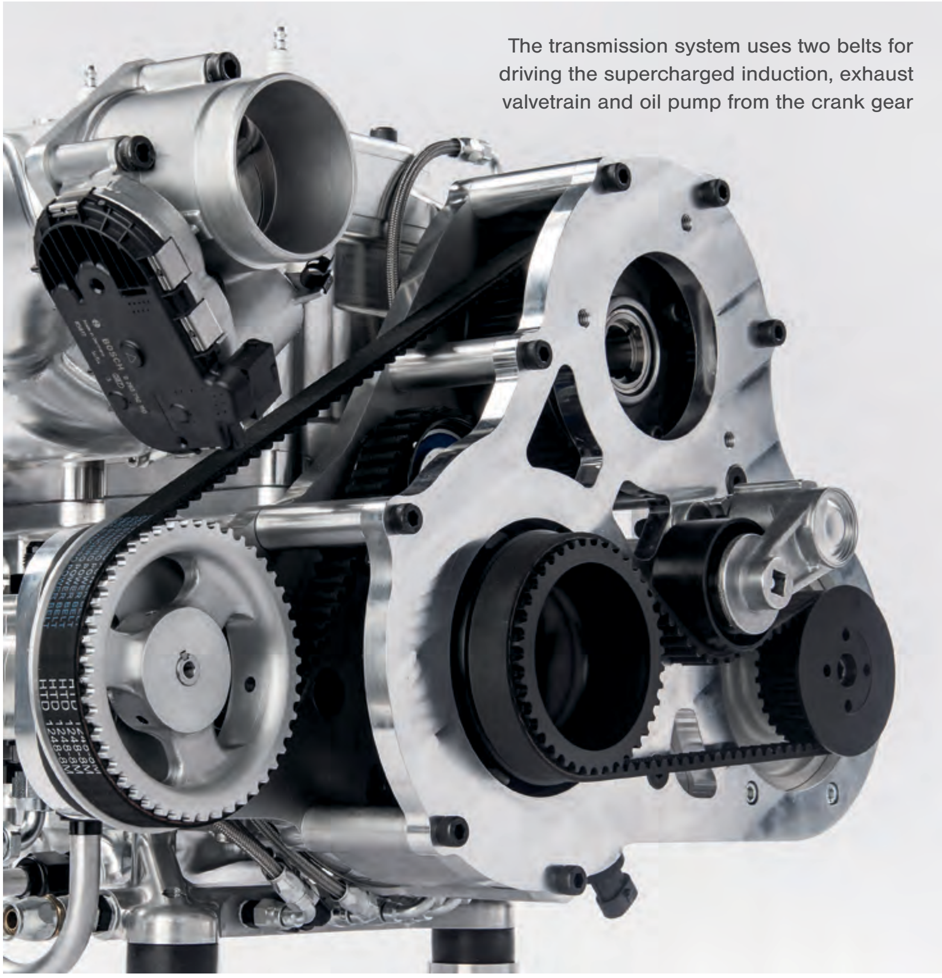
"When the piston goes back up, the reed valves shut. That effectively creates a vacuum under that piston, limiting the rotational losses, because you're not forcing the con rods and crank parts to move and spin through air anymore.

"If you have a diesel engine running at 1000-3000 rpm, that's not really an issue, but with a two-stroke gasoline engine spinning at 7000-8000 rpm, there are actually a lot of losses owing to air-induced drag inside the crankcase. That's why our engine is designed the way it is, with the reed valves and shaft-mounted seals.

"It's not a totally new idea. For example, there have been a few studies in four-stroke designs that used reed valves in this way to reduce drag losses, but our system was designed from a blank sheet to suit our requirements for vacuuming the air and pumping out the oil."

Cylinder design

Each cylinder has a factory-set injector bore angle as well as a perpendicular cylindrical valve seat. The cylinder liner is iron alloy (with carbon chrome and molybdenum) and as discussed it



The transmission system uses two belts for driving the supercharged induction, exhaust valvetrain and oil pump from the crank gear

has five air ports and one exhaust port designed to optimise the scavenging dynamics.

The fuel injectors sit inside the intake port, very close to the piston clearances. “We’re using two extended-tip injectors per cylinder,” Krzeminski says, “There’s actually very little space between the fuel injectors and the piston skirt, and immediately after cylinder flush the injectors spray right after the piston thrusts down past them, almost directly into the cylinder.

“While this is technically port injection, because the injectors sit in the intake port and spray from inside the port, it actually works almost like a low-cost version of direct injection. There’s effectively no fuel in our intake airstream.”

Four injectors are installed because earlier CFD studies showed that using two points of injection per cylinder with smaller injectors provide more balanced atomisation and fuel-air mixing at wide-open throttle (WOT) than a single larger injector. This arrangement also allows one injector to be switched off when idling, to reduce emissions.

“At idle, we’ll use just one injector at a higher flow rate, as using two injectors at half that rate can lead to inconsistent flow control,” Krzeminski notes. “At the lower ends of their power curves, injectors often experience sharply upward-curving rates of flow, so there’s the potential for wasted fuel and unnecessary emissions due to very slight changes in power.

“Having trialled this approach for a while, we’re increasingly limiting the use of the second injector to WOT, to increase the accuracy of fuel usage.”

Strange Development has also trialled direct injection systems in the earliest versions of the REVolution, in which the fuel can be injected any time before a spark and after the cylinder flush stage.

Krzeminski explains, “We went to port injection for the standard version to reduce the cost and complexity of the prototype. We can easily add more complex subsystems once customers are used to running and maintaining the basic REVolution, and they’re confident in our ability to provide quick servicing and replacement parts when needed.”

The cylinder head is made from two aluminium plates, with 12, M8 fasteners – six around each cylinder – bolting the upper plate atop the lower (and both onto the engine block).

Once fastened together, the head encloses a figure-eight-shaped cooling jacket designed for balancing water flow and thus temperature as needed across the tops of the two combustion chambers; a pair of inlet holes allows the water to enter upwards from the cylinder jackets. The upper plate also has an exit port for the water to leave the engine through an external hose.

Transmission

The assembly of gears and belts on the engine’s front is removable and modular, in order to accommodate any need for a UAV to drive different alternators or package the ancillary systems differently.

“Modularity for hybridisation is key for reducing operating costs, heat signature and noise, without relying on the 30 kg of batteries you’d need to achieve the kind of endurance a fuelled range extender can give,” Krzeminski says.

“I worked for a time for two major US automotive OEMs, and I noticed that their intake manifolds, exhaust arrangements and accessory drives were always different depending on the engine packaging they were paired with. We took that kind of approach, to enable quick modifications of everything around our engine block, especially when seeing how many UAVs were using engines built specifically to fit within their airframes.”

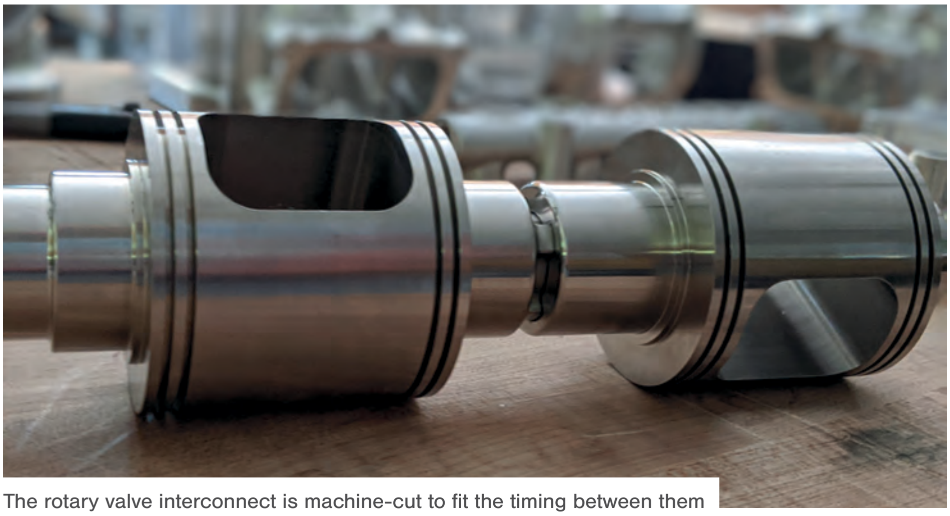
He adds that his automotive experience proved very useful when designing the engine’s transmission, resulting in something akin to a serpentine belt

Specifications

Inline two-cylinder
Two-stroke
Gasoline
Supercharged
Liquid-cooled
Weight: 49.89 kg
Dimensions: 400 x 350 x 300 mm
Maximum power output: 220 hp (164 kW)
BSFC at maximum power: 221 g/kWh
Maximum torque: 130 lb-ft (176.26 Nm)
Maximum rpm: 7000 tested, 8000 expected
Bore: 74.8 mm
Stroke: 65.8 mm
Displacement: 578 cc
Static compression ratio: 10:1
BMEP: 25 bar
TBO (expected): 1000 hours

Some key suppliers

Crankshaft: in-house
Cylinders: in-house
Con rods: in-house
ECU: Cosworth
Throttle: Bosch
Fuel injectors: Bosch
Supercharger: Eaton
Coatings: Line2Line Coatings
Bearings: NTN Bearings
Reed valves: Boyesen
Cylinder sleeves: LA Sleeve


The rotary valve interconnect is machine-cut to fit the timing between them

system for distributing the crank force to other onboard processes.

The transmission assembly has two timing belts. An upper belt looks after the timing and control of the valves and oil pump, while a lower belt drives the supercharger.

In the upper belt, the crank force is delivered via an idler wheel that sits above the crankcase on a bearing mounted on the transmission assembly's inner front plate, and is directly actuated by a crank gear near the front of the crankshaft. The belt runs over the top of the idler, and is kept taut by running down beneath the valve gear and the oil pump gear.

The forwardmost of the two REVs is machine-cut, and has a shaft extending out of the valve seat chamber, with a gear fastened on its end.

A larger crank gear sits on the very front of the crankshaft, driving a sprocket on the front of the supercharger via the second timing belt. A tensioner wheel presses down on the upper part of this belt to secure it.

"We've had to take care of a lot of different belt dynamics, and we've put a huge spread of design choices into the transmission to ensure the right tension and support during long-run operations," Krzeminski says.

Forced induction

Although the engine previously used a centrifugal-style supercharger, it was originally designed with – and has returned to using – a Roots-style supercharger (with a screw-type Roots charger from Eaton expected to be used in full production). It supplies 500 cc of air with each revolution of the crankshaft.

