MaxiMOOP: A Multi-Role, Low Cost and Small Sailing Robot Platform

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Abstract This paper describes the development, testing and operational results from a small, autonomous sailing vessel that was designed to be easily launched and retrieved by one person while carrying a 7.5 kg payload and with enough speed under sail to overcome reasonable current. The hull is 1.2 metres long and fits in the boot of a typical car. This paper focuses on the design and testing of four prototypes, two designed for short course racing and two others designed for long endurance all weather missions. Initial tests have shown top speeds of around 3 knots with a larger racing rig and 2.4 knots with a small all weather rig. One of the prototypes has attempted a transatlantic crossing, this was cut short when it was accidentally caught by a fishing boat. Two different autonomous control systems have been developed, one based around a pair of microcontrollers and intended for low power operation averaging less than 1 W and the other based around a Raspberry Pi and ATMega328 combination to ease development and test more complex sailing algorithms.

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Fig. 1 The MaxiMOOP ABoat Time beginning her transatlantic voyage in May 2014.

1 Introduction

The MaxiMOOP design was developed in response to a need for a small, inexpensive, easy to build and transport, special-purpose autonomous surface vessel (ASV) for use in oceanographic research and autonomous systems development. It was inspired by the original MOOP (Miniature Ocean Observation Platform) [10], a 74 cm long hull design that demonstrated the feasibility of a small scale hull but suffered from poor upwind performance. The MaxiMOOP is capable of multi-day missions without the need for refuelling or recharging. To-date, sail-powered ASVs were mostly adaptations of either small keelboats designed for one person or modified remote control model yachts. The former, while able to carry large payloads, have the problem of their size causing logistical problems. The latter have little payload capacity (typically less than two kilograms) and are not robust, but are relatively quick. This vessel was designed from scratch for the purpose of easy logistics and reasonable payload. The vessel can fit in the boot of a typical small car, costs less than US$1000 in materials to construct (approximately $250 for materials and $750 for electronics), can be carried and deployed by one person, has a payload of 7 kg and can maintain speeds of 1-2.5 knots in most wind conditions. It can serve as a base platform for students developing their first ASV system or for carrying small oceanographic research payloads. At least seven vessels have been built so far and they have performed admirably in both Europe and North America. The hull shape was developed with the needs for a reasonable payload and exceptional sea-keeping ability while remaining durable and easy to build. The hull is similar to many sail-powered inshore fishing craft of the 19th century with the addition of a proportionately much deeper keel that is integrated to the hull with slack garboards. The hull/keel joint was desired to ease construction, reduce stress concentrations in the hull to keel joint and provide additional storage space. The leading edge of the keel is swept back to ease weed shedding. The large lateral plane is needed in light air and waves while it provides a keel sump with sufficient volume down low for ballast. The flat deck eases construction and the mounting of hardware. Table 1 lists the Principal Characteristics and Figure 2 shows the hull lines.

Table 1 Principal characteristics of the MaxiMOOP hull

Length Overall	1.2 m
Waterline Length	1.1 m
Displacement/Max Payload	16-23/7 kg
Draft	0.41 m
Beam max overall	0.35 m
Depth overall	0.6 m
Ballast	9-10.5 kg
Sail Area	0.24-1.0 m^2

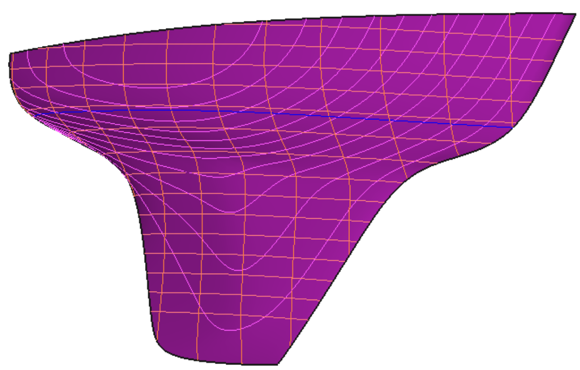

Fig. 2 MaxiMOOP hull shape lines.

