MAYFLOWER AUTONOMOUS SHIP

BUILDING THE WORLD'S FIRST FULLY AUTONOMOUS RESEARCH SHIP

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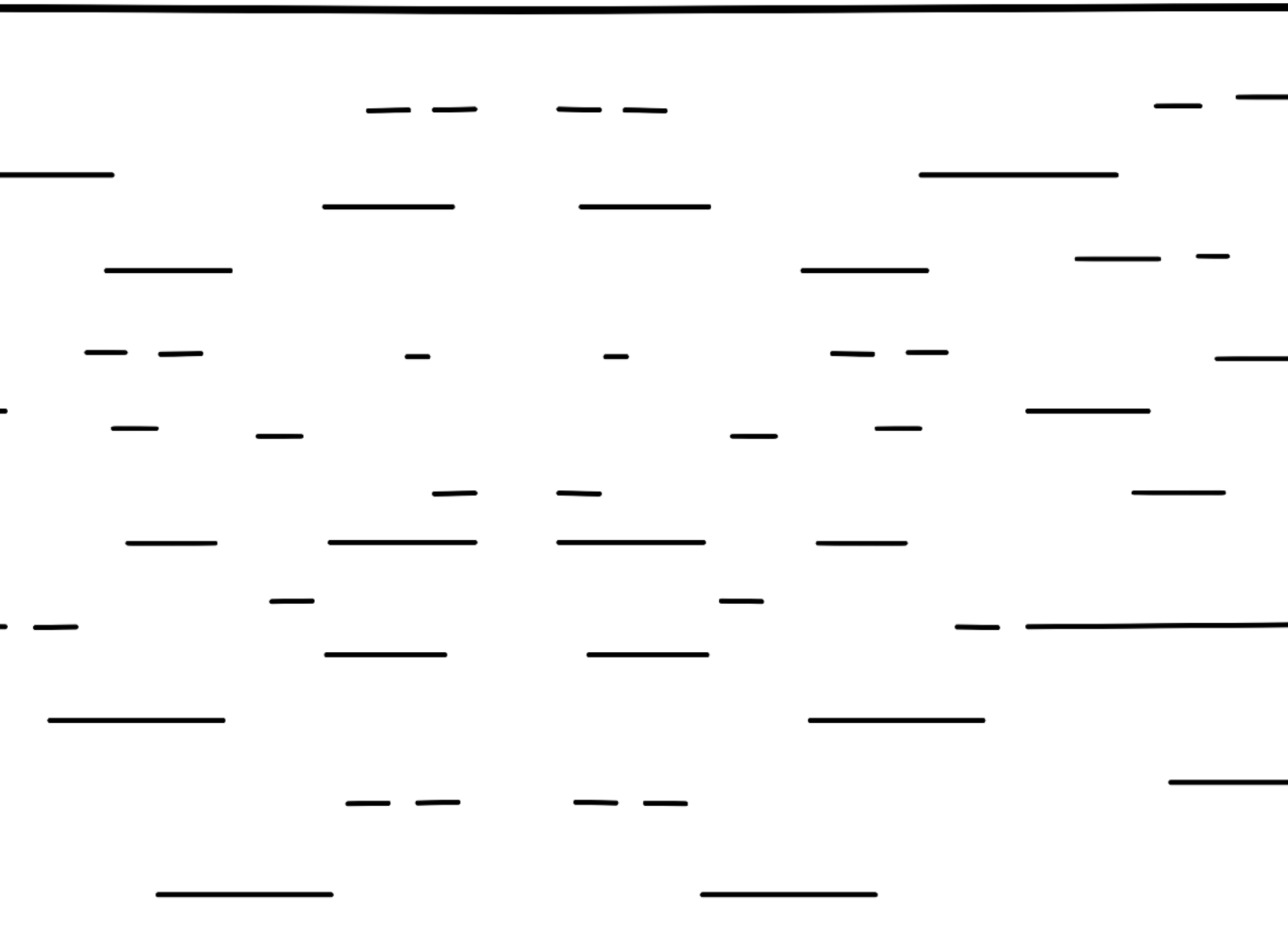

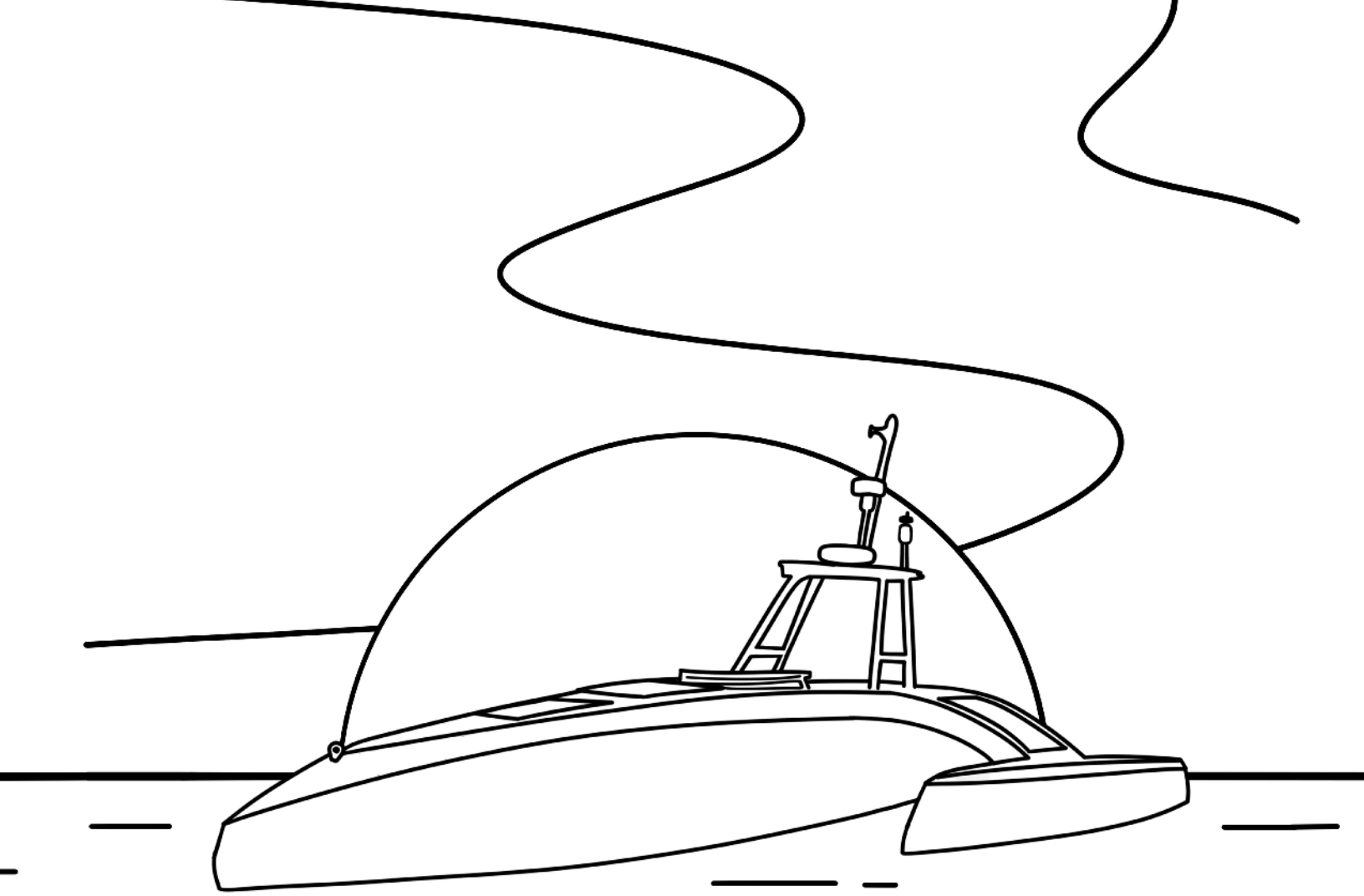

Mayflower Autonomous Ship

Dedication

To our team who worked so diligently on the pioneering Mayflower Autonomous Ship project over the many years that it took to accomplish.