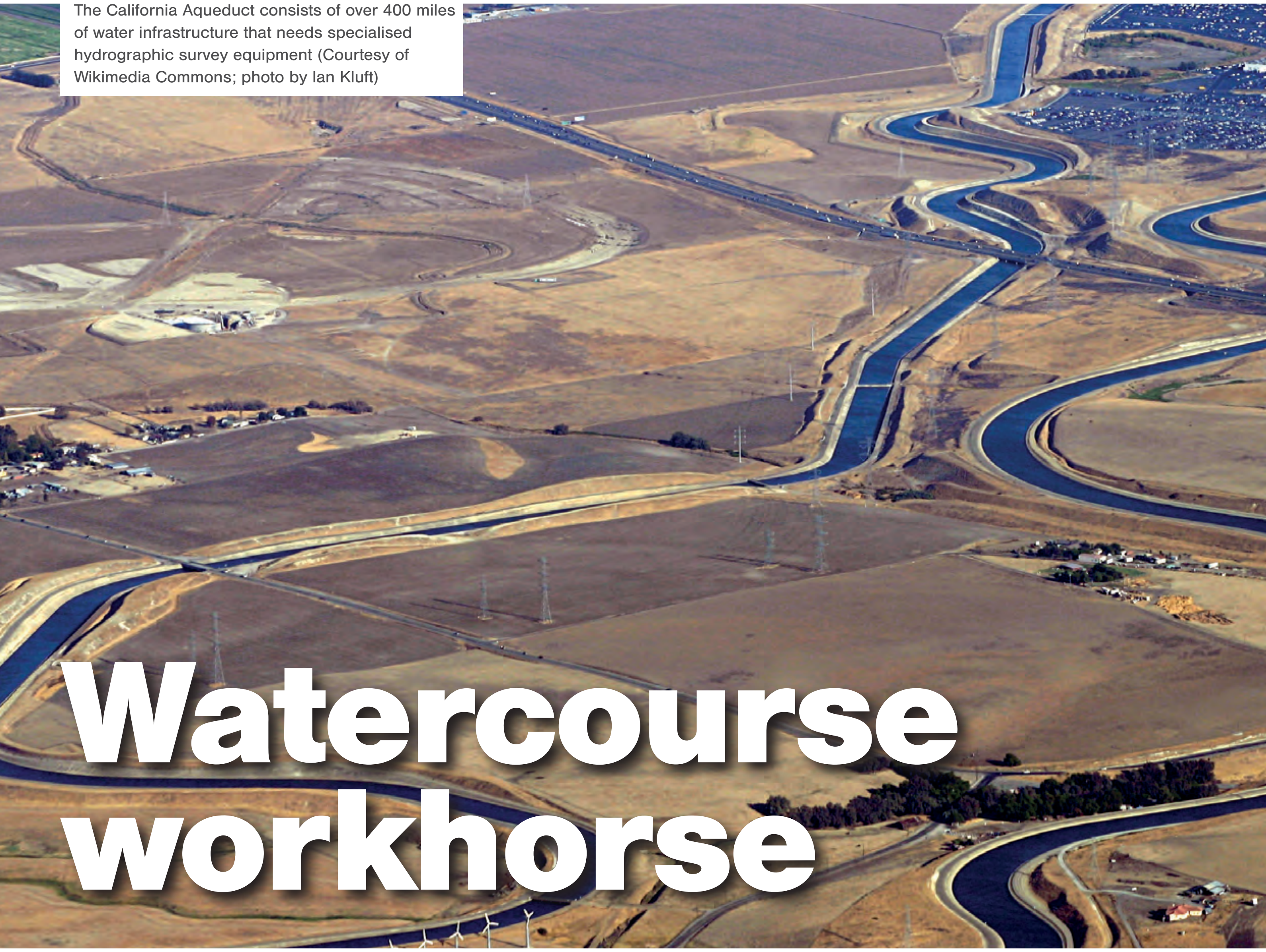
"When we used a centrifugal charger, we had a lot of idle-stability problems, because we simply weren't moving enough air at idle," Krzeminski recalls. "We looked at several types of supercharger, and simulated and dyno-tested a range of them. The centrifugal charger works with no problems at higher rpm, but the idle stability was so poor that we switched back to Roots-type positive displacement."

Strange Development plans to develop a twin-charged REVolution. This will use a high-efficiency Roots supercharger to help with idle and low-rpm stability without incurring parasitic losses, and a turbocharger at the higher rpm – most likely a BorgWarner model or one from Garrett Motion – to better drive the airflow through the engine. It also intends to use an intercooler between them to cool the charge air, resulting in what the company envisions as an even more power-dense version of the engine.

The future

As mentioned, the company is also working on a heavy-fuel version of the engine, which will feature moderate changes to the cylinder head and injection system, although the block and other components are expected to remain largely unchanged.

At the time of writing, Krzeminski and his team were finishing calibration work on the standard REVolution, studying how the engine responds at different throttle inputs. The next planned step is to run UAV-specific durability cycles before planning flight tests with an appropriate partner.



The California Aqueduct consists of over 400 miles of water infrastructure that needs specialised hydrographic survey equipment (Courtesy of Wikimedia Commons; photo by Ian Kluft)

Watercourse workhorse

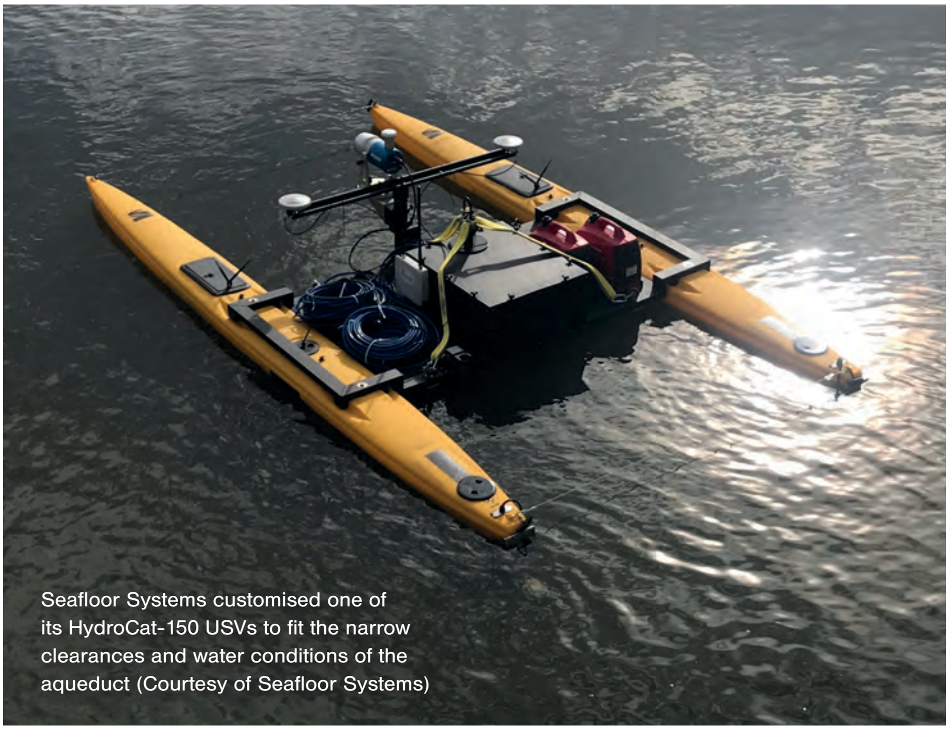
Customising this survey USV has helped to maintain the integrity of California's water supply network. **Rory Jackson** explains how it was done

The Governor Edmund G Brown California Aqueduct is a vast network of canals, tunnels and pipelines that runs largely from northern to southern California, covering around 450 miles of terrain. It is by far the single largest component of the state-wide water management and delivery system in what is one of America's most water-dependent agricultural centres, and simultaneously one of its most drought-ridden states.

As John Tamplin, CEO of Seafloor Systems tells us, "The California Department of Water Resources, which manages the aqueduct, has made it their priority to be more proactive towards leak detection on the canal. It is 50-60 years old and its infrastructure is ageing badly.

"To make matters worse, I've seen an overlay that shows the routes of the aqueduct compared with the San Andreas fault – the two line up almost perfectly. To be fair though, the aqueduct was built before anyone really understood exactly where the fault runs and what a huge geo-tectonic risk they were taking."

The common approach to determining when and where a blowout or leak in the aqueduct is occurring has been to wait to see wet spots growing on its outside. Human divers typically go in afterwards to perform inspections and assess how best to carry out repairs.



Seafloor Systems customised one of its HydroCat-150 USVs to fit the narrow clearances and water conditions of the aqueduct (Courtesy of Seafloor Systems)

To identify pre-emptively any area of damage where leaks are likeliest to occur, the water department decided in 2017 that it needed to accumulate a clear and comprehensive body of data covering the waterway, and identify any problems that could threaten the Golden State's water supply.

"They needed to find every single little crack before it could turn into a large one, every chunk of potentially harmful debris, any shifting of the concrete liner owing to soil slumping and creep. That's where the idea came from to carry out a hydrographic survey," Tamplin explains.

To acquire the vast amount of data needed, the water department reached out to USV manufacturer Seafloor Systems to source an unmanned system to carry out the many and lengthy surveys while keeping the need for operator input to a minimum.

The customised HydroCat-150

"The department has been a customer of ours for at least 10 years, using our smaller USVs for surveying the inland California Delta – another hugely important asset they need to monitor and manage – and we resell them some Teledyne products to do those surveys," Tamplin says.

"So they presented the problem to us, and after considering their requirements we agreed in 2018 to build a USV to their specifications for size and performance. Also, we proposed building it at our own cost and demonstrate it on the aqueduct to prove that it would work."

Most of Seafloor's USVs have been built to survey harbours, reservoirs and similarly wide-open bodies of water. The California Aqueduct project, however, presented an enclosed and winding stream (confined to 100 m at its widest points, and 10 m at its deepest) which would require great accuracy and security in the survey vessel's GNSS-INS capabilities.

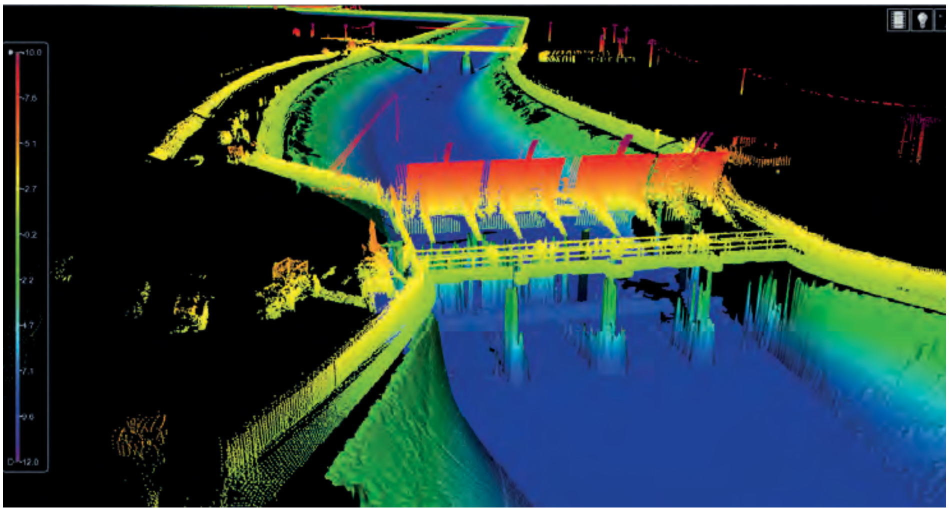
Even more problematic though is that the air above the water's surface is often crossed by low-hanging power cables, overpasses, footbridges and other obstacles.

"That means we had a height limit of 20 in [50 cm] above the water that we had to design for, so that the vessel could pass unimpeded under the utilities and crossings over the aqueduct, or else the vehicle would have to be retrieved every 500 m, to pick it up and carry it around an obstacle," Tamplin says.

"We also had to carry out each part of the survey in a single pass, with no going back upstream or any need for swapping equipment in and out, other than batteries perhaps. So we had to cover a 100 m-wide swathe and a 10 m vertical height above the bottom."

To ensure a full breadth of sensor coverage across these distances, Seafloor Systems selected a dual-head Reson T50 multi-beam echosounder from Teledyne Marine, which gives a swathe width of more than 20 times the water's depth.

Furthermore, a Carlson Merlin



While sonar was used to inspect infrastructure beneath the water's surface, Lidar was used to capture structures and potential points of risk above the water (Courtesy of Seafloor Systems)

Lidar was integrated in order for the water department to measure obstacles and potential sources of debris hanging over the water's surface.

As well as selecting an echosounder with the appropriate swathe, Seafloor built a customised version of its HydroCat-150 USV.

This version of the catamaran has a dry weight of about 1200 lb (544 kg), measures 4.5 m long and 2.5 m wide, and extends just 0.2 m above the water's surface. The tallest structure on the vehicle is a mast for mounting the GNSS antennas and the Lidar, giving enough space between them so that they can operate without obstructing or interfering with each other.

