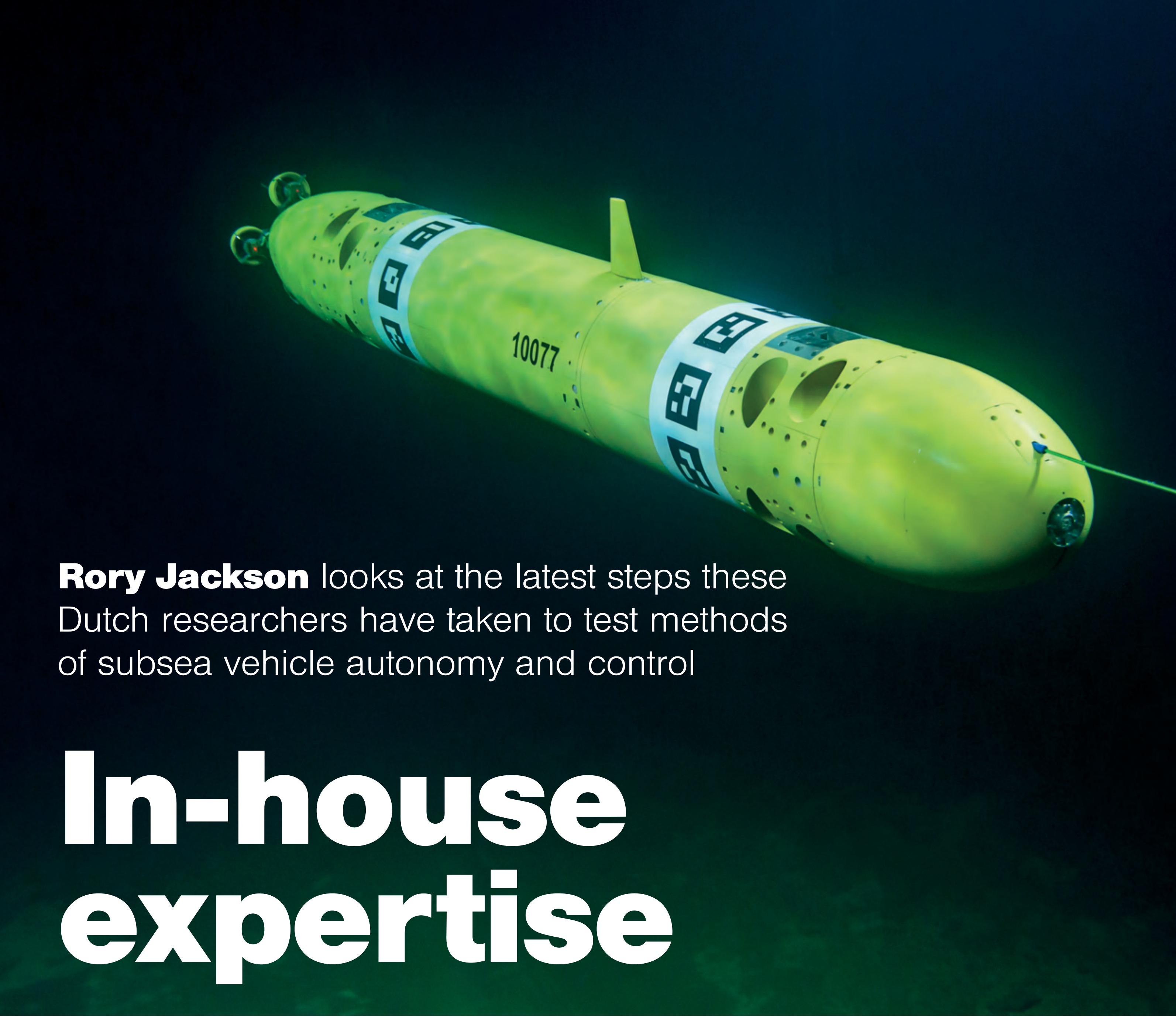


Rory Jackson looks at the latest steps these Dutch researchers have taken to test methods of subsea vehicle autonomy and control

In-house expertise

The Maritime Research Institute Netherlands (MARIN) has for a long time developed autonomous test and demonstration platforms to find better ways of providing independent expertise and scientific consultation to maritime industries. Its newest vehicle, the mAUV (modular AUV), has been designed to carry out research in its in-house model basins into the capabilities of underwater vehicle autonomy and control systems.