A two-part (port and starboard) hull plug was machined of foam at the U.S. Naval Academy (USNA) and molds were taken off the plug at Aberystwyth University and at USNA. Most hulls have been built of approximately $800\,\mathrm{g/m}^2$ of fibreglass cloth set in epoxy. Decks are typically 3 mm plywood covered on each side by $200\,\mathrm{g/m^2}$ fibreglass cloth set in epoxy. Recycled lead shotgun shot was used for ballast. It was poured in to uncured epoxy in two or three steps to reduce heat build-up. The top of the lead line is approximately 100 mm above the base of the keel, providing a low centre of gravity and high stability. Due to the variety of missions it was designed for, the vessel has the option of three different rudder configurations; attached to the keel, under hung spade and transom hung. The first boat, Morwyn was built by Aberystwyth for research in ASV systems in the Irish Sea and has an attached rudder to reduce the likelihood of catching weed or other floating debris. The second boat (Dewi) was built by Aberystwyth students for competing in the SailBot competition and featured a transom hung rudder to provide more manoeuvrability while being easily removable for transportation. Figure 3 shows the two vessels.

Fig. 3 Morwyn (left) and Dewi (right) showing attached and transom-hung rudders.

The sixth (Mid Life Crisis) and seventh (ABoat Time) vessels were built by the midshipmen at the United States Naval Academy and feature permanently attached spade rudders for reduced drag. Figure 4 shows the spade rudder design on MLC.

In addition to the ability to use different rudder designs, the MaxiMOOP was also designed to accommodate different rig designs. Two rigs have proven the most successful. The first is a relatively standard sloop with a 15/16 fractional foretriangle as seen on MLC in Figure 4 and in the right drawing in Figure 5. The height of the mast was chosen so that the two-part mast, when disassembled, could be stored on

Fig. 4 Mid Life Crisis showing spade rudder design and racing sloop rig.

deck without overlapping the ends of the boat. The sloop rig is suitable for when the boat is used in competition as it provides higher boat speeds and allows the boat to point closer to the wind. The Aberystwyth University team used this rig to achieve third place in the 2013 SailBot competition. Although their rig was trouble-free, the multiple parts inherent in a stayed sloop rig will lead to lower reliability over a long period of time. The second rig is a smaller, lower-aspect ratio fixed gaff rig shown in the 1 and the left drawing in Figure 5. The lower portion of the mast is offset to reduce the sail's yaw moment, which results in lower energy consumed to trim the sail and reduced weather helm. The balanced rig was discussed in earlier IRSC papers [8, 12].

To achieve higher rig reliability three features must be factored in; fewer moving parts, fewer free edges and fewer point loads. To reduce the moving parts, a free-standing rig (without shrouds) is the best choice due to its few parts. A typical main sail has three edges, the luff, which is attached to the mast, the foot, which is attached to the boom, and the leech, which is a free edge. Most sail damage occurs along the free edges due to the higher stress resulting from large movements during luffing. Point loads on sails occur when the sails are attached via grommets or webbed straps, rather than a boltrope or sleeve. The point loads can easily overload the local material and cause failure.

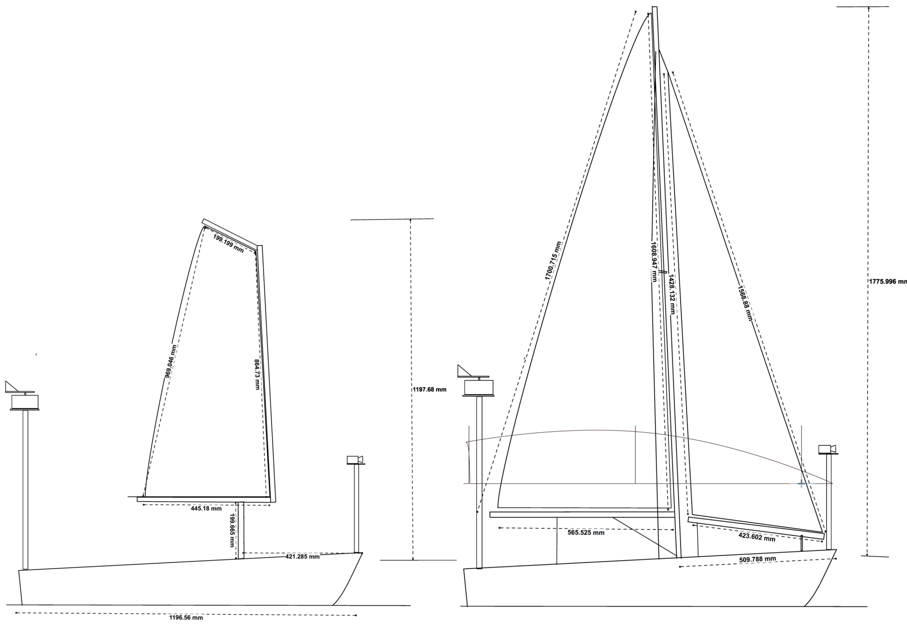

Fig. 5 Racing sloop rig (left) and free standing, rotating balanced gaff rig (right).