"The width was considerable, relative to our usual architectures, for reasons of stability," Tamplin explains. "A little wind is all it takes to make the water's surface very choppy, so keeping the pontoons about 2.5 m wide apart helps a lot to ensure the echosounder's coverage can continue uninterrupted without being too affected by splashes or swells.

"Also, if the vehicle were to lose power while on the aqueduct, and hurtle towards one of the gates or water-lifting stations, it could both suffer and impart some real damage across the infrastructure," Tamplin adds. "So we installed redundant motors, generators, batteries, GNSS receivers, everything."

The generators are a unique feature among Seafloor's USV designs. Having two Honda EU1000i gas inverter-generators ensures a dedicated and redundant power supply to the sensors without drawing power from the battery.

As a final precaution, a construct with a series of fabric cords is installed atop the USV, so that in the unlikely event of total loss of control or power, its handlers can either shoot a line across or reach over with a bargepole to catch the vehicle before anything can go awry.

Survey preparations

Customising a USV to suit the aqueduct project was the biggest challenge for Seafloor. It required input from its specialists in mechanical, marine and robotics engineering to come up with designs – several of which were rejected along the way – and incorporated lessons from previous trials.

In preparing for the operation proper, however, Seafloor had to be certain that the USV's design was based on correct assessments of the aqueduct. Initially, the company requested – and was given – the department's own blueprints of the aqueduct and its sections, many of which were drawn up in the 1950s and '60s.

Seeing a need for fresh data, Seafloor made two trips to the aqueduct to conduct its own survey. Taking a DJI Mavic Air UAV fitted with an EO camera, it mapped and measured the aqueduct to gauge and validate key points of its geography.

"Our investigations showed that there were some parts of the aqueduct where that 20 cm we've got above the water would be the absolute limit of how far the USV could safely protrude," Tamplin says. "If we build a future version, we might look into shaving off one or two more centimetres to be on the safe side."

Furthermore, Seafloor ran SolidWorks simulations of water flows on the USV's hull, as well as the mechanical stresses, power loads and a range of other mission variables before running the first proving trial.

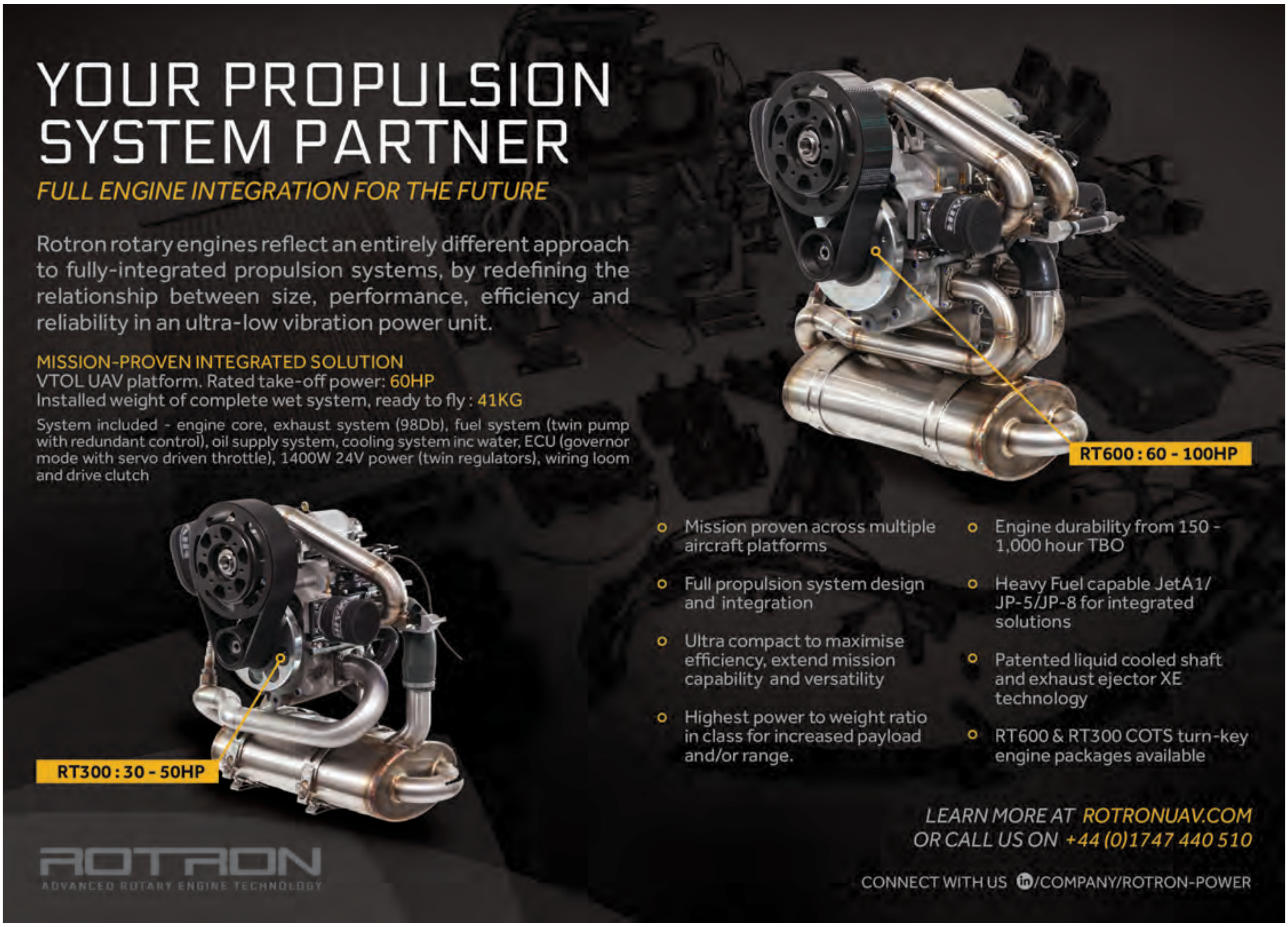
After confirming that the mission could go ahead safely, Seafloor transported the customised HydroCat to the Central Valley of California for the pilot project, a task made easy by the fact that the catamaran had been built to fit directly onto a standard trailer. This set-up also ensured that the USV did not have to be dismantled and reassembled between each survey run.

Before the launch, Seafloor was unsure how to safely deploy the USV, as the aqueduct had a concrete liner sloping about 15 m down into the water. However, the water department's maintenance division provided a boom truck with a crane (typically used for repairs), which has since been used to pick up the HydroCat, lowering it into and hoisting it out of the water.

Sailing down the aqueduct

The pilot project took in one of the long sections of the aqueduct to prove its performance and viability before official surveys began. Over 12 miles and 6 hours, the obstacles overhead never hung closer than 1 m to the surface, ensuring that the USV's 0.2 m height was more than enough clearance for safe sailing.

"As well as microfractures in the aqueduct walls, we found shifts in the concrete plates at the bottom, and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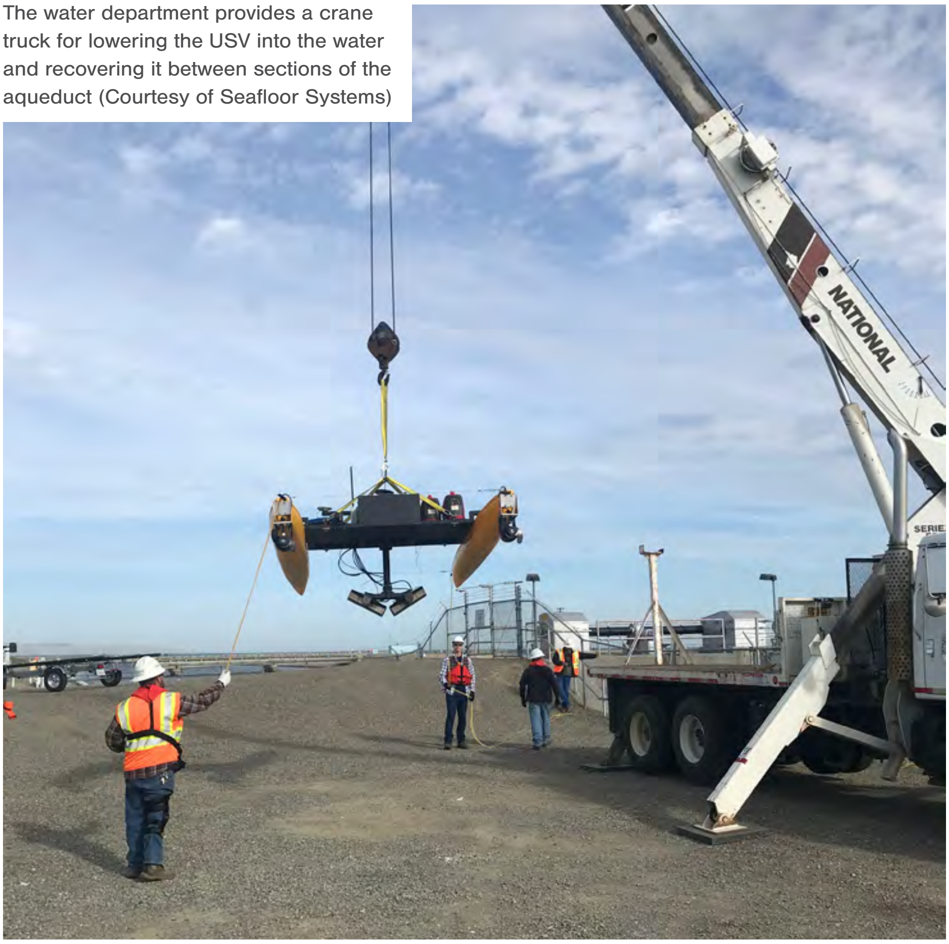


The water department provides a crane truck for lowering the USV into the water and recovering it between sections of the aqueduct (Courtesy of Seafloor Systems)

Some key suppliers

GNSS-IMU: Applanix Corporation
Wi-fi datalink: MikroTik
Generators: Honda
Sonar: Teledyne Reson
Lidar: Carlson
Electric motors: Torqeedo
Batteries: Torqeedo

a grand total of 13 cars that had been dumped or driven into the waterway over the years," Tamplin notes.

"Also, the projected power curves and other data we'd gathered from our CAD simulations matched up almost perfectly with what happened in the pilot project. Going in, I was sceptical about how much – or, more precisely, how little – power the operation would need, but the amount of battery power worked out surprisingly well."

With no incidents and around 1 Tbyte of survey data gathered, the pilot was deemed a success, and the department took the USV to begin carrying out similar surveys on the remaining sections of the aqueduct. It carried out the bulk of operations, with Seafloor providing a few technicians for on-site consulting during the earlier legs.

Because the current in the aqueduct varies depending on the flow of water, there is a risk that the speed and handling of the USV could vary, which could have reduced the accuracy of the surveys. To help stabilise this load – and by extension the point cloud data from the echosounder and Lidar – the department typically closes nearby water gates upstream, which reduces the current to between 1 and 2 knots.

"To provide even further stability for gathering data in that current, we designed this USV with skid-steer functionality," Tamplin says. "Essentially we've put in two fixed thrusters, which are used in a differential steering mode that keeps the vehicle in the centreline down the aqueduct, and moving at about 2-3 knots."

In addition, the T50 operates at a beam width of 0.5 x 0.5°, with 1024 beams across the swathe. This is to enable imaging of very small cracks, as well as compensating for the strong reverberations coming from the aqueduct's concrete walls.

And as the standard swathe of the sonar reaches much farther than the boundaries of the aqueduct, in actual operations the survey team can reduce the T50's power consumption. By how much varies between different sections, but in general the 400 W sonar (200 W per head) is operated at an average of 350 W.

"The survey team can also turn down the power on the IMU and other systems through a PC interface to save on main battery power," Tamplin adds.