The battery-electric mAUV has a 3.1 m-long, 0.35 m-wide hull, 12 thrusters, and various sensors, LEDs and other onboard electronics, giving it an approximate displacement of 235 kg.

While many UUVs (and other unmanned vehicles) these days are being produced with minimalism and simplicity in mind, the mAUV has come from a blank-sheet design with a range of complex and sophisticated features in its propulsion, navigation, control software and other systems.

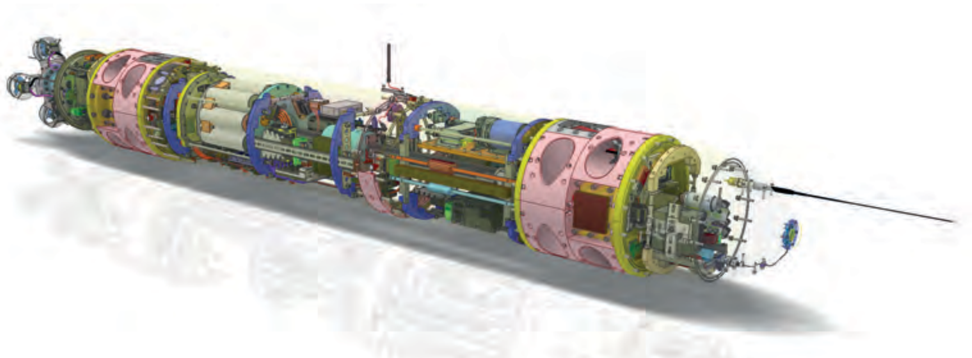
All these systems have been arranged into a modularly defined AUV architecture, which divides the vehicle into six function-based modules. Starting from the back, these are the main propulsion section, a steering thruster module, the battery pack, a module for control and positioning systems, another steering thruster module and at the front a sensor dome.

Such is the modularity of the structure that the MARIN team can change each section of the vehicle at will, for example to test out an experimental subsystem configuration, gather data at new parameters or change the vehicle's operational envelope and capabilities for an end-user's particular needs.

As Bas De Kruif, senior researcher for autonomy and decision support says, "At a demonstration day we held a while ago, we showed several use-cases for the mAUV. It can inspect docks, survey an area or inspect an object from every possible angle, then move vertically to the surface to transmit its survey data as the nose antenna breaks the surface.

"This is enabled by having a full six

The mAUV has been designed for indoor basin experiments, to trial and advance MARIN's UUV technologies



The mAUV's main propulsion section is at the rear, with batteries and control systems in the middle and a sensor dome at the front

degrees of freedom in the prototype mAUV's control system. Having designed it from a blank sheet ourselves, we have complete freedom to alter the software and hardware in ways that would be impossible with a closed system.

"As we can modify and test out the vehicle as we please, we can rapidly improve our simulated model [or 'digital twin'] of the mAUV, to increase the accuracy of how we predict it will behave, such as when operating near structures or how currents or waves influence its motion."

Egbert Ypma, the team leader for autonomy and decision support, adds, "We've developed common components for use on the mAUV and our previous autonomy platforms, such as our small, sailing wavebuoy or our 6 m RHIB. This, and the way the mAUV is designed, make it quite easy to test or demonstrate new application payloads, different actuator configurations and so on."

ROV control, AUV speed

The availability of six degrees of movement control came from a few key project requirements that had been decided from the outset. One was a desire to combine the accurate hovering and orientation control of an ROV with the high forward speed and range of torpedo-shaped AUVs.

This flexibility in vehicle control enables an AUV capable of manoeuvring in confined spaces (providing that the space allows for the mAUV's length and diameter in the first place of course).

It also means potentially major improvements in acoustic sensor data quality, as the body of the AUV can always be tilted to point its scanning sonar in the optimal direction (and hold that position and orientation over the required duration) for gathering close imagery of subsea assets or other survey targets.

Hans Cozijn, MARIN senior project manager, says, "Our approach was to start development with a full six degrees of freedom in control. Later on, depending on the application or end-user's requirements, it will be reasonably easy to reduce the number or power of the thrusters, or remove one or more degrees of freedom, to simplify the system according to a given need."

Haite Van Der Schaaf, principal project manager for measurement systems, adds, "As the vehicle design is modular, we can add passive fins or active rudders to investigate how it performs using alternative design configurations used across different ROVs, AUVs, glider-type vehicles and so on – all using the same baseline of hardware and software."