2 Sail Tests

To determine the relative efficiency and reliability of different free-standing rigs for the MaxiMOOP, a MaxiMOOP was built as a rig test platform. MLC (Figure 4) has multiple mast step tubes to accommodate 14 different mast positions, corresponding to everything from a stayed sloop to very low aspect ratio freestanding sails. Midshipman Padraig O'Brien compared results from the PCSail Velocity Prediction Program (VPP) [7] to on-the-water results for four rigs. The VPP takes the boat's physical characteristics, such as length, beam, displacement and sail dimensions and applies a wind velocity and relative direction as the input force and iteratively solves for the boat speed, heel and leeway. Based on the earlier work on route planning for the Microtransat [6], the rig tests focused on mostly sailing on a reach (close and broad) due to the expected conditions in a transatlantic crossing from west to east in winds of 8-30 knots. The four rigs all had $0.24\,\mathrm{m}^2$ of sail area and the height of the boom above the deck was constant at 125 mm. The maximum draft was 13% and the draft was located at 45%. The sail area selected was chosen as a compromise of minimal light air performance versus heavy air controllability. Figure 6 shows the four rigs, which included an aspect ratio (AR) of three and six Marconi (three sided) and gaff (four sided) rigs in the positions that gave neutral helm balance. In both rig types all the spars were joined together with fixed connections, increasing reliability but potentially sacrificing some performance. Unlike the gaff rig shown in Figure

6, these rigs were not self-balanced in order to reduce construction complexity and time. The figure also shows the boom overlap with the solar panel, an important consideration in solar charging.

Fig. 6 Four tested rigs: Marconi (AR=3), Marconi (AR=6), gaff (AR=3), gaff (AR=6)

Figures 7 shows the results from the VPP and multiple on the water tests normalized to the seconds required to sail one nautical mile with a wind speed of nine knots. The course sailed in both prediction and on-the-water cases was a combined close and broad reach. While the VPP favours high-aspect ratio sails over low-aspect ratio sails due to their greater upwind efficiency, the on-the-water (OTW) tests showed the low-aspect ratio sails performed better. The reason for this was that the very small size of the MaxiMOOP results in large amounts of rolling, causing greater apparent wind shifts, which the low aspect-ratio sails are more foregiving of. The VPP also favoured Marconi over gaff rigs. This was not seen on the water possibly because the fixed gaff controls twist more effectively than the rotating gaff normally used. The overall speeds seen on the water were also much higher than predicted by the VPP. This is not uncommon for VPPs, which are generally considered more accurate for relative performance than absolute.

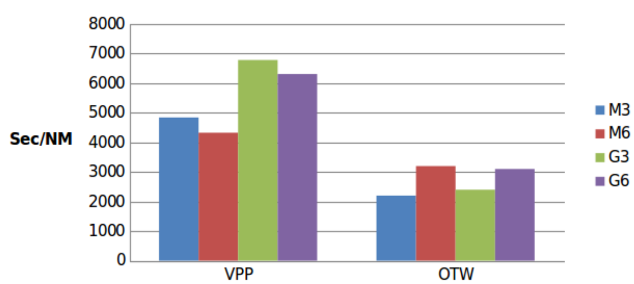

Fig. 7 VPP and on-the-water results for the four rigs.

The final rig selected for the voyaging boat was the AR=3 gaff rig. It showed nearly the performance as the Marconi rig and had a shorter boom, which was desirable as it would not cover the aft solar panel as much. Using the racing rig and with a low centre of gravity consistent with participating in the SailBot competition, the VPP results are shown in Figure 8 and show a top speed of three knots while running in 20 knots of breeze. In comparison, with the smaller sail and higher centre of gravity and displacement consistent with ocean voyaging, the performance is noticeably less, as seen in Figure 9. Convergence was not reached with the VPP in winds of less than 11 knots for this case.