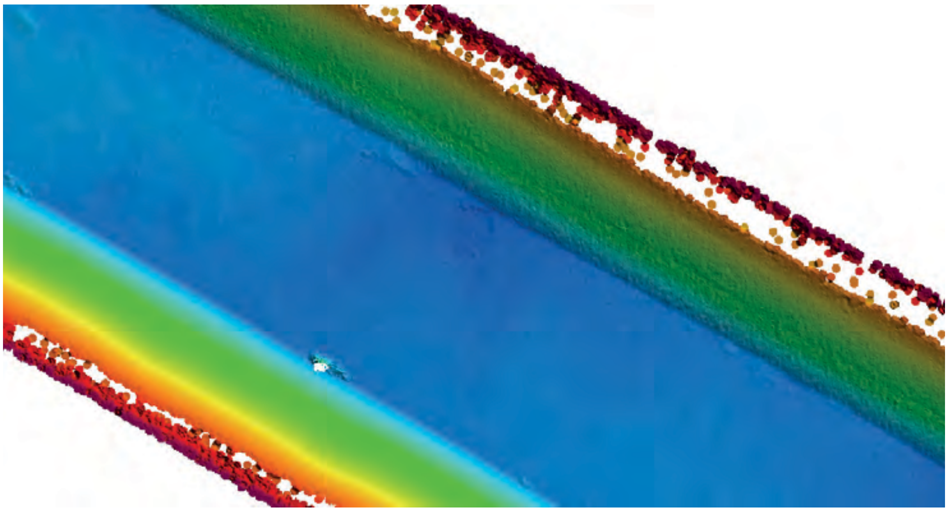
"That said, we installed almost 880,000 mAh of battery capacity on the catamaran, because we were worried about endurance. But because it's travelling downstream at such a gentle speed, the vehicle pretty much always has quite a lot of leftover endurance at the end of each survey leg."

Further to this, the water department wanted not only to survey for cracks and debris beneath the water but for structures, walkways and other potential sources of debris falling onto the surface.

"That's why we installed that Carlson Merlin Lidar in the vehicle, to simultaneously map below and above the water," Tamplin says.

"We'd already picked the echosounder and the IMU, and we chose this unit because all the other high-end Lidars we were using already came with their own internal IMUs.

"We didn't need one of those though, because the Applanix POS MV IMU that came installed on the echosounder was more than good enough for navigation and geo-tagging all the incoming point



The Reson T50 echosounder's firmware compensated for reverberations of acoustic pulses against the aqueduct walls to produce clear imagery (Courtesy of Seafloor Systems)

cloud data – both acoustic and laser points, that is.

"A second IMU integral to the Lidar would have just added unnecessary weight and power consumption. As it stands, about nine out of 10 of our USVs use Applanix or Trimble systems pre-packaged with the sonar for geo-referencing and navigation. At no point during GNSS outages [caused by bridges or other overhead structures] did the IMU fail to kick in and carry the navigation system forward via dead reckoning – and extremely accurately, at that."

As the USV travels autonomously down the waterway, the water department's command vehicle typically uses one of the service roads running alongside to maintain visual line of sight between the vessel and its operators, for safety's sake.

Inside the customised HydroCat, the vehicle's PC runs the popular Hypack software package for processing hydrographic survey data; a wi-fi data link then transmits it to the command vehicle in real time to the operator's laptop (using TeamViewer as a compressed desktop interface).

The operator can control and analyse the data visualisations, as well as monitor the mission's progress, change sensor settings and double-check that the USV is still in the centre of the aqueduct's canal.

"We use a dual-chain wi-fi system from MikroTik, which gave us a throughput of 200 Mbit/s. That is enough for video, and more than enough for the amount of hydrographic and Lidar data being generated. We weren't remotely transmitting all the data at once, just a remote desktop view of it was enough," Tamplin adds.

At water's end

Between surveys, the USV is typically carried from the endpoint of one section to the start of the next using the aforementioned boom truck, and back onto the trailer for transport back to the water department's workshop at the end of the day.

After returning the USV to the trailer, the echosounder, IMU and Lidar are disconnected, and the vehicle is returned to its workshop.

"All our USVs are made from roto-moulded high-density polyethylene, which is very durable and corrosion-resistant," Tamplin says. "And the hardware is largely stainless steel or aluminium, so maintenance pretty much never drags much longer beyond disconnecting the electronics.

"We've provided training and support to the water department to get their folks up to speed with operating the USV. They've successfully used it since August last year without incident."

For the future

In addition to manufacturing and training, Seafloor Systems has signed a three-year maintenance warranty (at no charge) with the department, so if there is an apparent stall in performance, Seafloor will get the custom USV into its workshops for assessment or repairs if necessary.

Elsewhere in California, Seafloor is now concluding a similar project with the US Geological Survey (USGS) to build two modified versions of its HydroCat-180s for monitoring and analysing the growing intrusion of salt water into the California Delta.

"This region is the salad bowl of the US, as well as the biggest wine-growing region and one of the biggest habitats for salmon and a wide range of other fish stocks," Tamplin notes. "Changes in salinity levels caused by seawater ingress therefore pose a dire threat to all those aspects of our economy."

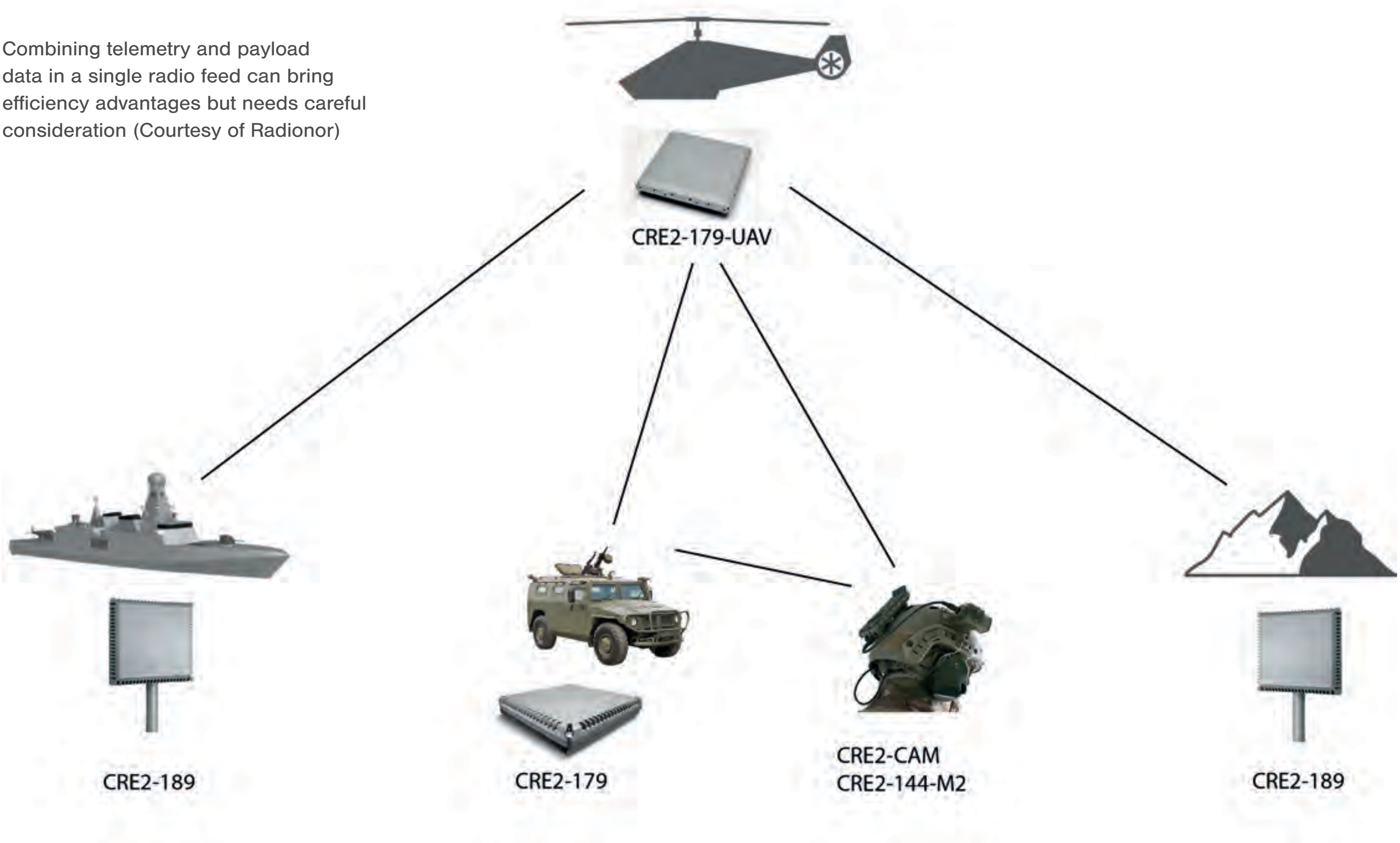
The 5.5 m-long HydroCat-180s are being built with individually articulated hulls and gimballed decks – unlike the monohull or catamaran designs for most USVs – to ensure their acoustic doppler current profilers (ADCPs) can maintain a strict downward-looking angle amid the waves and swells they will experience.

"Typically, the USGS will operate ADCPs on their vehicles and run them across the tide as it rises on the delta, but the tidal bore in this area is too strong and fast, which makes such readings too inaccurate. Our customised large USVs will therefore be deployed from either side of the delta and converge in the middle, to accurately correlate the tides and currents of the different waters and their salinities.

"They'd used our smaller vehicles previously. One such project encompassed their first-ever autonomous ADCP cross-sectional survey, and that got them thinking about trying out our bigger vessels."

With the trial of this autonomous ADCP survey having been successfully concluded, the USGS placed an order for the two customised vehicles in late 2019. Delivery is expected shortly. ◻

Combining telemetry and payload data in a single radio feed can bring efficiency advantages but needs careful consideration (Courtesy of Radionor)



A growing trend for combining different types of data in a single high-bandwidth link is spurring developments in radio technology. **Nick Flaherty** reports

Gathering momentum

Telemetry for unmanned systems is changing. While data transmission from UAVs and cars has previously been relatively simple, by relaying location and general system health information separately from payload data, the latest generation of UAVs aims to combine telemetry and payload data in a single radio link, to take advantage of packet radio technologies and the latest beam-steering and multiple-antenna designs. That makes the whole radio system more efficient.

In driverless cars the requirements for telemetry are also changing. Rather than relaying system health information, operators of driverless car fleets are looking at using video feeds from the sensors in the cars for a number of applications. This video can be used to refine the machine learning algorithms that control the vehicle, or even allow a remote driver to take over. That would happen if the vehicle met a situation that the onboard controller could not handle, but it requires a high-capacity, low-latency link.

Driverless cars

This highlights one of the technology challenges for the radio links to driverless cars. There are two competing standards for these vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) links, with different levels of maturity and performance.


A 5G New Radio prototype system for testing on a car (Courtesy of Qualcomm)

The more mature technology is the IEEE 802.11p standard, also called Digital Short Range Communications.

It is a modification of 802.11a wi-fi technology operating in the 5.9 GHz band without the need for a base station. It is designed to work with fast-changing multi-path reflections and doppler shifts generated by relative speeds as high as 500 kph with a typical line-of-sight range of 1 km. The multiple access mechanism (the Carrier Sense Multiple Access protocol with Collision Avoidance protocol) efficiently handles high-density use cases when combined with Distributed Congestion Control.

However, this requires dedicated infrastructure to be built on roads to receive the data from the cars, and this data has to be fed back into the network.

The competing technology is based on the next-generation cellular phone standards developed by the 3GPP standards group. The current 4G (also called LTE-V2V) technology does not have the capacity or latency needed for such telemetry links to vehicles.

However, the latest versions of the 3GPP standard for 5G specifically address this. The 5G New Radio specification in 3GPP rev 15 allows higher performance links and is now undergoing trials in the US, Europe and Asia.