In its current form, the AUV has no need for fins or rudders (aside from just one fin on top of the hull, which also acts as a wi-fi antenna housing). As MARIN's research has noted, relying on fins and rudders means having no orientation control when forward motion is zero – a problem that the mAUV has neatly avoided.

As mentioned, the mAUV uses 12 thrusters in total. Control in the vertical and transverse directions is achieved via eight of these: two pairs of tunnel-mounted thrusters near the front (one pair pointing vertically and one pointing horizontally), and two more identical pairs near the back.

The MARIN team installed thrusters in pairs rather than singularly, so that the mAUV could roll in each axis as well as move sideways as needed. Also, if one thruster breaks down during a mission, the mission can still continue, albeit with lower overall thrust in the direction of the thruster concerned.

Forward propulsion comes from four backward-facing thrusters

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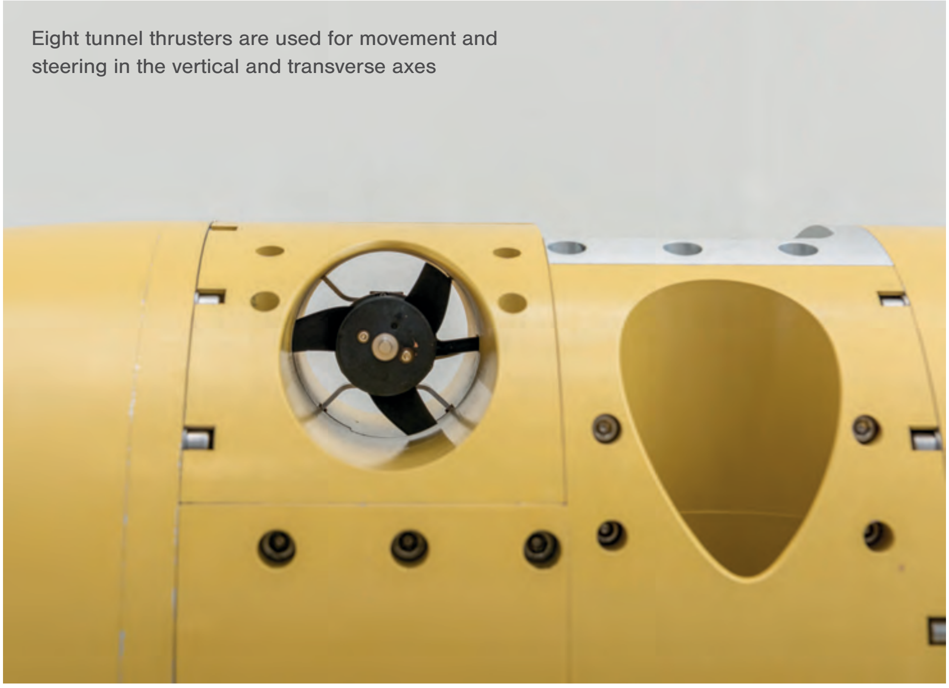


Eight tunnel thrusters are used for movement and steering in the vertical and transverse axes

mounted at the rear of the hull, which give an operating speed of 4.5 kph. It's a limitation chosen for safety reasons, with higher speeds expected in future experiments when needed. All 12 electric thrusters use the T200 model from Blue Robotics, modified to include Hall effect sensors.

"This sensor type was included in the thrusters in order to measure their revs," Cozijn explains. "That gives us the possibility to design a control strategy based on rpm, and by extension on electric currents."

In addition to the modified thrusters, two ballast tanks are installed – one at the bow and the other at the stern – as well as a 5 kg mass that moves back and forth along a rail inside the middle of the mAUV.

A piston inside each tank actuates the flow of water entering and leaving them, making the control of submerging and surfacing of the mAUV slightly more energy-efficient than using the thrusters. The 5 kg mass measures 10 cm across and is servo-actuated along a 1 m internal space, further contributing to the control of the vehicle's tilt by changing the longitudinal CoG.

Operations with the mAUV consume a maximum of 2 kW, the lion's share of which is taken up by the thrusters. To ensure energy efficiency (in terms of the rate and accuracy with which power is allocated and consumed), a comprehensive blank-sheet approach was taken to writing the control algorithms and allocation logic needed for distributing the required forces across all the thrusters – from a mission-overview perspective down to the operational commands to the thrusters.

"The control of the mAUV is divided into three layers," De Kruif explains. "The mission is planned at the top layer, and a set of actions is defined that makes up the mission. Which actions are executed, and the order of them, depends on environmental and mission conditions.