About the authors

Fredrik Søreide is a founding board member of ProMare and co-director of the Mayflower Autonomous Ship project.

David LaFontaine is a Lead UX Designer, author, and video host, whose work can be found at DavidLaFontaine.com.

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For more information and to follow the Mayflower Autonomous Ship on its future endeavors, please check out our websites at:
www.promare.org
www.mas400.com

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FOREWORD

We established ProMare in 2001 to promote marine research and exploration throughout the world.

ProMare is a non-profit corporation and public charity: 501(c)(3).

For the past 20 years, our team of experienced archaeologists and marine professionals have executed a variety of research projects—both independently and in concert with academic, corporate, public, and governmental organizations and agencies—that are designed to advance humanity's knowledge of history and science.

The Mayflower Autonomous Ship (MAS) has been our most challenging project to date. The trimaran hull form design ensures high levels of hydro- and aerodynamics. Waterproof solar panels fitted to its upper surface enable it to draw on energy from the sun whenever possible, with a modern, high-efficiency generator acting as a backup in case solar power is in low supply.

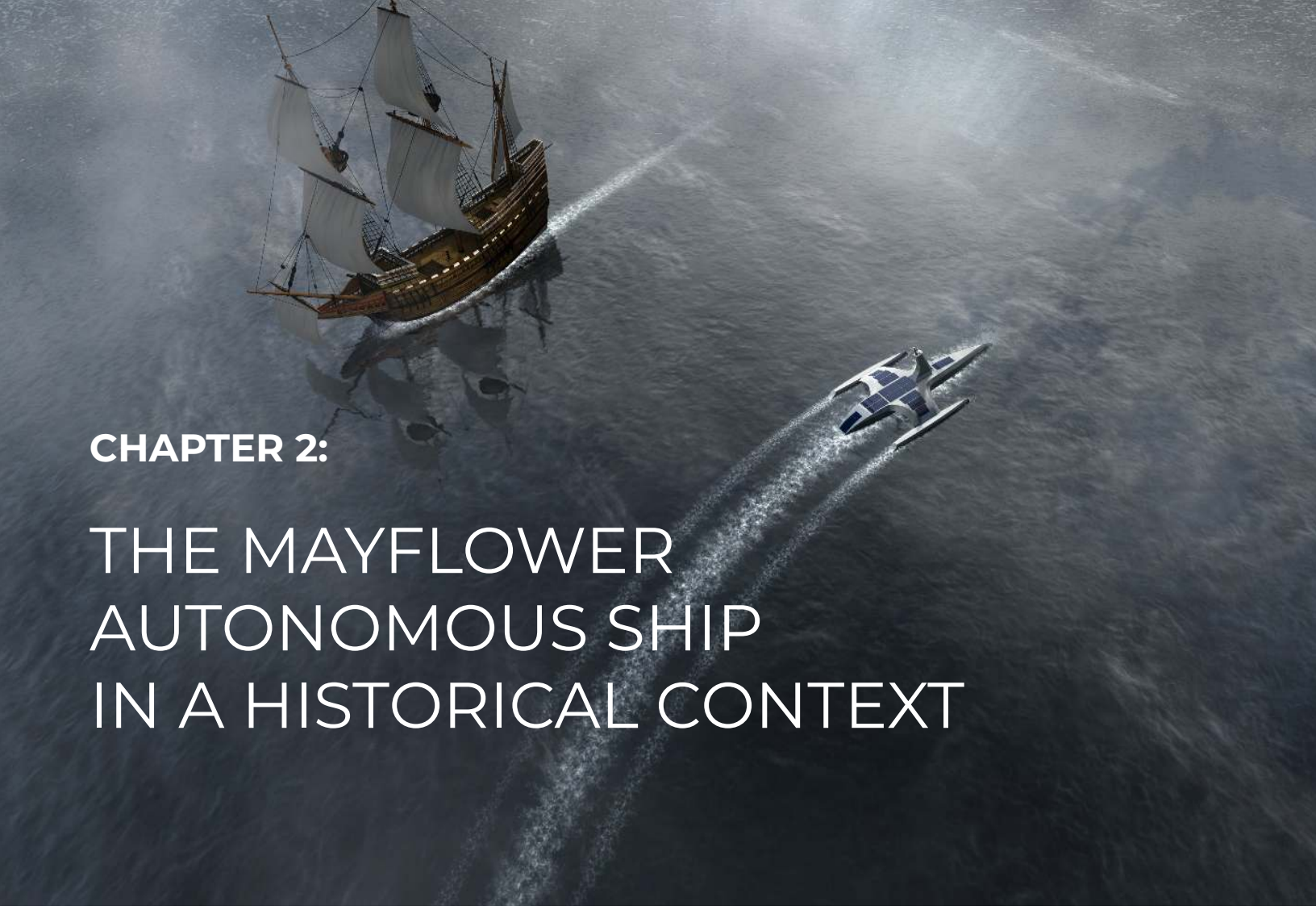
The ship has many safeguards built into it, meaning that its systems are both isolated and duplicated, in order to reduce the chance of a single-point failure.

Rather than mindlessly following a pre-charted course, the AI Captain evaluates all available data and constantly updates the ship's route and speed, second by second.

As we continue to explore the oceans, our vision is for humans and machines to continue to work in tandem, using agile, intelligent, and autonomous solutions to augment and extend people's capabilities. It is smart tech at its finest.

Brett A. Phaneuf, Gregory M. Cook, and Fredrik Søreide

Photo courtesy of ProMare/IBM.



CHAPTER 2:

THE MAYFLOWER AUTONOMOUS SHIP IN A HISTORICAL CONTEXT

(Above) The historical *Mayflower* sails opposite the modern Mayflower Autonomous Ship (MAS), in a digital creation courtesy of IBM.

(Facing page top) An oil painting of the original *Mayflower* by Julie Hammond, a Plymouth, UK-based artist.

Image courtesy of Julie Hammond.

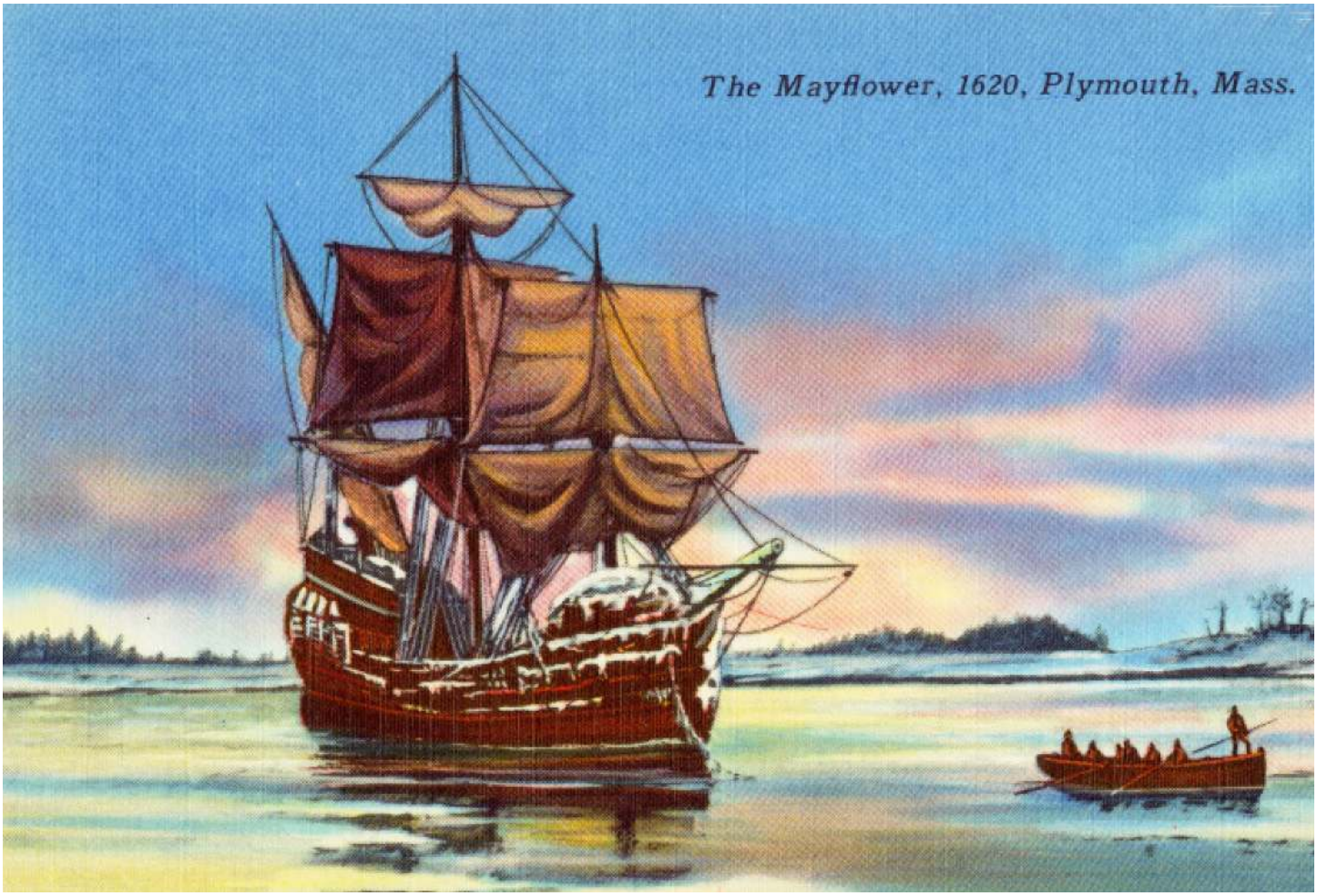
(Facing page middle) A postcard created to commemorate the *Mayflower*'s arrival in Plymouth, Massachusetts, USA.