> It is predcted that autonomous vehicles will use up to 4 Tbytes of telemetry data per day, which is not feasible on a 30-40 MHz band

The resulting 5G cellular vehicle-to everything, or V2X (C-V2X), standards were approved in January, leading to three chipset suppliers and seven module makers developing products to automotive quality. These will be available for production designs during 2022. However, many chip and module makers also have 802.11p implementations.

The upcoming 3GPP Release 16 adds extensions for ultra-reliable and low-latency comms, as well as lower power consumption and support for multiple antennas. It is expected to be agreed by the end of this year.

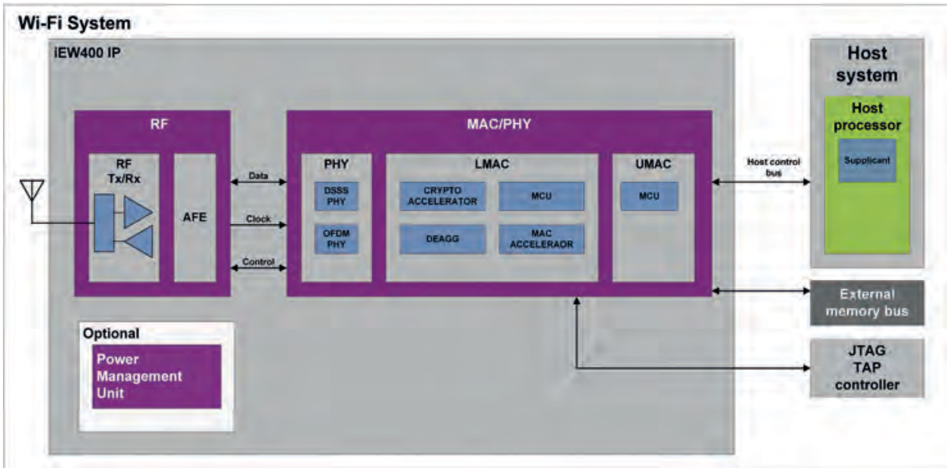
All this allows telemetry from cars to use the 5G networks that are now being rolled out, prioritising telemetry packets from driverless vehicles to minimise the latency. However, there are predictions that autonomous vehicles will use up to 4 Tbytes of telemetry data per day, which is not feasible with a 30-40 MHz band at 5.9 GHz.

That is driving the need to use the same digital architectures over links in the millimetre band, from 59 to 71 GHz, for links of even higher bandwidth.

WiFi6

The next generation of wi-fi is also giving significant advantages for unmanned systems, particularly in the air. WiFi6 (which is the IEEE 802.11ax standard) adds significant power efficiency enhancements that will be an advantage for UAVs. Some already use a 2.4 or 5 GHz link, and WiFi6 will also give the opportunity to use the 6 GHz band.

New technologies added to WiFi6 to boost data rates and reliability also lend themselves to low-power operation to mix telemetry and payload data over line-of-sight links.



WiFi6 brings power efficiency advantages for UAV telemetry applications (Courtesy of Imagination Technologies)

The latest chip designs for WiFi6 add orthogonal frequency-division multiple (OFDM) access so that the bandwidth can be segmented, allowing multiple devices to receive data in the same time frame. That increases data transmission efficiency and reduces power consumption for network applications.

New features such as Basic Service Set (BSS) Colouring in WiFi6 increases robustness in environments with lots of wireless, enabling better data throughput in areas where there are multiple access points and many clients, such as urban areas. With BSS Colouring, data from each access point is prescribed a 'colour', so that clients can identify which one is transmitting, resulting in improved network performance.

Signal robustness is essential for telemetry, so the WiFi6 standard also has a dual-carrier mode. This allows the same information to be modulated on a pair of sub-carriers, which can ensure data gets through even in noisy environments.

The advantage of course is that millions of WiFi6 chips will be used in networks in homes, offices and factories, driving down the costs. That gives UAV radio designers a single low-cost chip with the radio front end and all the processing to simplify the design process.

The sweet spot for long-distance, high-bandwidth comms that can combine telemetry and payload data is from 4 to 8 GHz

Combining telemetry and payload data

There is a clear trend to having a broadband radio system that is capable of IP traffic networking and which gives the flexibility to include payload data as well as command & control data.

The more services that can be combined in a single radio the better, as it allows the platform – a UAV or UGV – to be used as a node in a mesh network. That means any spare bandwidth can be used to provide data to other vehicles on the ground or in the air, giving the system operator much more flexibility.

This relies on sophisticated packetisation algorithms to ensure the Quality of Service (QoS) is maintained and that there is full control of the priority of the telemetry traffic for essential services.

This radio system can reach over 200 km for UAVs (Courtesy of Radionor)

The sweet spot for long-distance, high-bandwidth comms that can combine telemetry and payload data is in the C band (from 4 to 8 GHz). This is the optimum frequency band from a physical perspective, where the frequencies are high enough to enable a compact unit, as the size of the antenna decreases. The radio signal attenuation from rain at frequencies above 8 GHz becomes a problem that limits the maximum operational range for the link.

Using a phased array antenna with beam steering gives the best trade-off between range and bandwidth, but there are no suitable protocols. The proposed standards for 5G use beamforming/ MIMO technology but also use stationary base stations as a master to link to relatively simple handheld terminals. Complex algorithms for UAV designs need to support a moving base station with a narrow beam and with no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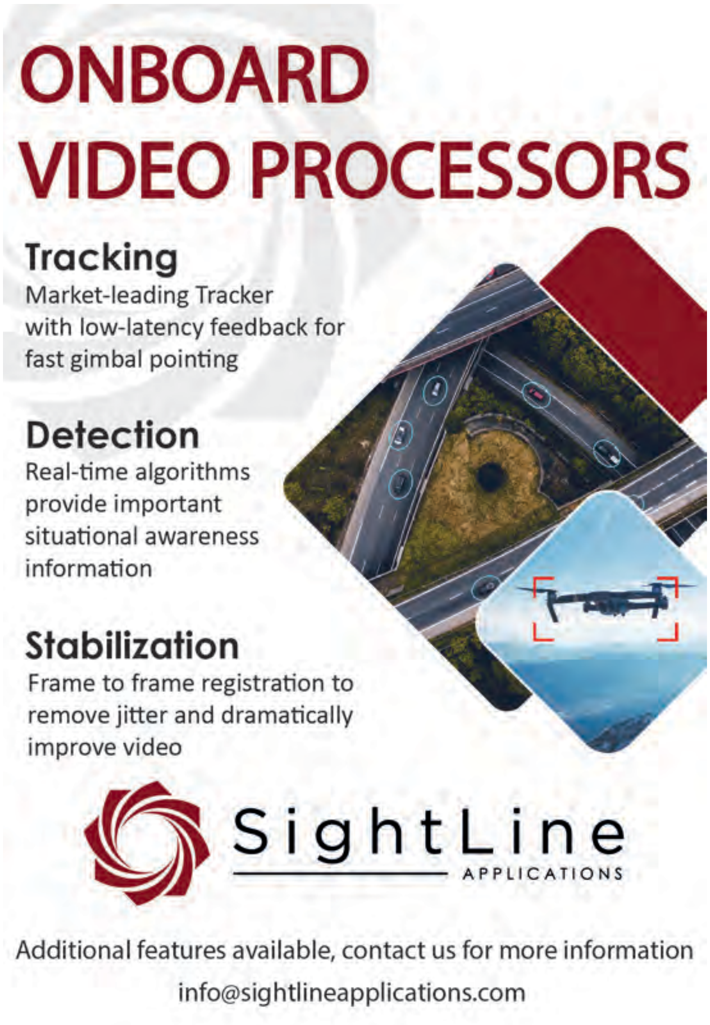
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This S-band amplifier weighs only 57 g (Courtesy of Triad RF)

master in an ad hoc network for long-range links of up to 250 km.

To achieve this range needs a set of different waveforms, both short range and long haul. Waveforms known from the telecoms industry such as 5G or wi-fi are designed for short ranges of about 2 km, which can handle multiple reflections in a short time window.

The long-range waveforms cope with reflections coming from distances of 1-100 km, so they are fundamentally different from a physical perspective. These need to be a robust waveform with a long delay spread, dealing with reflections from mountains, hills and man-made structures.

That means the protocol has to handle a larger delay difference to eliminate the first, second, third and higher order reflections. In the air the delay can be huge, so designing an efficient protocol that operates effectively from a few kilometres to 200 km is challenging.

Another design consideration with phased array is the need for a radio system with an array of radios and amplifiers. High power efficiency on the modulators is key to generating as little heat as possible.

The optimum design gives 15 Mbit/s of user data throughput, with the protocol and encryption overhead on top with a range of more than 150 km. A 7 Mbit/s mode gives a range of more than 250 km. Both modes have a configurable latency via the QoS down to 5 ms.

A by-product of using a custom waveform and protocol is that it gives full control over the location of other nodes in the mesh network

There is a key trade-off however between the latency, which is key for control & command signals, and the efficiency in such single-channel systems. A longer latency, perhaps 50-100 ms, allows more data aggregation and higher transmission efficiency. Short latency breaks up the waveform and hence is less efficient. Users can configure the balance of latency, data rate and bandwidth for missions.

The technology can also be adapted for different applications. One version of the radio is suitable for a typical 150 kg take-off-weight rotary UAV or a fixed-wing aircraft with a 5 m span. The phased array antenna measures 25 x 25 cm and weighs 2 kg; it has a peak transmission power of 250 W and consumes 150 W for a 200 km range.

The smallest version weighs just 85 g with four phased array RF antennas and beamforming for smaller UAV platforms. Combined with a phased array antenna on the ground, the 85 g radio in a small, 2 kg take-off-weight quadcopter offers a range of 160 km with a data rate of 600 kbit/s.

The system is a fully software-defined radio, with full flexibility for designing the waveforms and modifications, such as the ability to add algorithms for beam steering that keeps track of the position of the other antennas.

A by-product of using a custom waveform and protocol is that it gives full control over the location of the other nodes in the mesh network. The incoming signal from other nodes gives the bearing and range of the other nodes. Locating one node accurately creates a positioning system that can replace GPS or a satellite service.

The link is fully encrypted but doesn't share location data. The relative position is calculated from the link, so applying one reference point provides the location of all the other nodes.

Of course, adding amplifiers is a traditional way to boost the range of the radio link, but the challenge is making them small enough with low power consumption for UAV designs.

For example, an S-band bidirectional power amplifier that operates from 2.2 to 2.5 GHz measures 2.3 x 2.3 x 0.45 in

A millimetre-wave evaluation kit (Courtesy of Blu Wireless Technology)

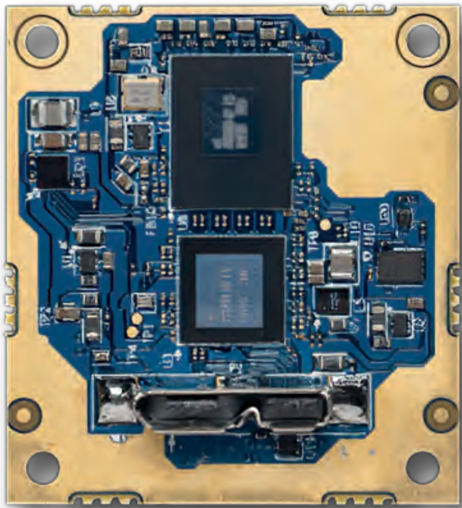
and weighs only 57 g. It draws 1.16 A at 28 V while providing more than 10 W of OFDM power using binary phase-shift keying coding, or 0.65 A at 28 V with 2 W of OFDM power using 64 quadrature amplitude modulation coding.

Millimetre wave

The millimetre wave (mmwave) band comes into its own when the data rate is high, for ultra-high definition 4K or even 8K cameras, but it can struggle with range. Mmwave tends to refer to 28 and 38 GHz bands specified for 5G and the unlicensed band from 59 to 72 GHz. Tests in the 28 GHz band have shown that 5G links can run at 2.8 Gbit/s.