"The next layer is the mission execution layer, and the third is the vehicle control layer. The former provides the latter with set points for the craft's position and velocities, while the latter ensures in real time that the set points are reached.

"The onboard INS gives measurements for the real-time [angular] velocities and the absolute pose. Based on the difference between where we want to be and actually are [according to quaternion representations], a required adjustment force is calculated 20 times per second. This force is then divided between the thrusters as appropriate to minimise this difference."

A Windows PC is installed in the mAUV's central module to run the functions needed for the layers. The code for the control systems was written in Python and C#, and the monitoring and recording of INS data and motor performances are handled by additional embedded software applications, which were developed using C# and C++.

Future experiments are aimed at exploring how best to specify high-level mission goals such that the mAUV can perform them amid unforeseen events, through different AI-based approaches established in prior research.

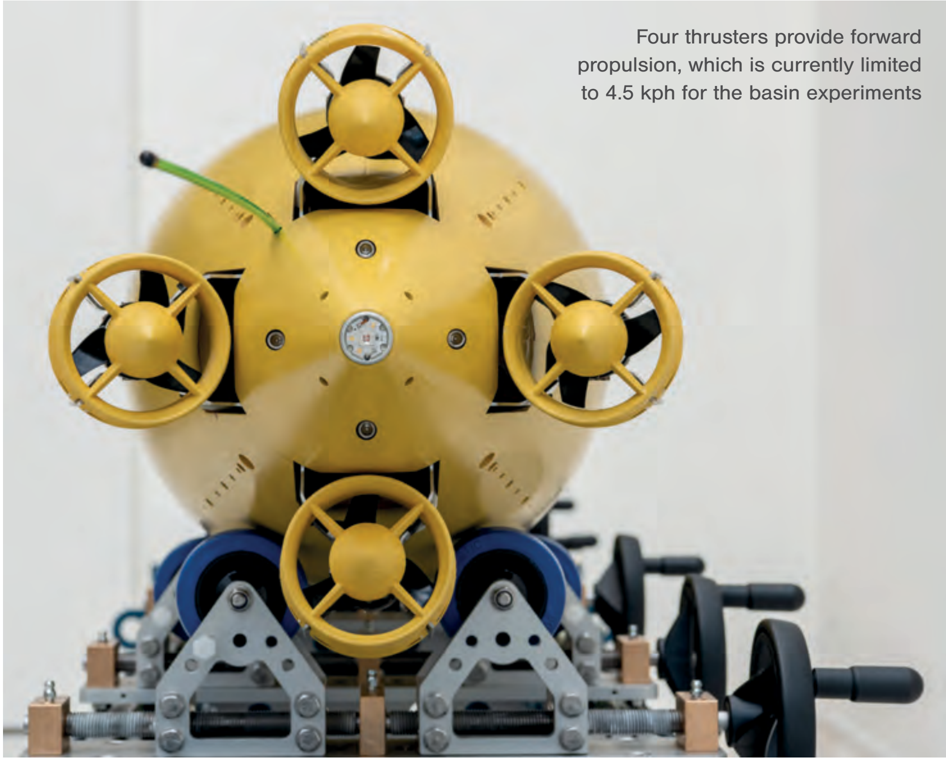
Hull design

A design geometry known as the Joubert BB2 was chosen for the craft's hull. This is a well-established generic submarine hull, and gives the mAUV a tubular, torpedo-like shape (with an elliptical bow and a parabolic stern), which is intended to minimise drag while maximising the amount of internal space for electronics.

The key exceptions to this design, as indicated above, are the eight thruster tunnels installed near the front and rear, which replace any outward protrusions such as fins or rudders along the hull's length.

The hull's main structure is made from aluminium, chosen partly because of its strength and durability but also to enable precise machine-cutting of each hull module. That makes it relatively easy (compared with other metals or manufacturing approaches) to accommodate changes in mounting points, dimensions and other variables between section configurations.

"For manufacturing these large aluminium parts, including minor modifications to individual hull segments, we have good experience with a nearby subcontractor, which we also worked with in previous submarine testing projects," says Van Der Schaaf. "Aluminium



Four thrusters provide forward propulsion, which is currently limited to 4.5 kph for the basin experiments

gives other advantages too, such as hull rigidity, sufficient strength for installing lifting hooks on the main structure, and good pressure resistance."

The aluminium modules are designed with connection points for O-ring seals, which waterproof the joints between segments to a maximum depth rating of 200 m.