Images courtesy of Wikimedia, Public Domain license.

The original *Mayflower* was 27.4 meters (90 ft) long, 7.3 meters (24 ft) wide, and weighed about 180 tons. She was built in Harwich, England in around 1609, and was normally used to transport cargo such as wine, cloth, and lumber.

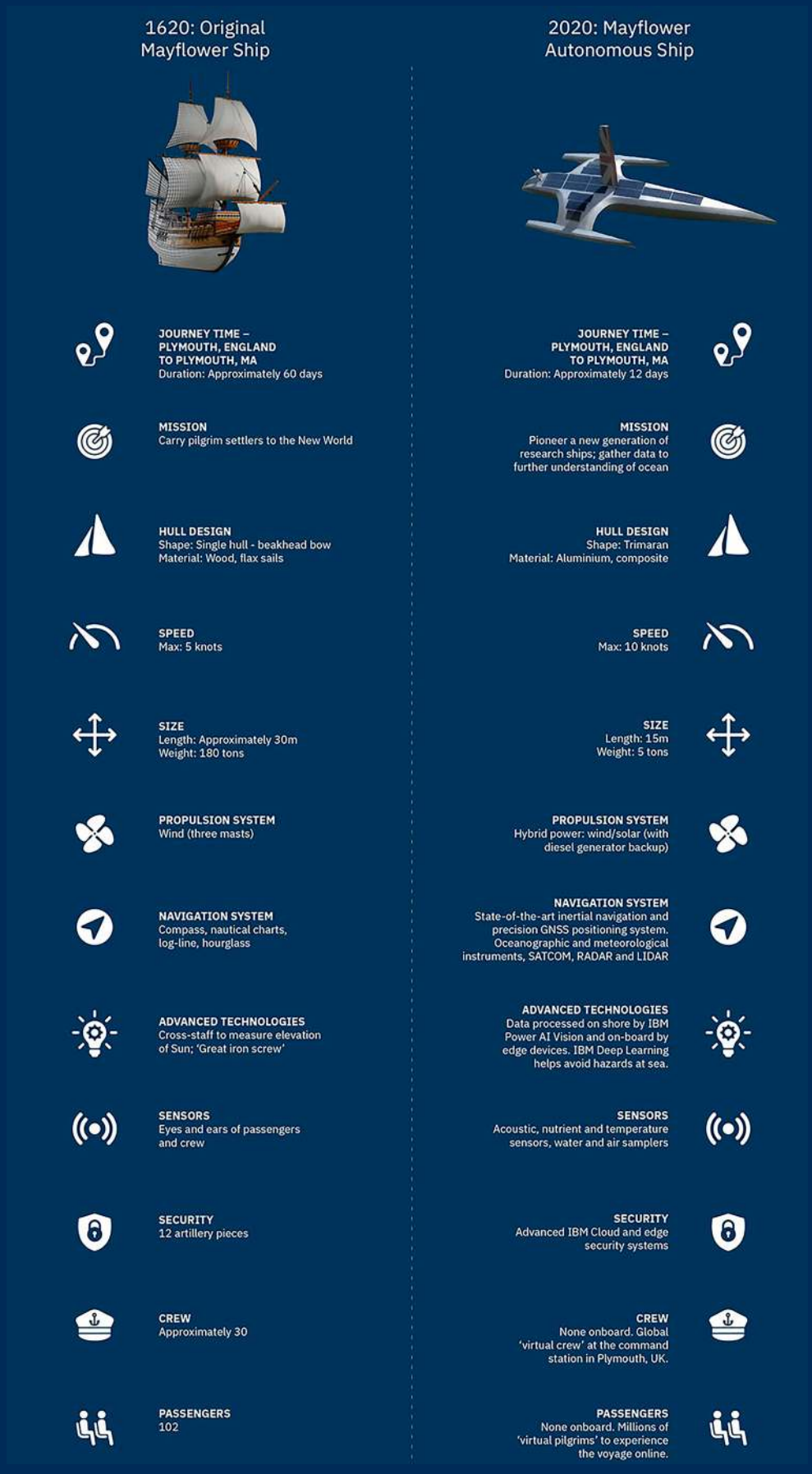
The design of the *Mayflower* is called "Dutch fluyt." It is not considered especially elegant—it was the equivalent of a removals van; not fast, maneuverable, pretty, or fun to drive, but capable of conveying a large quantity of goods cheaply from one place to another. Its sole standout feature was that in 1620 it was used to carry the so-called "Pilgrims" to America.

The *Mayflower* was initially accompanied by another ship, the *Speedwell*, but after putting out into the Atlantic twice, the latter started leaking badly and had to turn back. Some of the Pilgrims muttered that they thought that the crew of the *Speedwell* had deliberately sabotaged their ship in order to avoid having to make the trip to America. Whether or not this was true, ultimately, the *Speedwell* passengers simply jumped ship and crammed themselves aboard the *Mayflower*.



When the *Mayflower* finally set sail on its famous solo voyage there were 102 passengers and at least 30 crew on board. Of the 74 male and 28 female passengers, 19 were servants and 30 were children. Just 46 of these people identified as religious “Separatists.” The rest were attempting the risky voyage for a variety of commercial purposes, having been sent by companies in London and Plymouth to establish settlements in the New World, to serve as both trade outposts and taxable entities for the English Crown. It is interesting to note that “Pilgrims” is a label that only started being applied to all the passengers of the *Mayflower* in about 1800—180 years after the ship landed in America. Back in 1620, the Separatists instead referred to themselves as “Saints” and were fleeing first Holland and then England because neither country welcomed their particular version of ultra-strict and devout Protestantism.