In the 60 GHz band a radio with 40 dBmi of transmit power can provide 300 Mbit/s. This can be used to provide high data rate links for high-resolution camera feeds or provide telemetry data using much less power than other links. That comes from the higher spectral efficiency of the modulation used.

As a result, this is being explored for



Millimetre-wave systems need a complex RF design (Courtesy of Peraso Technology)

high-altitude pseudo-satellites (HAPS), which fly at up to 70,000 ft (23 km) to provide broadband services or surveillance. Fleets of HAPS aircraft have also been proposed, and these would need to communicate at that altitude.

The difference in operation is important, as at around 60 GHz the radio signals can be significantly reduced by absorption by water droplets and oxygen for a link to the ground. That means links at high altitude can be inherently longer range, although ground stations can have much larger, more powerful beamforming receivers to provide high-bandwidth links.

The WARC-19 2019 global radio frequency conference authorised a band at 38 GHz for HAPS, so it is now feasible to broadcast 1-2 Gbit/s to a UAV at 66,000 ft (20 km) altitude using beamforming with the right link budget – that is, with enough power. This would be 10 W of broadcast power, or 10 mW of power consumption for the radio.

However, the whole radio system uses around 35 W for the radio, modem and network processor packetisation. It is the network processor that takes most of the power.

As of the end of 2019, 3GPP also specifies 28 and 38 GHz for 5G links. With flexible processing, this would allow the mmwave bands to be used for high-bandwidth links such as video, and the lower bands for other telemetry.

The 802.11 standards also extend into the millimetre wave band, particularly above 59 GHz. 802.11ad and its successor, 802.11ay, add support for beamforming and phased array antennas to improve the range of mmwave links in these unlicensed bands.

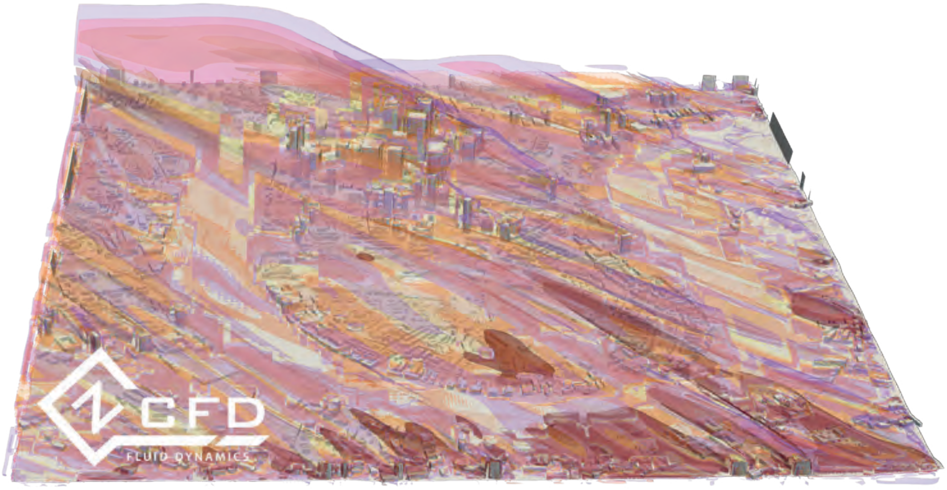
The channels defined in 802.11ad are 1.8 GHz wide, which gives much more flexibility than lower frequency bands. Halving the channel width halves the noise, and gives a 3 dB improvement in the link budget. A quarter-channel gives 6 dB and doubles the range, albeit at lower data rates. If the required data rate is only 100 Mbit/s then that gives the longer range.

These standards – 802.11ay is being approved this year – also add beamforming and phased array antennas. This is driving a new generation of active antenna designs that can be integrated alongside the radio in a single module. Different antennas can be used for the 24-29.5 GHz band with 5 Gbit/s data, and the 57-71 GHz with 7 Gbit/s. These provide support for six full RF channels according to the IEEE 802.11 standard, with additional support for half- and quarter-channels.

The performance of the antennas is critical to the performance of the links in the mmwave bands. While the wide bands give higher bandwidth links, the antennas have to send and receive over much wider bands than mainstream 5G or wi-fi.

While radar system designers have experience of working with such antenna technologies, they have to be miniaturised and reduced in cost for use in ground vehicles and UAVs. That means adopting multi-layer construction techniques optimised for low cost using fibre-resin substrates and standard process technology, and eliminating exotic soft-board or ceramic substrates.

A 64-element beam-steering antenna configured in a two-dimensional scanning array with 22 dBi gain across the full frequency range can be



Telemetry data can include simulations from CFD for safer operation of UAVs in urban areas (Courtesy of Zenotech)

used with a 60 GHz radio and digital processor to achieve a 1.5 km link without having to use a dish antenna. With a 390 mm dish with 44 dBi gain, a complete system can achieve a 5 km link with a data rate of 1 Gbit/s.

Urban environments

Computational fluid dynamics (CFD) is used in the design of UAV platforms, but for the flight profile and flight envelope the presumption for most of the design is that the aircraft is flying in clean air.

An urban environment doesn't have that, so the industry has had to add gust responses for example as part of the certification, and there are standard gusts defined with a mathematical description. CFD analysis shows that a fixed-wing platform is more susceptible to gusts than a rotary craft, as there is more wing loading.

CFD can also be used to model the environment around an unmanned aircraft in real time, which is especially useful in urban areas. This can be used to allow a UAV to avoid hazardous airflow features such as vortices to keep both the aircraft and any people on the ground safe.

That is important, as the urban environment is likely to see a range of different craft being used, from autonomous air taxis in take-off/landing modes, to logistics delivery aircraft and surveillance UAVs. This closes the loop of the CFD design process of the platform, to quantify the areas in a city where they can safely operate.

> Urban settings don't have clean air, so gust responses have had to be added to CFD analysis, and there are standard gusts

CFD is already used to create a double-precision floating-point simulation of the airflow in a built environment, for example to model the airflow through a city from a scale of kilometres down to metres. However, the data set is exceedingly large, too large to broadcast to a vehicle.

So engineers are looking at how that data can be sent to a UAV effectively. There are a number of issues, mostly around the size of the platform. Larger platforms for example have more storage for the data, and are less susceptible to gusts. In smaller craft the payload is more crucial, so there is less storage and more susceptibility to changes in the airflow.

This data can be communicated to a platform as command & control instructions to widely available autopilots. These have clearly defined interfaces to the control systems, and understand how to avoid obstacles so long as the aerodynamic hazard can be represented as an obstacle to avoid.

This approach takes advantage of the existing infrastructure so that craft can avoid problem areas by imposing a no-fly zone rather than having the autopilot compensate in real time for changes in the airflow.

That means there will be a dynamic data set, but the unanswered question at the moment is which data should be used to specify the size and position of a hazardous air feature as an object.

The data is site-specific. Some airflow features are periodic, such as a vortex in a vertical cylinder created by buildings.

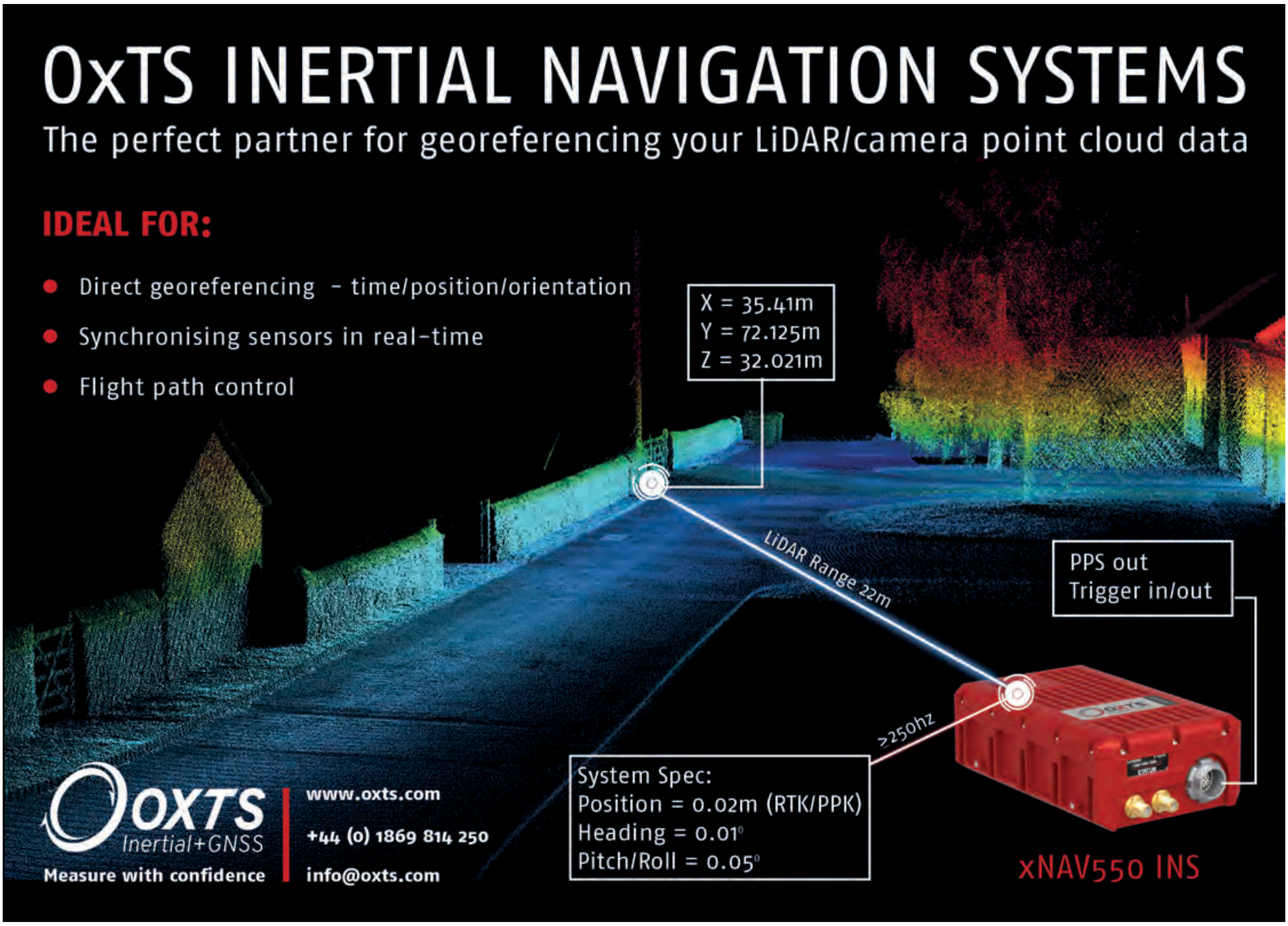
Then there are asymmetric vortices for example, when wind is flowing past power lines, setting up vortices with a particular frequency. This is already a key issue for UAVs used to monitor such power lines.

Whether there is similar periodic dynamism at a site determines how much the data can be compressed for the telemetry link. There are different types of data at different levels.

For example, the CFD model in double precision for a city block would be Terabytes of data. Modelling this to specify the surfaces of the threat compresses that down to hundreds of kilobytes.

Using simplified geometric primitives that approximate the surfaces reduces this further, to kilobytes of data.

However, the amount of dynamic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data needed varies with a mission's profile. A short mission can reduce the need for a dynamic data set, as the initial system state has sufficient validity for the entire mission. A longer mission can need more dynamic data to be sent to the aircraft.

This airflow data could be added to an unmanned traffic management system in the same way that mapping data has been combined with the position data of UAVs to indicate no-fly zones.

Conclusion

Developers are looking to combine telemetry and payload feeds in a single, high-bandwidth link that has more spectral efficiency. This is changing the design trade-offs for unmanned systems designers.