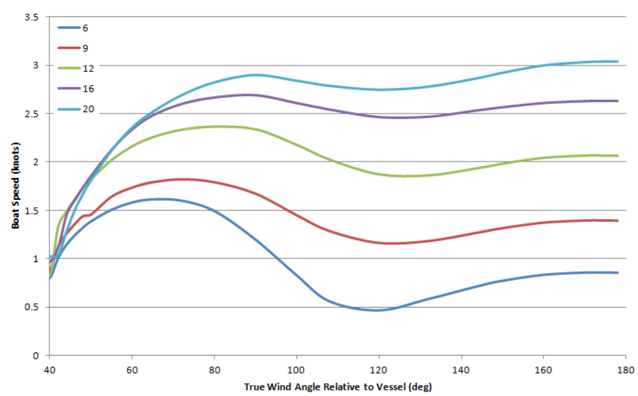

Fig. 8 Predicted MaxiMOOP performance versus wind angle in wind speeds of 6 to 20 knots with the $1.0\,\mathrm{m}^2$ racing rig, lower centre of gravity and 16 kg displacement.

3 Energy balance

A challenge with all vessels is power management at sea. In the case of sail-powered ASVs, while the main propulsion system uses the wind, the computers, rudder and sail winch need power. For the small vessels such as the MaxiMOOP, the ability to be self-sustaining offshore is a practical requirement. Initial work was carried out in 2012 [8], which showed the solar panels mounted on the ASVs produced about 13-27% of their rated capacity. Two experiments were run by Midshipman Chris Hein, testing whether the relative angle of the panel to the deck was significant and whether a newer model of marine solar panel by Boulder produced higher output. The first test varied the angle of the panel relative to the deck. As the course from North America to Europe is a relatively constant course, with the wind mostly from one direction, the question was raised whether some tilt angle other than flat was optimum. For the mid-latitude of the course track and using a standard solar tilt equation, the optimum tilt would be 24 degrees from horizontal, pointing south. As the vessel was expected to heel an average of 15 degrees to port, the theoretical best angle would be 39 degrees from the deck. Two experiments were conducted; the

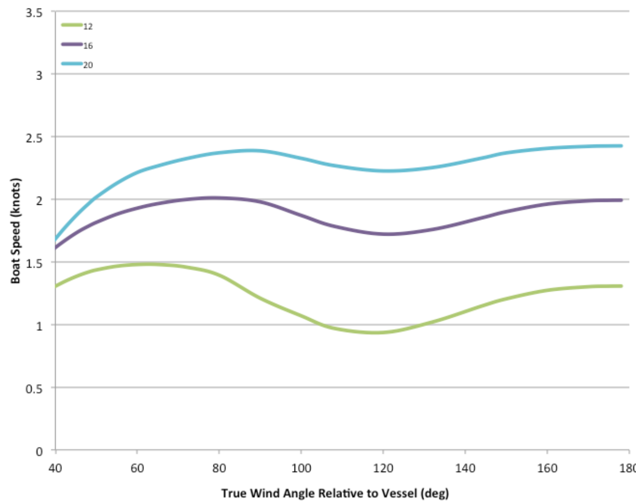

Fig. 9 Predicted MaxiMOOP performance versus wind angle in wind speeds of 6 to 20 knots with the 0.24 m^2 voyaging sail and higher centre of gravity and 20.5 kg displacement.

first on shore and the second on MLC while sailing a relatively constant course. The tilt angle varied from zero to sixty degrees. The total energy produced was measured using a WattsUp watt-meter. The mean value was 63% of the panel's rated output with an 8% coefficient of variation. No discernible trend was seen however based on the tilt angle. On the water tests also did not show a discernible trend in tilt angle, but the amount produced was roughly 42% of the rated output, which was nearly double the output of the panels tested in 2012. The doubled output of energy collection likely resulted from the combination of Boulder solar panel and the addition of a Maximum PowerPoint Controller (MPPT) device put inline between the solar panel and the battery. The MPPT better matches the battery draw conditions to the solar panel given the current efficiency of the panel at any given time. The MPPT used was purchased from Genasun LLC in Cambrige, Massachusetts, USA and was specifically designed to work with our LiFePO4 4-cell battery.