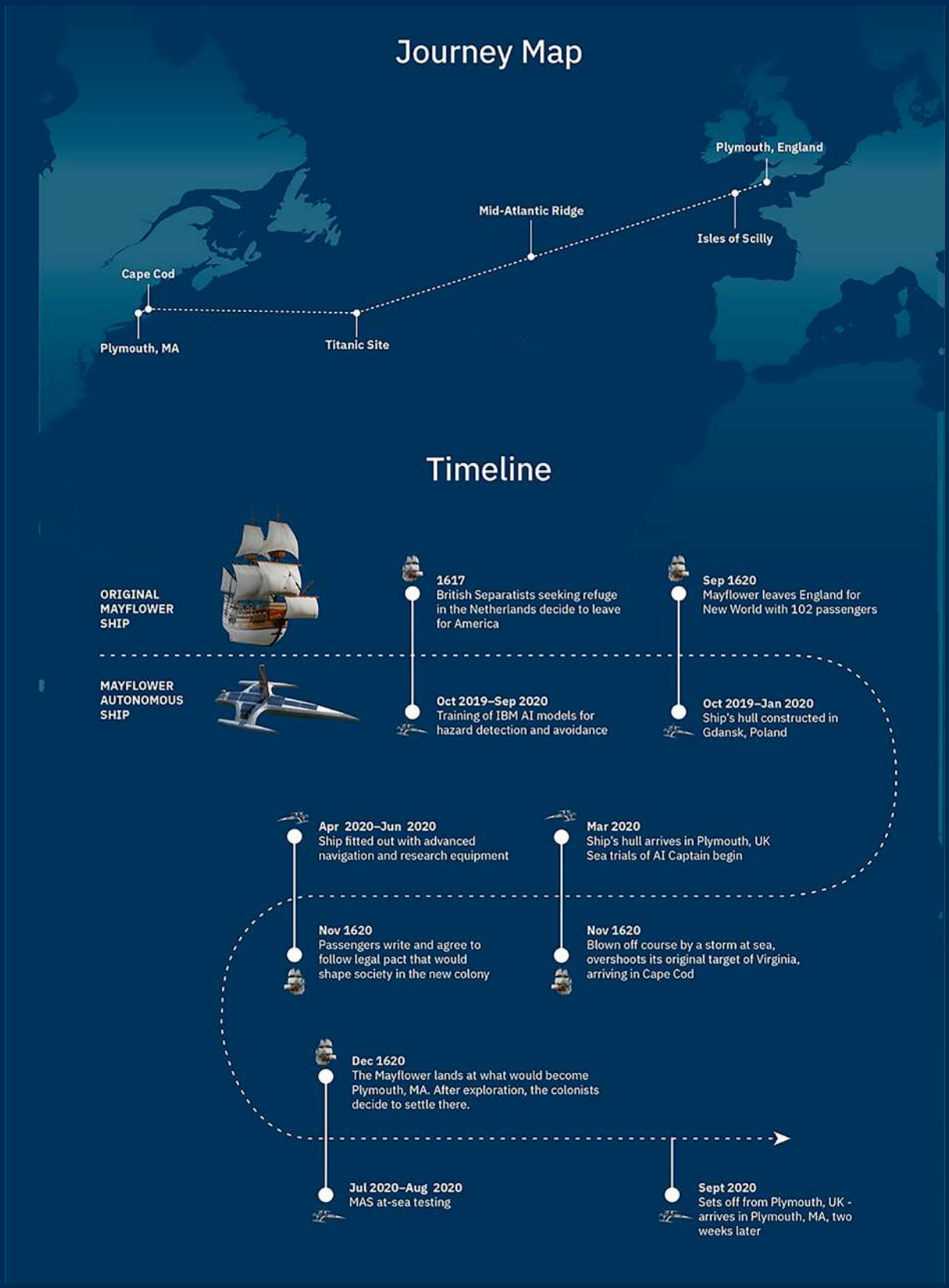
The original *Mayflower* vs. the MAS



An infographic created by IBM at the concept stage of the MAS project outlining the timeline and the original planned dates for the Atlantic crossing.

Image courtesy of IBM.

A side-by-side comparison



(Above) An oil painting of the original *Mayflower* sailing into some threatening weather.

Image courtesy of Julie Hammond.

It was September 16, 1620 when the *Mayflower* finally set out from Plymouth, England to cross the Atlantic. This was much later in the year than was originally planned, the voyage having been delayed by the issues with the *Speedwell*. Still, the first part of crossing was fairly pleasant, and the little *Mayflower* initially made good progress across the ocean. Then, predictably, fall storms blew in. It was reported that the waves reached 33 meters (100 ft) tall, with the wind coming from all directions. Everyone on board was so seasick they could barely move, and one young man was blown overboard. Not surprisingly, the *Mayflower* was blown way off course.

The ship eventually landed in Provincetown Harbor, Massachusetts (not Plymouth Rock, as was intended) on November 21, 1620. The vessel had attempted to make its way south to where it was supposed to be in Virginia but had run into shoals around Cape Cod. So, the passengers and crew were stuck in Provincetown for a desperate winter that was far colder than they had planned for. As a result, half of those on board starved, froze, or caught a disease and died.

The following year, the 53 people who had survived celebrated the colony's first fall harvest along with 90 Wampanoag Native American people—an occasion that in later centuries was declared as the first American Thanksgiving.

Despite its mishaps, as one of the earliest colonial vessels, the ship has since become a cultural icon in the history of the USA, with an enduring legacy. According to the General Society of Mayflower Descendants, there are now approximately 35 million *Mayflower* descendants in the world.

The ship itself sailed back to England in 1621, where it resumed hauling around cargoes of hats, hemp, vinegar, and herring until 1624. Historians quarrel about the fate of the ship at that point, with many claiming that it was broken up into weathered timbers and refashioned into a barn in Buckinghamshire, England. This later became a tourist attraction.

(Above) A replica of the original *Mayflower* is a tourist attraction in Plymouth, Massachusetts, although purists sometimes argue that this ship, built with modern methods and materials, is in far better shape than the original *Mayflower* ever was.

Photo courtesy of Wikimedia, Public Domain license.

(Left) The "Mayflower Barn" in the Chiltern hills, near the village of Jordans in Buckinghamshire, England. The barn was possibly built using the timbers of the *Mayflower*, purchased for £50 from a shipbreaker's yard in Rotherhithe, London.

Photo © Nigel Cox and licensed for reuse under creativecommons.org

CHAPTER 3:

DESIGNING THE MAYFLOWER AUTONOMOUS SHIP

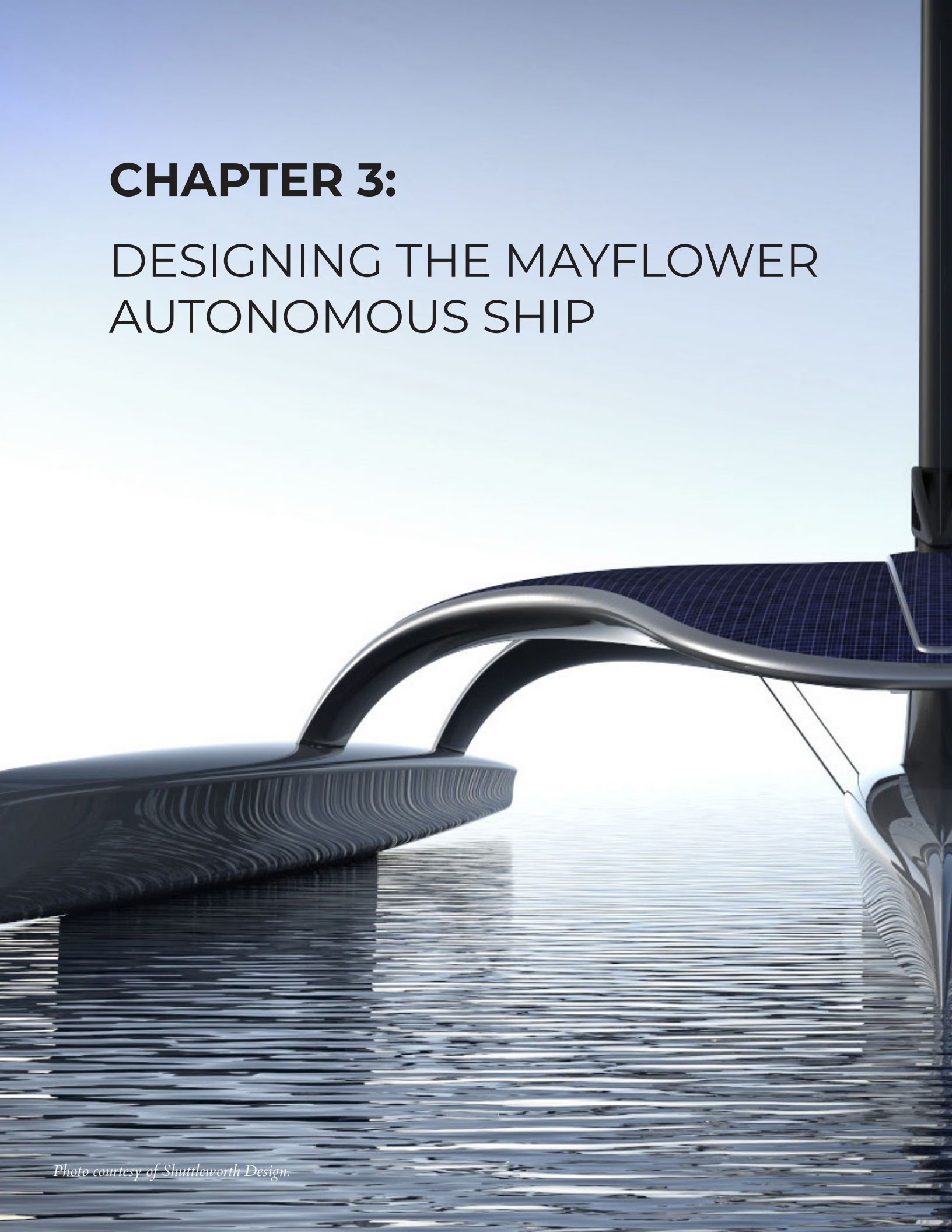
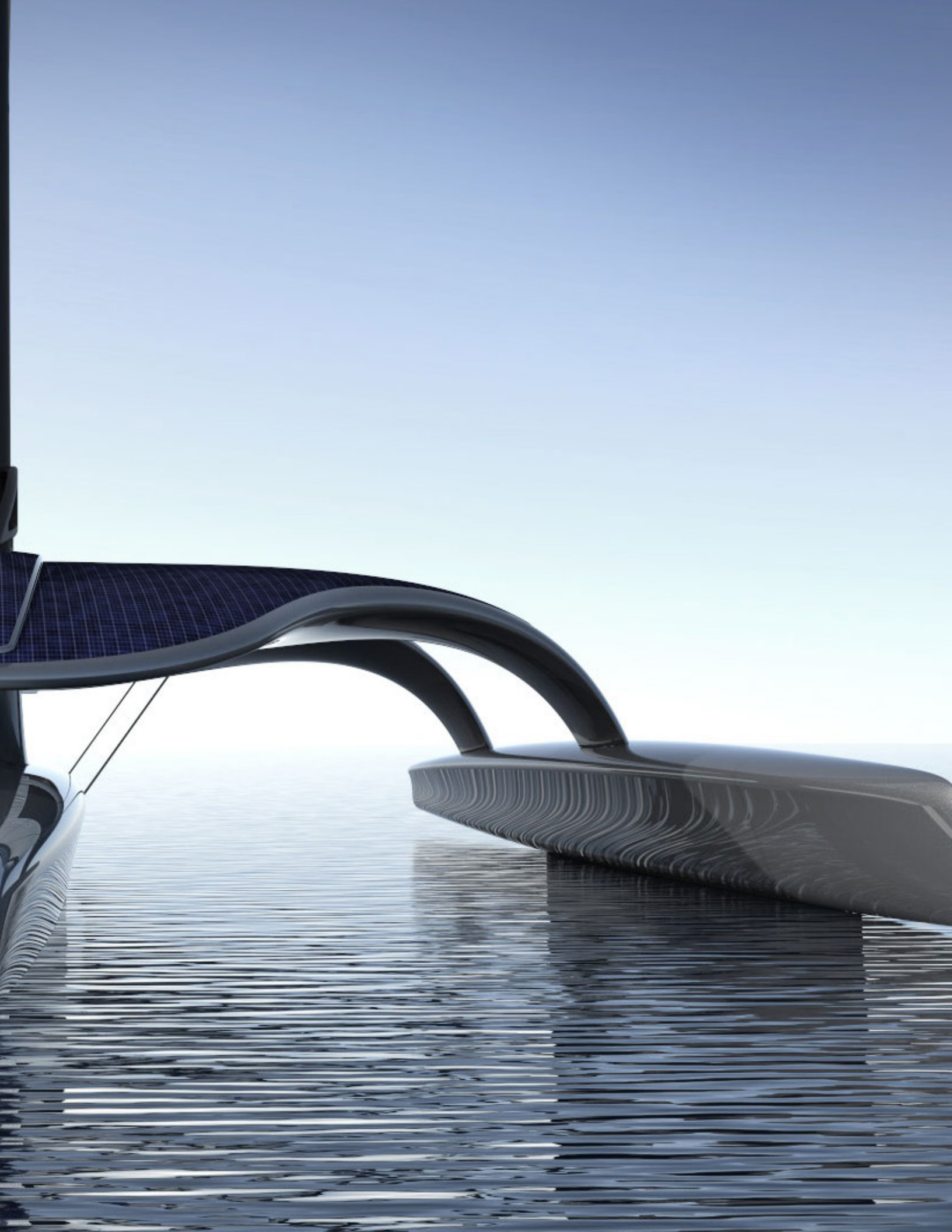
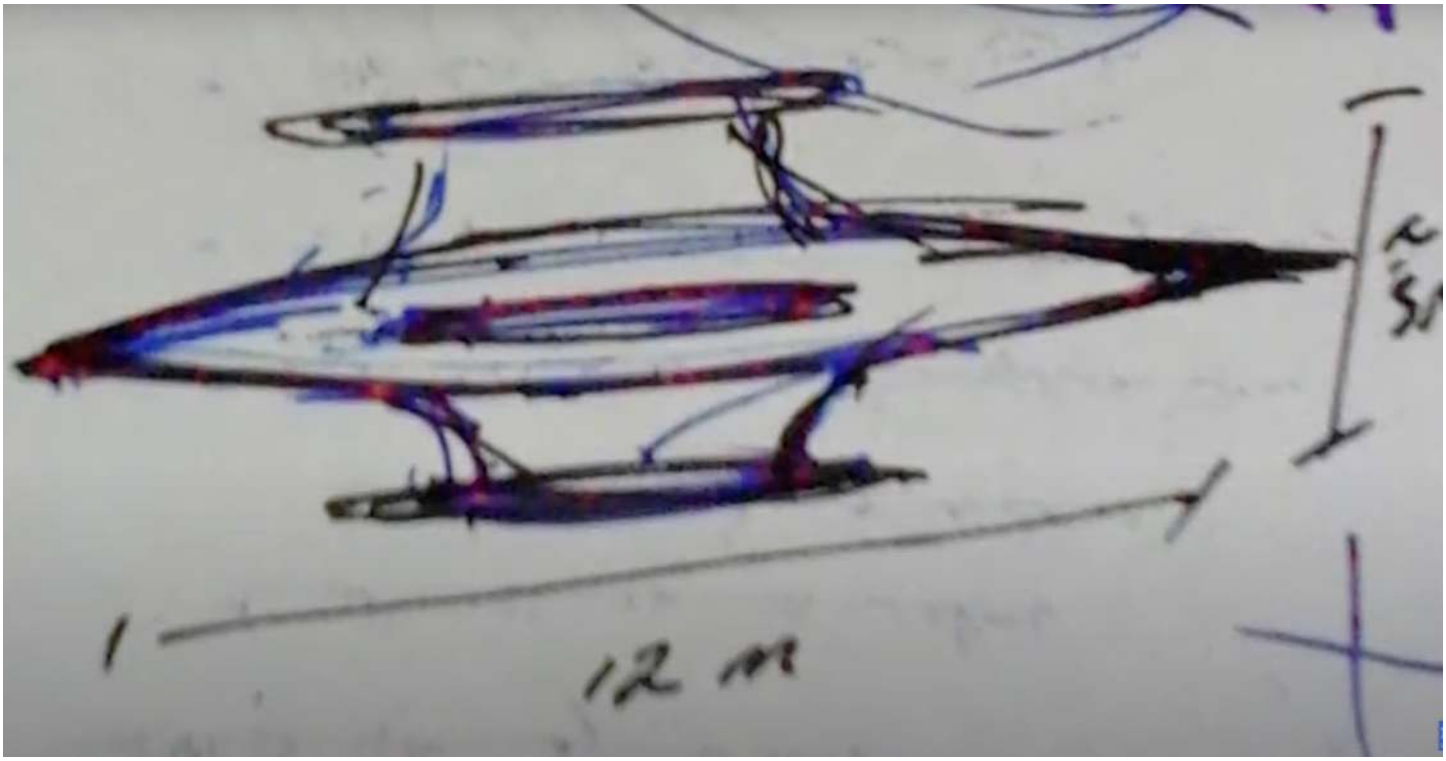


Photo courtesy of Shuttleworth Design.