Optical-aided navigation

To achieve the high degree of control needed for the vertical and transverse thrusters to orient the mAUV as desired, MARIN needed to select inertial sensors capable of outputting position, speed and acceleration measurements to a high degree of accuracy.

To achieve this, an iXblue PHINS C3 fibre-optic gyro IMU has been installed to estimate attitude, rotation speed and position. An Xsens MTi-300 attitude and heading reference system is also installed and operates as a secondary source of these data estimates.

For further positioning precision, most UUVs will use some form of acoustic aid such as USBL, LBL or DVL systems. However, as the mAUV's trials are to take place largely in MARIN's test basins – which have concrete walls and floors – acoustic positioning technologies would be hampered by reverberations.

Also, although the UUV can surface frequently thanks to its shallow test operation depths, GNSS cannot be used as an occasional source of position reference updates, as the test basins are indoors.

Instead, the team has installed an optical aid system in the test chambers. This is based on stereo vision cameras (installed on a moving rail-based carriage located above the basins) that detect and localise ArUco markers across the mAUV's body in real time, to measure its position and attitude underwater.

In addition to being recorded in the team's test equipment, this information is also intermittently transmitted to aid the onboard INS. This is achieved using VHF radio antennas (one on the nose and another at the rear, near the main propulsion thrusters) which use the restricted bandwidth in the basins to transmit inertial data estimates as correction aids to prevent INS drift, as well as receiving basic operational commands.

Lastly, this measurement data tells the overhead towing system where it needs to pull the camera carriage in order to keep a close eye on the UUV's whereabouts.

Naturally, for tests outside MARIN's basins, acoustic aid systems such as DVLs and sidescan sonars (and possibly USBL transceivers) will be integrated.

De Kruif adds, "In a future research project we will look into the position estimation of an autonomous vehicle – underwater or on the surface – based on information coming from a camera mounted on the vehicle itself.

"As well as the question of how to do this in a harsh maritime environment, we're very interested in how accurate and fast the data and processing would need to be for this kind of system to work.

"This is crucial for autonomous vehicles: steering actions are based entirely on this information. If you want to recover your vehicle in a high sea state, your positioning measurements need to be reliable and fast, with robust algorithms to interweave your vision sensors with your control systems."