Being able to use video as part of the telemetry link is increasingly important, and this is driving the use of more advanced radio designs in higher bands as well as beamforming, phased array antennas and mesh networks. New types of data will also have to be carried over these links to boost the performance of unmanned platforms in challenging environments.

Acknowledgements

The author would like to thank Atle Saegrov at Radionor, David Staningford at Zenotech, Mark Barrett at Blu Wireless Technology, and Richard Edgar at Imagination Technologies for their help with researching this article.

A technician in Fukushima oversees key flight planning details before the Penguin C's first flight over the Daiichi nuclear plant (Courtesy of Clear Pulse)

Nuclear reaction

This commercial aerial system is being tailored to monitor and mitigate the fallout from disasters at nuclear powerplants. **Rory Jackson** reports

In March 2011, the Daiichi nuclear power plant at Okuma, Fukushima, suffered three nuclear meltdowns, three hydrogen explosions and widespread leakage of radiological contaminants, caused by the Tohoku earthquake and subsequent tsunami.

The radiation unleashed into the atmosphere resulted in a government-ordered evacuation zone that gradually reached 20 km in diameter and required the movement of around 154,000 nearby residents.

With a government commission having found that the Tokyo Electric Power Company failed to meet basic safety requirements, a number of measures have been taken to prevent a repeat of the disaster's various impacts.

For example, new sea walls have been built to better prevent tsunamis from flooding and damaging the plant's infrastructure, and a 1.5 km 'ice wall' of frozen earth has been installed to prevent irradiated or contaminated water flowing from the premises.

Most recently, a Penguin C UAV from UAV Factory has been acquired by local company Clear Pulse, to be used in the event of another disaster. In such a situation, the fixed-wing UAV will perform airborne radiological surveys to detect, study and map the radiation levels. These flights will then give a better idea than before about the safety and evacuation decisions needed.

Clear Pulse manufactures radiation measurement products, and its contract with UAV Factory, signed in 2018, covers delivery and various follow-up support services for the Penguin C and its ancillary equipment.

The company notes that when radioactive material is released into the air after a nuclear accident, it is important to know its concentration in real time, to determine how best to reduce the risk of exposure to nearby residents.

The most reliable way to gather that knowledge is to measure the radiation directly. By using a UAV, Clear Pulse can reduce the risk of exposure to its staff and therefore make the measurement process safer, since they can launch and fly it some distance from the nuclear plant – and, unlike manned aircraft, they wouldn't be putting a pilot in harm's way.

The aircraft will be operated through Clear Pulse's subsidiary JDrone, which successfully carried out the first acceptance flight trial of the Penguin C over Fukushima in May. Clear Pulse's role will be to oversee the operation and handle the processing and analysis of radiological data.

UAV Factory's launch catapult collapses to fit into a man-portable container for ease of transport (Courtesy of Clear Pulse)

Project requirements

The origins of the contract came from an inquiry that Clear Pulse received in 2017 from one of its (unnamed) customers who was studying aerial radiation monitoring. The subject of UAV Factory's Penguin C arose, hypothetically as a candidate aircraft to be used if ever another nuclear accident occurred.

To ensure satisfactory performance during a nuclear crisis, Clear Pulse drew up a list of requirements for the project's UAV. First, it would need to have long endurance, and have a distance of at least 5 km between the UAV and its GCS to keep the operator clear of the radioactive zone.

The system would also need to be fully autonomous, with an autopilot capable of integrating and operating a radiation sensor payload. Lastly, it could not be dependent on a runway; the launch and landing processes would need to be flexible, as the ground team might be forced to move at any moment.

According to Clear Pulse, although it and JDrone were familiar with a number of locally manufactured and potentially suitable UAVs in 2017, many of them were not yet at full technological readiness. The Penguin C on the other hand was fully commercialised, with its own hardware, software and customer support. These were the main reasons for its eventual selection.

> The UAV's launch and landing processes would need to be flexible, as the ground team might have to move at any time

While JDrone and Clear Pulse are continuing flight trials to determine the optimum protocols to follow during a nuclear accident (depending on its nature and scale), a few key options and models for how to conduct the operation are available. The companies are also experimenting with the best model of radiation detector to install into a payload for the UAV.

The Penguin C

The Penguin C is a twin-boom aircraft (described in *UST* 1, November 2104) with a 3.3 m wingspan and measuring 2.3 m long. It is built largely from carbon and fibreglass composites, which give it a MTOW of 23 kg and a payload-carrying capacity of up to 4 kg, and is launched by catapult.

As mentioned, being able to fly long-endurance missions was a critical requirement for the end-user in Japan. Accordingly, the Penguin C is capable of flying for up to 20 hours, at a cruising speed of 68-79 kph.

Its endurance and cruise (as well as a top speed of 115 kph) are enabled by the company's own UAV28-EFI engine (described in *UST* 19, April/May 2018). This is a two-cylinder, two-stroke, electronically fuel-injected gasoline engine that provides up to 150 W from its starter/generator for onboard systems, payload included.

It has undergone highly accelerated lifetime testing to identify and eradicate long-term points of failure that might occur after hundreds of hours of

The Penguin C was chosen over other UAVs for its long endurance, autonomy, technological maturity and follow-up support options (Courtesy of UAV Factory)

mechanical and thermal stresses, aiding the longevity of the powerplant after it is handed over to its end-user.

The aircraft and engine are rated to a maximum operating altitude of 5 km. They can operate in ambient temperatures of between -40 and +50 C, in up to 5 mm/hour of rain (the Fukushima area has a wet climate).

Furthermore, the Penguin C can remain in contact with its GCS over 100 km, more than satisfying the project's minimum operational range of 5 km.

A data link secures the command reception from (and data stream to) JDrone's GCS and Clear Pulse's radiological equipment, on the 2.3, 2.4, 2.5 or 5.8 GHz bands. However, flight control is handled autonomously, using a Piccolo autopilot from Cloud Cap Technology, freeing up the team to focus on incoming measurement data.

> Most UAVs and catapults for this kind of endurance are much larger, but everything for ours fits on a standard pallet

Scramble and launch

Until it receives an alert from the power plant, the Tokyo Electric Power Company or some other pertinent group, the Penguin C and its equipment are expected to be stored in a central station for quick retrieval. They can then be transported to within a safe distance from the accident.

It is worth noting that while many UASs require bulky transportation containers and vehicles for moving small, fixed-wing aircraft and their peripherals, all the systems delivered by UAV Factory are collapsible. Each is thus packaged into a man-portable handheld container, and they can all be loaded into the back of a small truck or normal passenger car for fast deployment.

"Since the UAS has a very small logistical footprint, it was no trouble sending all the systems by air cargo, as we normally do," UAV Factory's CEO Konstantins Popiks says. "Most UAVs and catapults for this kind of endurance are much larger, and face bigger disruptions as a result, but we designed ours so that everything in their cases would fit together on a single standard pallet."

The Penguin C's wings collapse into three separate sections, as does its inverted-vee tail. The twin booms joining these two aerofoils are removed from the mid-wing and the tail ends.

The fuselage meanwhile breaks into two parts, with the avionics and payload bay in the front section and the engine and prop in the rear (and a few detachable coverings associated with either half that also come off for transport and maintenance). This disassembly enables the UAV to fit into a standard-issue ruggedised case measuring about 1300 x 700 mm.

The exact launch location will vary. Depending on the reported epicentre of the accident, several potential points for setting up a command centre and the pneumatic catapult will be established beforehand.

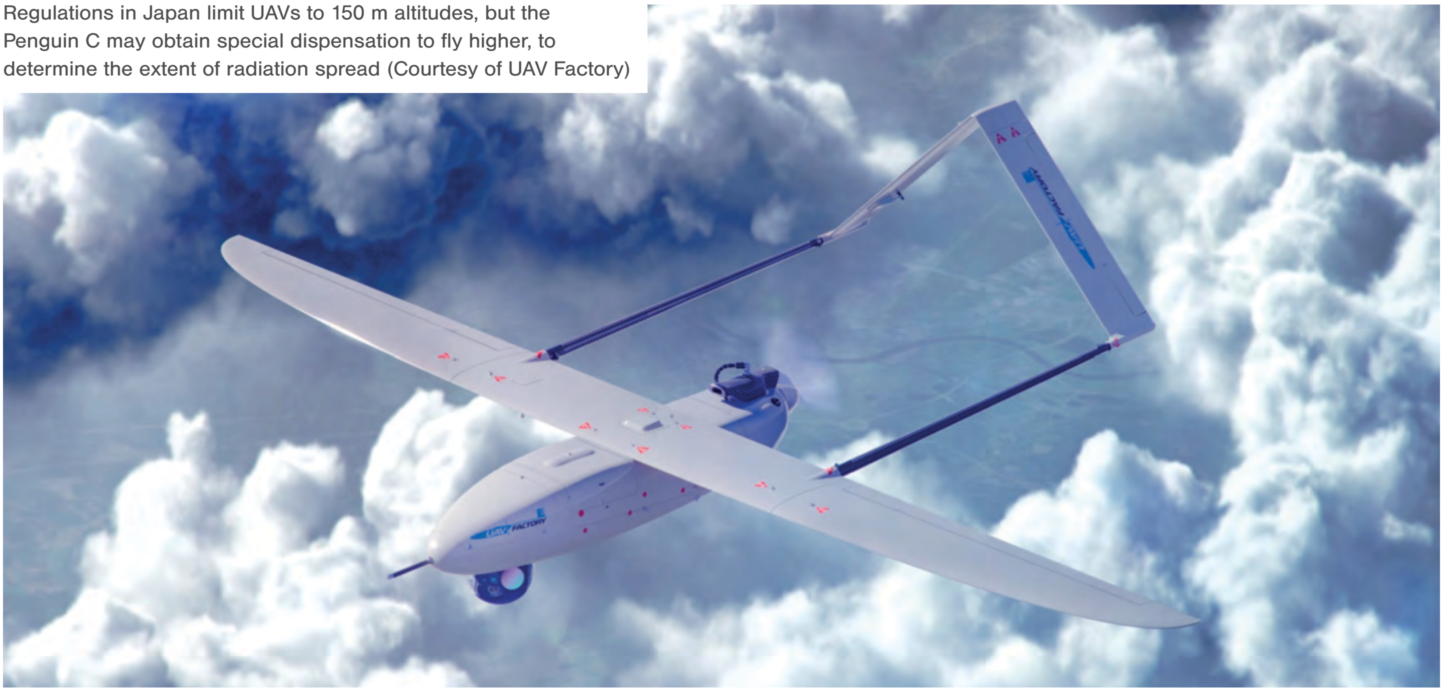
Like the UAV, the catapult is collapsible, but it comes with a higher degree of modularity. Its carriage rail is formed from identical, interchangeable sections that can be added or removed as needed, to construct a launch system with the length (and hence launching power) appropriate for the end-user's needs.

"The angle also changes as the catapult gets longer, but that doesn't matter much because the Penguin C will pitch and steer upwards as soon as it has a manageable airspeed, to get to the mission altitude as quickly as possible," Popiks adds.

"The launch energy is the most important thing, which is usually measured in kilojoules. A catapult with a four-piece, 4 m rail nominally produces 6 kJ; a six-piece, 6 m rail produces around 12 kJ."

The modularity comes as a result of having the same quick-connection systems on the ends of every carriage piece. It is a specialised joint mechanism developed by UAV Factory that uses internally threaded connections

Regulations in Japan limit UAVs to 150 m altitudes, but the Penguin C may obtain special dispensation to fly higher, to determine the extent of radiation spread (Courtesy of UAV Factory)



that are secure enough to withstand the shock-loads of launching the Penguin C.

"It takes around 5 minutes at most to assemble or disassemble the catapult," Popiks says. "All its pieces, as well as the compressed-air tank, fit into a box the same size as the UAV's, enabling quick transport to the nuclear plant in whatever road vehicle is available.