After factoring size and weight of solar panels, it is clear lower voltages are more efficient to produce energy with current solar technologies. In order to minimize power requirement's, two independent power systems were installed on A Boat Time. All electronic sensing and decision making devices were powered by a nominal voltage of 3.7 volts and a 6 volt rated solar charging system. In order to keep the current consumption low, the actuator motors were run on a different power system with a nominal voltage of 14.2 volts, which was paired with the charging system Midshipman Hein tested.

4 Control System Design

A variety of control system architectures have been developed for sail-powered ASVs, ranging from single low power microcontroller systems [5, 4] to FPGAs [2] and single board computers [11, 10, 9, 3]. Each of these brings a different set of trade-offs between power consumption, computing power, ease of use and reconfigurability. A single microcontroller system is most suited to longer term low power operations but this comes at the expense of the ease of development and testing or the ability to execute more complex algorithms. In Dewi, which has been built for short races lasting at most a few hours, a Raspberry Pi single board computer has been used together with an Arduino Uno microcontroller. The Raspberry Pi is responsible for high level control decisions, logging and sending telemetry data over WiFi or an XBee Pro radio modem. The Arduino is connected directly to the servos, compass and wind sensor, with a series of simple commands issued by the Raspberry Pi either requesting data or sending positions to these. This split architecture sees the timing critical code such as reading the PWM wind sensor and controlling the servos moved to the Arduino while the bulk of the code is run on the Raspberry Pi using the Raspbian Linux distribution. The presence of a full operating system greatly simplifies the development and testing of control system code, makes performing “over the air” code updates easy, allows threading/locking or concurrent processes and allows logfiles to be easily stored and accessed.

Similar to the control design and testing in Dewi, AT system development started with a Raspberry Pi and Arduino combination. Uniquely, a combination of Arduino boards were used for sensing, actuator control and decision making processes. Due to the Pis relatively higher energy consumption it was used for remote interaction with the Arduino for troubleshooting, with the intended purpose to remove the Pi for the actual transatlantic launch. The primary controller on AT is a 3.3V Mega Pro running at 8 MHz Atmel 8-bit microcontroller provided by Sparkfun Electronics in Boulder, Colorado, USA. The system takes data in from a GPS device with a helical antenna allowing for greater reception in moving seas, a tilt compensated compass (running its own configurable microprocessor), and an IP67 industrial rated hall effect potentiometer for the wind sensor, located on a separate stern mounted mast. In order to improve survivability of the wind sensor, an industrial grade sensor was chosen. Sensitivity was sacrificed due to greater friction in the devises bearings. This friction was overcome by increasing the moment of inertia of the wind sensor by increasing its length. An additional logging device was added that received serial signals from the main microprocessor and writing it to a miniSD card. An independent satellite tracking devise was installed to monitor the performance of A Boat Time while in the ocean. The tracker was installed separate and independent of any other system to increase its survivability probability. The combination of all these components led to an average power consumption of approximately 50mA. System survivability was a key addition for the A Boat Times system design. Two GPS and Compass systems were installed and coded to act as fall back redundant systems by Midshipmen Kevin Flaherty and Aaron Dougherty. Additionally, wind sensor performance was tracked by the system and if a failure was identified, follow on conditions for sail trim and steering were used to maximize the ability for A Boat Time to reach its desired location.

Morwyn has been designed for long distance voyaging and power consumption is a key concern in extending endurance. Her target power budget is 1 W average, although this has not yet been confirmed under real world conditions. If this is achieved then working on a conservative figure of 10% average efficiency, a 10-15 Wpeak solar panel should be sufficient to power her. She uses two Olimexino 32U4 boards, these were selected for their very low power consumption of approximately 20 mA when active and less than 1 mA in sleep mode. One of these is responsible for controlling the sail and rudder actuators, reading the GPS, compass and wind sensor. The other is responsible for logging data to an SD card and transmitting it via a RockBlock Iridium satellite transceiver. The control system board periodically sends data via an I2C bus to the other board, which wakes from its sleep mode, records the data and if enough time has elapsed sends a message via Iridium. The Iridium messages contain a summary of the compass heading, roll and pitch angles, battery voltages and currents since the last message. It also sends the current location, waypoint data and temperature. This design keeps the communications/logging board in sleep mode most of the time, the non time deterministic and blocking operation of sending Iridium messages is also moved away from the critical control system simplifying concurrency and ensuring that the control system does not freeze or stop due to problems with the communications system.