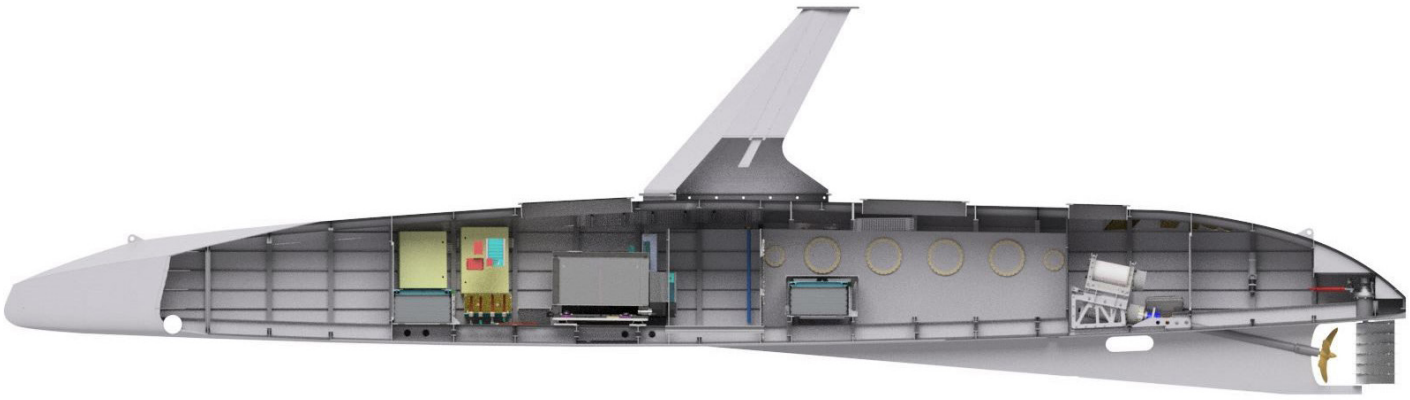


In 2016, Brett was invited to a meeting to discuss how to recognize the 400th anniversary of the 1620 *Mayflower* voyage. The primary idea was to build another replica of the ship. Brett did not support this. Instead, he suggested doing something bold, courageous, and new: building a *Mayflower* for the 21st century. And so, the Mayflower Autonomous Ship was born.



From this unique starting point, the details of this ProMare project became clear: The development of an unmanned research vessel that would offer a flexible, cost-effective, and safe option for gathering critical data about the ocean.

ProMare contracted Shuttleworth Design, a multi-award-winning design consultancy that has been working at the forefront of yacht design, engineering, and naval architecture with an international client base for more than 40 years.



They created the concept designs for a 33-meter (100-ft)-long trimaran sailing vessel that was designed to be built using carbon fiber. In a press release, Shuttleworth Design stated: “Our approach to developing the concept was to fully explore and take advantage of the opportunities that arise from not having to carry crew, and to create a vessel that is capable of using only renewable energy.”

This initial design really set the stage for the MAS. However, the cost of building the ship to this spec was too high for ProMare’s budget. The carbon fiber hull alone was projected to cost more than £7 million. Plymouth-based firm MSubs was therefore brought in, together with local naval architects Whiskerstay, to simplify the design.

(Facing page, from top) The MAS started as a napkin sketch by Brett Phaneuf, before becoming more defined. *Illustrations courtesy of ProMare/IBM.*

(This page) As the MAS evolved, 3D renderings were created to help designers envision where to place the engines, science gear, batteries, sensors, communications equipment, and most importantly, the AI “brain” that runs the ship.
Image courtesy of MSubs.

The ship was duly reduced to half the size, and the hull material was changed to aluminum. The complicated sail array was replaced by a mast for instruments, sensors, and navigation lights, and a small diesel generator was built in to support the solar panels and generate enough power for the long journey. A payload bay was included, from which the onboard science experiments would be carried out.