"A UAV's logistical footprint multiplies the cost of using it at every step of operations. For that reason we designed this system to need no more than two people to transport and operate it, and we supply our catapult to a number of UAV manufacturers around the world who want a small catapult to suit their smaller aircraft."

Mapping radiation

Although regulations in Japan currently restrict the flight ceilings of UAVs to 150 m, the Penguin C could probably fly higher than that during its survey missions.

Given the experimental nature of this project, among the many unknowns is which type (or types) of radiation detector to use. Since Clear Pulse produces many kinds, and time would be of the essence in the event of a nuclear disaster, it remains to be seen which sensor will be deemed the first priority for integration.

For example, ionisation detectors – a widely used type of radiation sensor produced by Clear Pulse – carry an internal chamber filled with air or some other gas that can be ionised by radiation.

When the particles within become ionised (as positive or negative ions), they migrate towards their polar-opposite electrodes, resulting in an electrical pulse. Once these pulses are amplified, they can be recorded and measured for radiation information.

Alternatively, the UAV might integrate Clear Pulse's semiconductor detectors. These work similarly to ionisation chamber detectors, but at a scale and voltage similar to MEMS devices.

They are designed with two layers of semiconductor material, one with a higher negative ion count than the other, so the ions migrate from the former to the latter. As the particles move, any radiation present will re-ionise them, producing a measurable electrical pulse.

These sensors tend to produce faster detection times and can withstand higher levels of radiation than many other types of radiation detector (and are the smallest type, measuring around 4 x 4 x 1 mm in some cases). These factors make them potentially ideal for this application.

The type and level of radiation measured can be stamped with the time, altitude and GNSS coordinates recorded by the Piccolo flight computer. These are then combined with additional geo-referencing systems using extensive post-processing at Clear Pulse's ground control centre, to produce a 2D or 3D map of a radiation plume.

Over two or three days, the process can be repeated to get enough of an idea of how the plume might be expanding or moving. The authorities can therefore determine which nearby towns or villages need to be evacuated first, and where the people should go to be able to give the plume a wide berth.

During the evacuation process, the Penguin C can also be equipped with one of Octopus ISR Systems' EO/IR/laser payloads to help monitor and coordinate the safe and orderly movement of civilians away from the nuclear plant.

Recovering the Penguin C

The Penguin C typically deploys a parachute in order to land, forgoing the need for any net or hook-type system for recovery, in line with the aforementioned design emphasis on logistical ease.

Future testing will determine exactly

Specifications

Wingspan: 3.3 m
Length: 2.3 m
MTOW: 23 kg
Maximum payload: 4 kg
Maximum endurance: 20 hours
Maximum range: 100 km
Top speed: 115 kph
Operating speed: 68-79 kph

Some key suppliers

Radiation sensors: Clear Pulse
EO/IR/laser sensors: Octopus ISR Systems
Engine: UAV Factory
Launch catapult: UAV Factory
Autopilot: Cloud Cap Technology

The new Penguin C Mk 2 features a rotating nose, enabling more accurate image capture, and belly-landings if the payload is rotated to face away from the ground (Courtesy of UAV Factory)

what PPE, decontamination equipment or specialised cooling system will be needed for safely handling the UAV after it returns from a mapping mission. However, the UAV might not be handled post-mission at all.

The returning UAV will probably be deemed a radiation hazard to the flight crew or other nearby staff – and even if it isn't, they may realise they have to relocate immediately and can't wait around to receive the UAV back at base.

In either event, the parachute would be deployed and the UAV can be left to land gently in a field or wood in the evacuation zone – which the public will not be allowed to enter and therefore cannot approach the aircraft – until such time when a hazmat crew or similar can retrieve it.

Future provisions

A number of matters remain to be proven-out through testing the UAV. For example, any protection of electronics or other systems against the effects of flying near a nuclear disaster will need to be determined through working with partners who can accurately simulate the effects of such an accident.

In the meantime though, UAV Factory will be unveiling its slightly larger Penguin C Mk 2, which while still weighing slightly less than 25 kg (55 lb) will have some new features that might be of interest to the Fukushima team and others.

For one, the Mk 2 will have an interchangeable nose section. Each of them is designed with a different payload to suit different missions, to enable much faster plug-and-play swappability for different missions.

The Mk 2 will also integrate a rotary servo in its nose section that enables the nose cone to turn 360° in the *z* axis, creating a fully gyro-stabilised seat for the payload. As the UAV banks to turn – as is typical near the preset borders of an area to be monitored or mapped – the nose adjusts its attitude to keep the payload's axis parallel with the horizon.

"This extra axis of stability means more accurately geo-stamped images during turning, less image blur – especially when using payloads that aren't typically designed for gyro-stabilisation – and more usable images per flight," Popiks says.

"This aircraft will also have many parts that are interchangeable with the older Penguin C, including the same GCS and catapult. The Fukushima project could adopt this for longer flight times and heavier payloads, with reduced downtime if they wanted to recover the UAV after a flight and change to a different payload.

"If it's safe for them to recover it, the Mk 2 can turn its nose upside down, to perform a belly landing in a nearby field and keep the payload safe from collision with the ground."

Eliminating the need for recovery equipment will no doubt be of huge value in a range of other missions, from disaster monitoring and relief to routine commercial and military operations around the world. ◻

"Now, here's a thing"

Dual- and multi-environment drones are now emerging, with several that can operate underwater and in the air, at least one family that can both fly and drive, and a conceptual machine designed to do all three (writes Peter Donaldson).

As ever though, nature is millions of years ahead of us in this, and there are many animals that can move about successfully in the air, on or under water and on land. Multi-environment animals have their limitations, however, because features that provide good capabilities in one area tend to bring drawbacks that affect one or more of the others.

It is always worth studying how evolution has solved these problems and the compromises that have been made along the way to get an idea of the challenges engineers face in creating multi-environment machines.

The most noticeable of these is size, as all multi-environment animals are relatively small and all are either birds or insects. The largest is the pelican, which can weigh up to about 12 kg and is a good flyer, surface swimmer and diver, regularly plunging into water from the air to catch fish. On the other hand, it waddles about rather awkwardly on land, although it does manage to project some swagger while doing so.

Gannets are probably the high-performance diving champions. They can hit the water almost vertically at up to 75 mph, folding their wings back on entry and reaching depths of 60 ft, where they chase after fish, propelling and manoeuvring themselves with their wings and feet. Hydrodynamics and aerodynamics are similar enough for wings to double as serviceable paddles, although of course webbed feet are no good for flying.

> Vehicles that can swim and fly tend to use the same propellers in both environments, although they have to be optimised for flight

Likewise, unmanned vehicles that can swim and fly tend to use the same propellers in both environments, although they have to be optimised for flight and their underwater limitations accepted, as is evident from their relatively long spans and narrow chords.

Moreover, most dual-environment drones are basically waterproofed multi-copters. This applies to the Corrosion Resistant Aerial Covert Unmanned Nautical System developed in 2016 by a team at the Johns Hopkins University Applied Physics Laboratory, the Naviator developed by Rutgers University, and the Spry and Spry+ developed by Swellpro for the sports and leisure market.

North Carolina State University has developed a fixed-wing drone called the EagleRay XAV that can 'fly' underwater, launch into the air and return to the water. More dramatically, the AquaMAV from Imperial College in the UK enters the water like a gannet, it too folding its wings back as it dives in.

Few unmanned vehicles combine flying and driving capabilities, but Robotic Research's Pegasus family of quadcopters has tracks built into the landing 'skids' that also pivot up and out through 90° to serve as rotor guards in flight.

Perhaps uniquely, Cyclopic's conceptual Cyclopter, which is in the early stages of development, is designed to operate in all three environments. It is a waterproof quadcopter that drives, flies and swims, using rotors built into the wheels that serve as propellers under water and pivot to a horizontal position to create a quadcopter configuration for flight.

Aquatic birds have survived for millions of years by finding ecological niches that favour this combination of capabilities; their drone analogues will have to find similar ones in the UAV market. ◻

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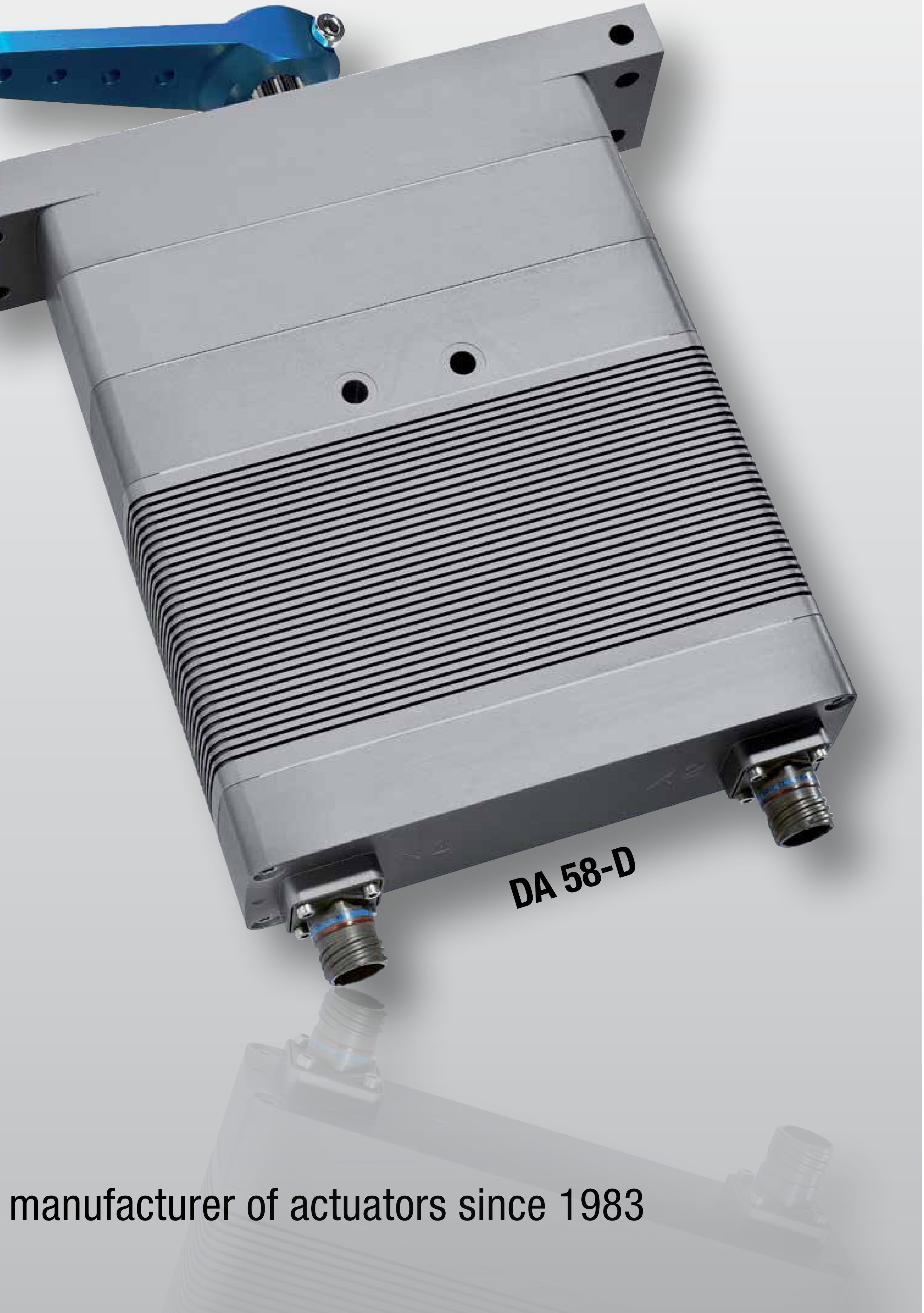

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