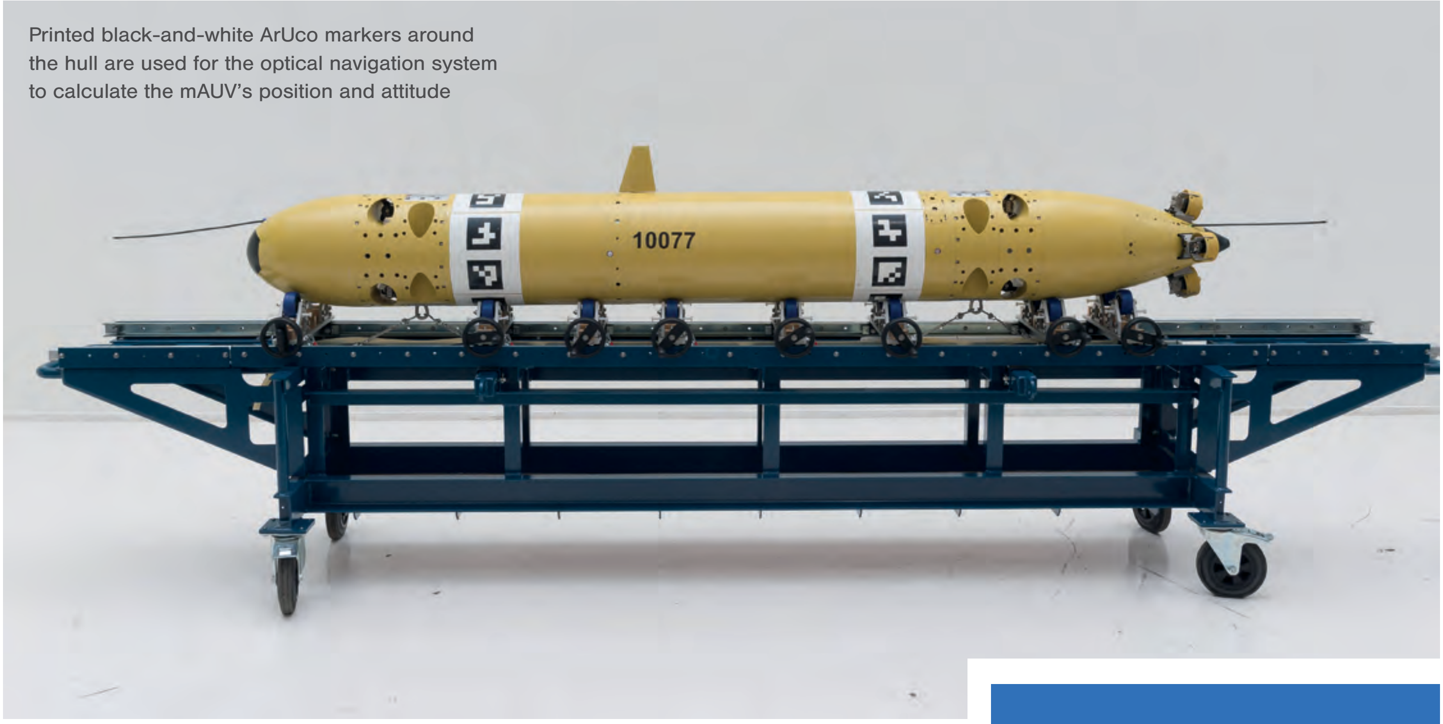
Power

Power to thrusters, sensors and so on is provided by a 24 V lithium-ion battery pack installed between the centre and rear of the vehicle. The pack consists of seven cylindrical NCA (lithium nickel cobalt aluminium oxide) cells.

Each cell measures 6 cm across and has a capacity of 45 Ah, or 162 Wh of energy storage. When the cells are connected together, the pack thus stores 1.134 kWh and supplies it at around 25 V to the onboard systems.

"The cells are mounted in a circular or annular way, to provide an open space through the middle, through which the aforementioned moving mass can travel to adjust the mAUV's CoG," Van Der Schaaf adds.

Ypma notes, "Currently, the capacity of the batteries is relatively limited compared with long-endurance UUVs, as the pack is tuned mainly to suit the



Printed black-and-white ArUco markers around the hull are used for the optical navigation system to calculate the mAUV's position and attitude

typical durations of our in-facility tests [around 2-4 hours between charging]. However, when we start going to sea trials, the need to improve the mAUV's endurance will require some rethinking of the power system.

"For example, we could increase the battery capacity, we could reselect or reconfigure the onboard electronics to make them more energy efficient, or we might provide underwater charging stations. A key requirement for subsea charging stations is that the UUV can be accurately manoeuvred to a docking and connecting position – something the mAUV is well-equipped for."

Digital twin

In the course of developing the mAUV, the team made extensive use of MARIN's pre-existing CFD simulation and calculation software tools. "These enable us to determine the hydrodynamic behaviour of any new hull form in the earliest stages of our vehicle design processes," Ypma explains.

"In addition, we can use the digital twin of the mAUV to develop our control algorithms and sensor fusion, and test the whole system using a hardware in-the-loop approach. And during the facility tests we collect measurement data that further validates and improves the digital twin."

The digital twin software models a vast number of different forces that act on (and are generated by) the mAUV during missions. These include the thrust and torque of the propellers, hydrostatic forces such as buoyancy, the effects of the ballast tanks and moving mass inside the UUV, wave forces against the hull, and of course key hydrodynamic forces such as drag and lift.

As the basin experiments continue, the team will amass more measurements that will further improve the accuracy of these simulated forces. In particular, the thruster models, simulations of the mAUV's manoeuvring, and calculations of wave forces are expected to more closely predict and capture real-life movements and behaviours over time.

The future

In addition to improving simulation data, and the planned experiments already mentioned, MARIN's engineers anticipate a few more critical modifications and tests in the near future.

Specifications

Dimensions: 3.1 x 0.35 m
Weight: 235 kg
Propulsion: battery-electric
Hull: aluminium
Operating speed: 4.5 kph
Endurance: 8 hours stationary, 2-4 hours moving
Ballast volume: 1400 cm^3

Some key suppliers
Thrusters: Blue Robotics
IMU: iXblue
Attitude and heading reference system: Xsens
Operating system: Windows

For one, the team plans to integrate actuators for rudders in order to perform tests at higher speeds (at which tunnel thrusters might be relatively less effective for pitch and roll). Also, more sensors will be added to expand the mAUV's range of data and functions, and enhance its autonomous capabilities; sidescan sonars, DVLs, or forward-scanning sonars for obstacle detection and avoidance are being considered here.