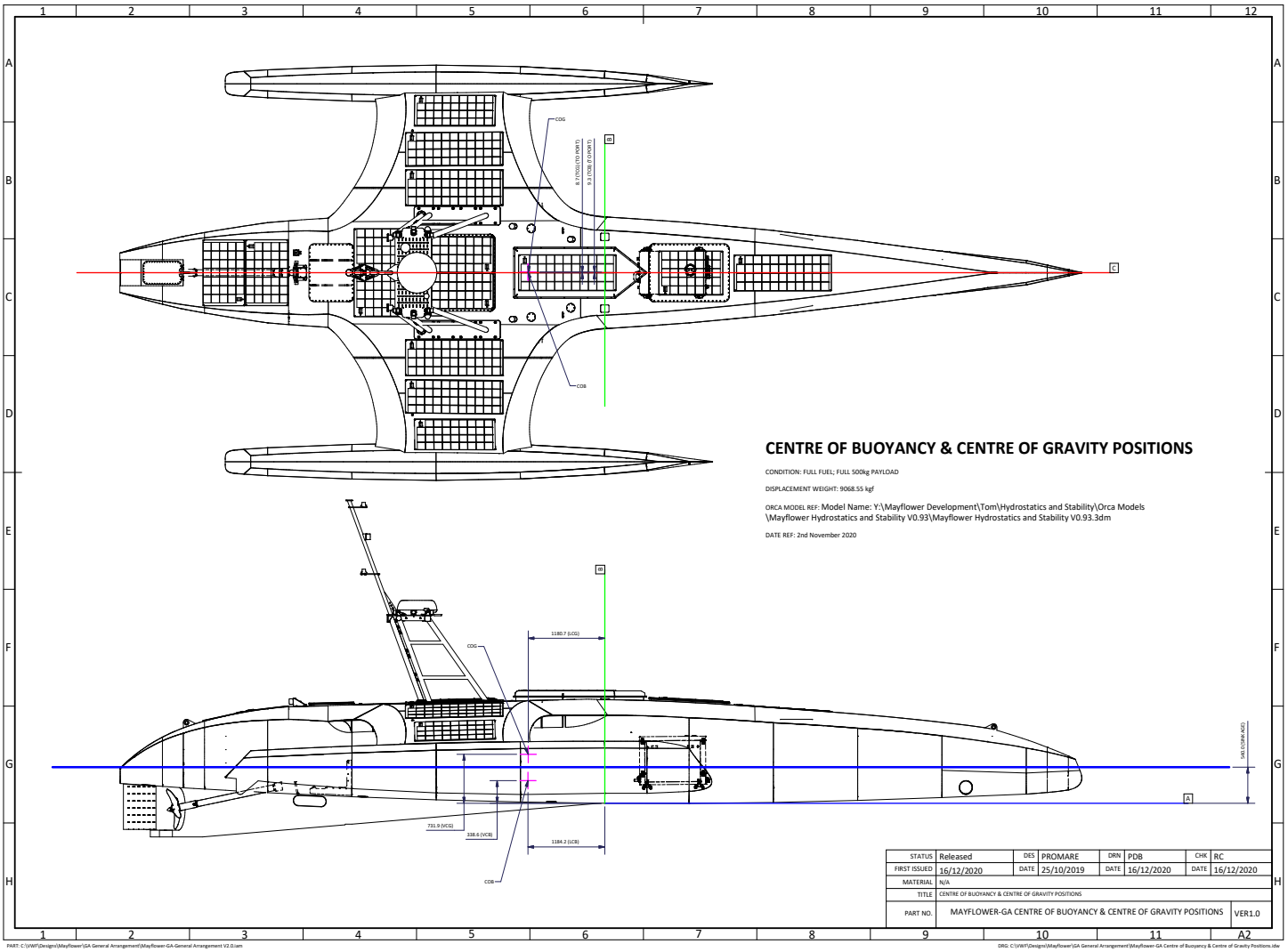


Photo courtesy of ProMare/IBM

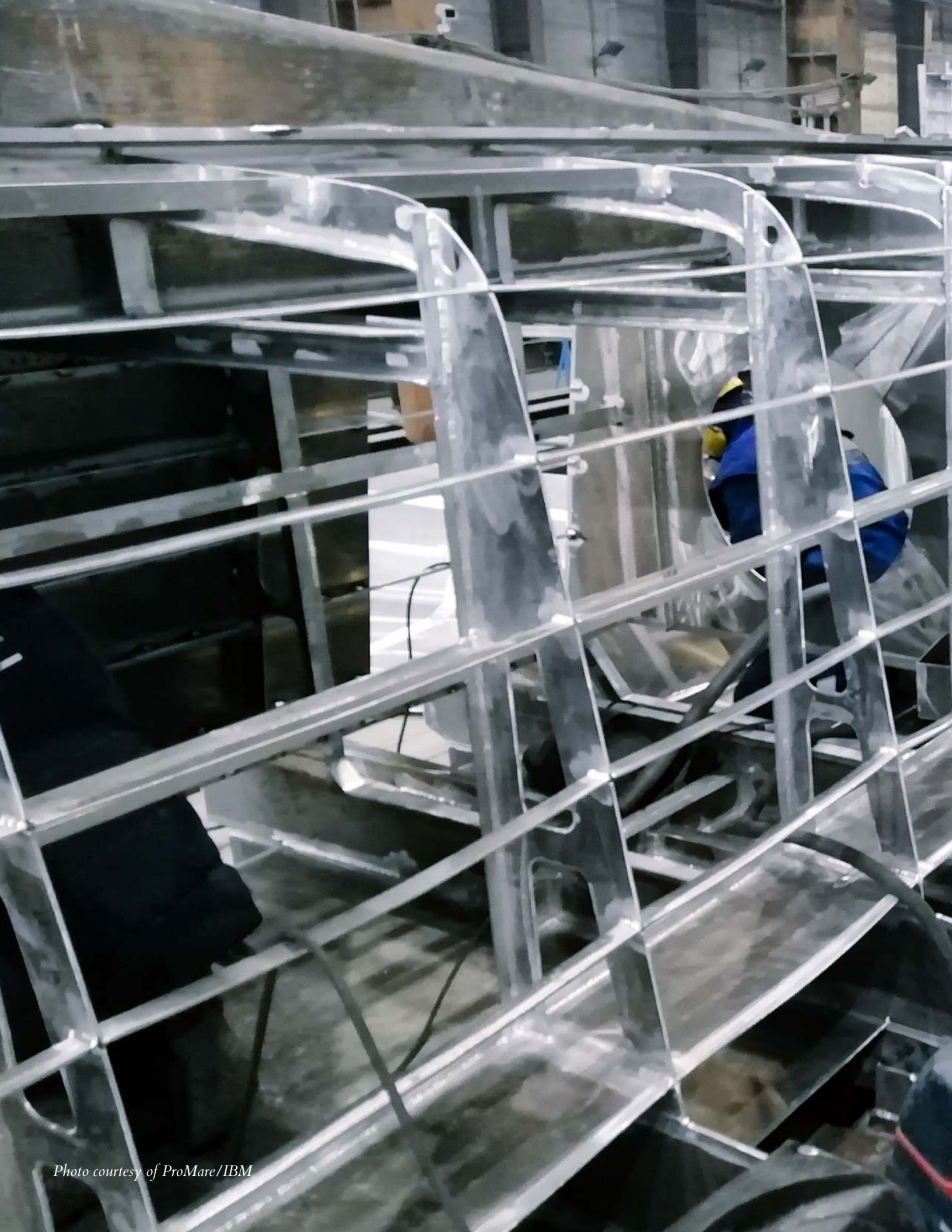
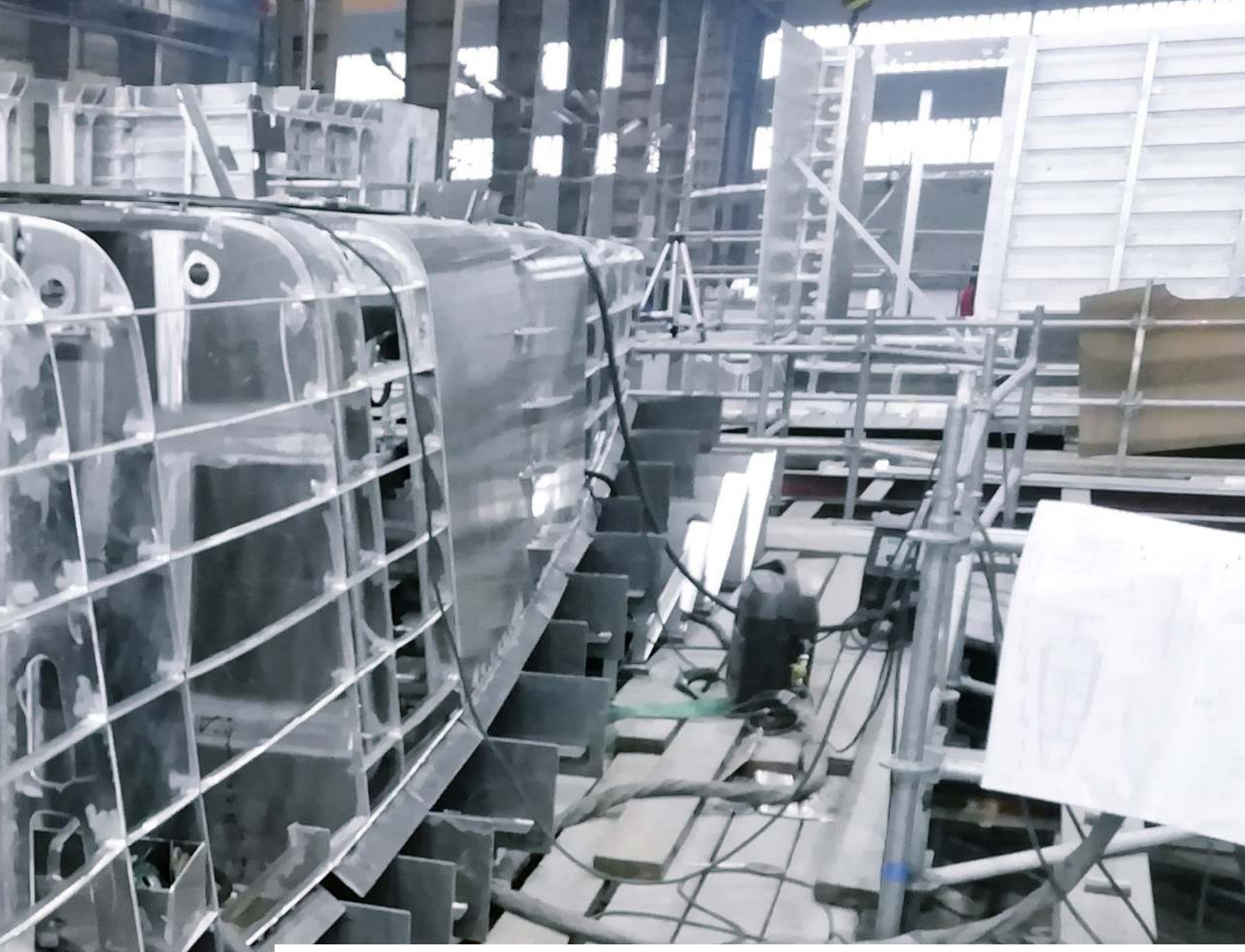


Photo courtesy of ProMare/IBM



CHAPTER 4:

BUILDING THE MAYFLOWER AUTONOMOUS SHIP

"When we showed the ship to IBM, they said, 'Well, this looks like a Star Trek vessel.' Then the younger people told me that it looked like a Ninja Turtle weapon [...] But I think that the science community is going to realize very soon that this is a very, very good tool."