5 Sea Trials

The versatility of the MaxiMOOP design is illustrated by the variety of tasks accomplished so far. Dewi successfully competed in the 2013 SailBot competition and completed all events, including a 6 hour long triangular course for the long distance event. Figure 10 shows the route taken by Dewi at the 2013 SailBot competition. This race took place on June 13th 2013 in Gloucester, Massachusetts, USA. Conditions were quite challenging for a small boat, with the wind blowing at 15-20 kts from the North West and with wave heights of around 50-75 cm. In this figure it can be seen that during the upwind legs of the course an average speed of 1 knot was achieved, while on the downwind leg a speed of between 1.5 and 2 kts was achieved. In addition to Dewi's successful participation in the 2013 SailBot competition and Morwyn's experiments in Wales, MLC has served as a successful test platform for a variety of experiments.

From May 16th-22nd 2014 AT attempted a transatlantic voyage from Cape Cod, Massachusetts to Fenit, Ireland. The voyage ended early when she was accidentally caught in a scallop dragger's net and hauled aboard, during which her aft solar panel was damaged. During her 220 NM voyage she saw winds to 35 knots and seas to 20 feet along with two days of calm winds and fog. This exceeded the previous Microtransat record of 123 NM set by Breizh Spirit DCNS in 2012 [1]. Figure 11

Fig. 10 A map showing the speed of Dewi during the triangular long distance course at the 2013 SailBot competition.

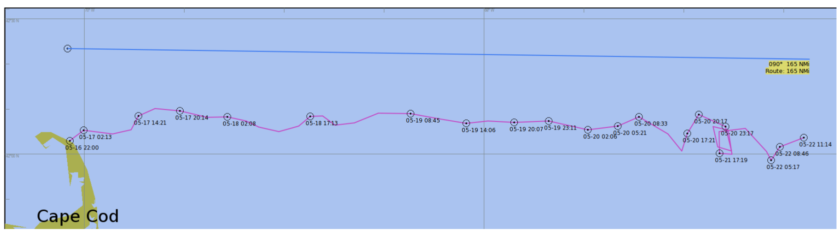

Fig. 11 A showing ABoat Time's route during her 2014 Microtransat attempt from Cape Cod, Massachusetts to Fenit, Ireland. The blue line indicates a measurement of 165 nautical miles to the East of Cape Cod and the purple line represents the path followed by the boat. The text at each point indicates the date (MM-DD format) and time (HH:MM format, in UTC) that the position report was transmitted.

shows her track and figure 12 is a picture taken on board the dragger. The crew reported she was sailing well at the time and when opened she was dry inside.

A similar fate is believed to have been suffered by at least two previous Microtransat entries (Breizh Spirit DCNS in 2012 and Erwan 1 in 2013) and highlights the need for path planning away from fishing areas, mechanisms to make sailing robots easily detectable and autonomous collision avoidance strategies.

6 Future Work

While the MaxiMOOP design has fulfilled its goals, it too can be improved. The keel is not as streamlined as it could be and stability is limited due to the relatively shallow draft. This was particularly evident when multiple pieces of equipment were mounted on the deck. Based on observation of the boat while sailing, a little more freeboard would also be beneficial. A hypothetical second-generation MaxiMOOP,

Fig. 12 ABoat Time on board the M/V Atlantic Destiny. Her damaged solar panel is evident and the taped-over wind indicator was necessary to stop her sail and rudder from adjusting when she was hauled aboard.

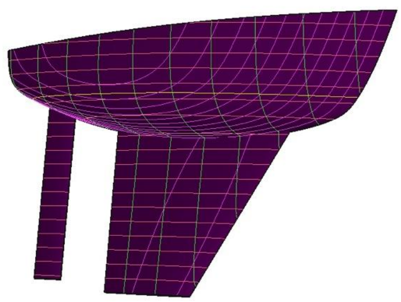

Fig. 13 Proposed lines of an improved MaxiMOOP.

including all the original characteristics but with some improvements, including 75 mm more draft and 10 mm more freeboard is shown in Figure 13. The newer model also has added volume for an additional 2 kg of payload. The VPP indicated a roughly 4-9% performance improvement in the voyaging condition. To date the MaxiMOOPs effectiveness as an oceanographic sensing platform has not been tested, although a salinity probe and water temperature sensor have been installed in the keel of Morwyn.

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