Eric Aquaronne
HW Systems Strategy at IBM

(This page, top to bottom) Slowly, the shape of the MAS started to emerge, as the workers at Alushipp Technology started with a metal skeleton, and built out the interior supports and bulkheads.

(Facing page, top to bottom) Attaching the metal hull to the frame was a suprisingly delicate job, but before long, the trimaran was in place.

Photos courtesy of ProMare/IBM.

To see footage of early stages of MAS' assembly and construction, scan this QR code.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ALUSHIP

In the spring of 2019, ProMare began the construction of the Mayflower Autonomous Ship based on the final design. Fredrik had built several research vessels previously and had spoken to various shipyards. Alushipp Technology in Gdansk, Poland, was selected for the construction of the aluminum hull.

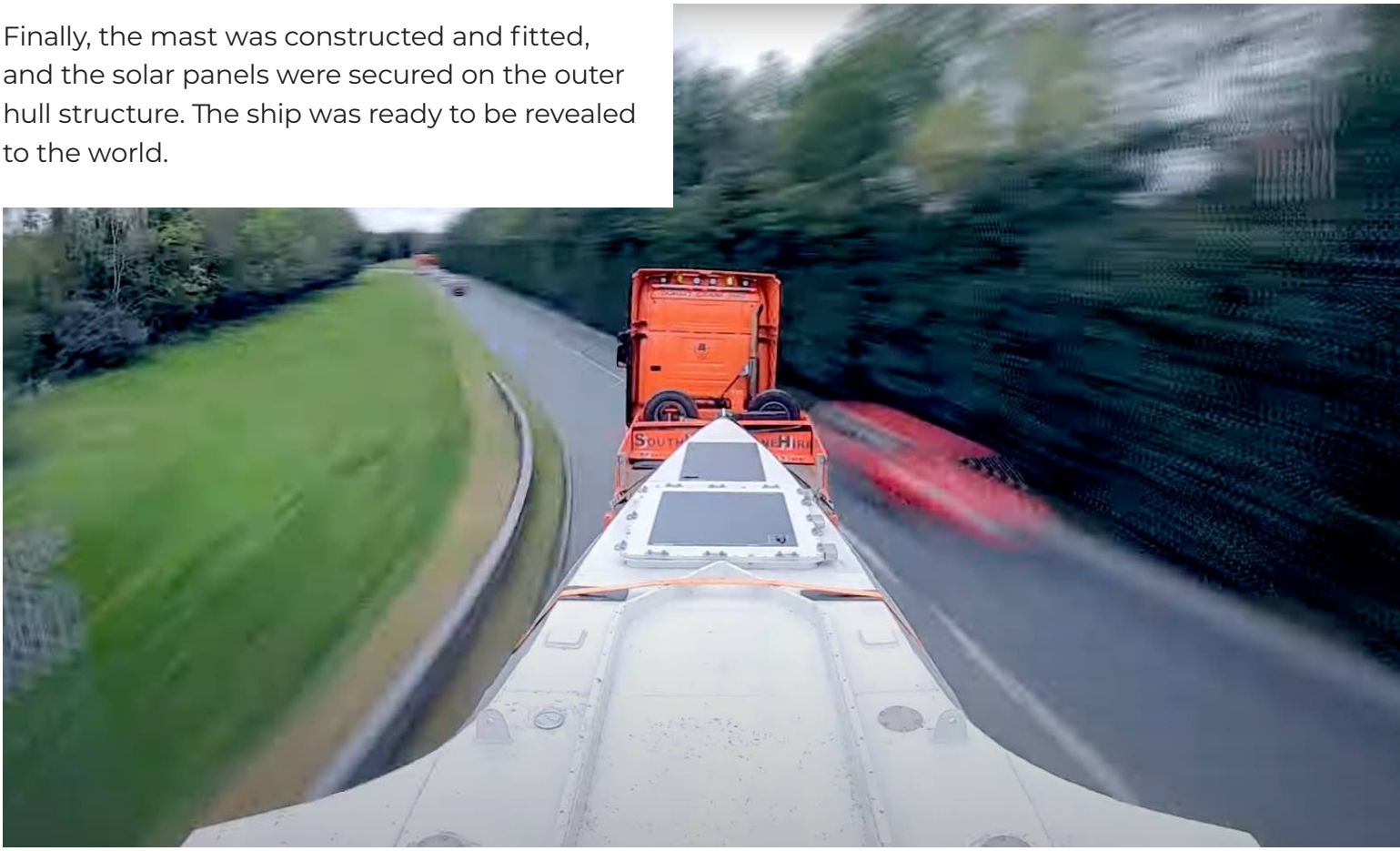
Alushipp became an important partner in the project, and assisted in both engineering and valuable design adjustments in cooperation with MSubs during the construction phase.

The shipyard started building the hull in the fall of 2019, and the construction was completed

in March 2020. The hull was transported from Poland to Plymouth, UK, on two trucks in early April, a few days before international traffic was halted due to Covid-19 pandemic restrictions.

With the ship having been safely delivered to Plymouth, MSubs could initiate the final assembly. The two outriggers were attached to the main hull, and the equipment and electronics were installed inside.

Finally, the mast was constructed and fitted, and the solar panels were secured on the outer hull structure. The ship was ready to be revealed to the world.



(Facing page, top to bottom) The now-completed hull was separated into three pieces for its journey across Europe, and then carefully strapped to trailers.

(This page, top to bottom) The main body of the ship leaving the assembly shed, a ship's-eye-view of the journey, and a joyful moment during the assembly of the MAS in England.

Photos courtesy of ProMare/IBM.

CHAPTER 5:

LAUNCH AND NAMING DAY

September 16, 2020, was both the 400th anniversary of the original *Mayflower* setting out from Plymouth, UK, and the day the Mayflower Autonomous Ship was officially lauched at the historic “Mayflower Steps.”

Photo courtesy of ProMare/IBM

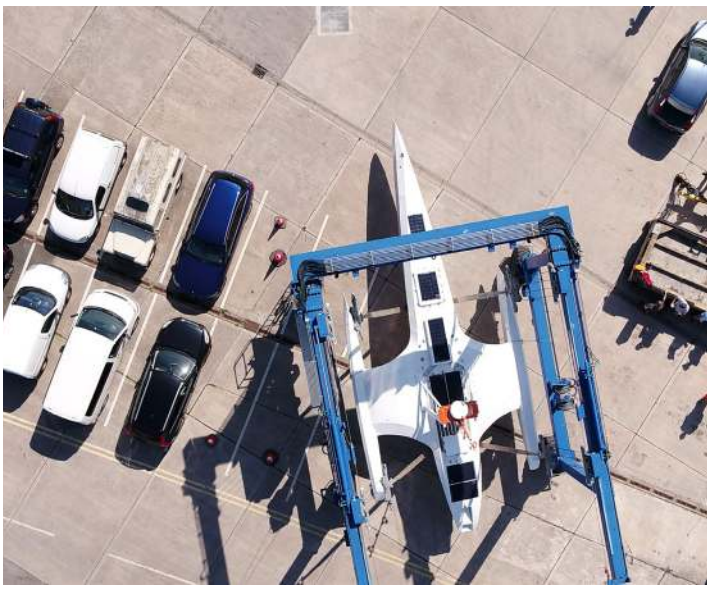
Summer of 2020 was subject to several rounds of restrictions related to the Covid-19 pandemic and even though ProMare/MSubs/Marine AI teams were able to continue work, progress was inevitably slower than anticipated. Atlantic crossing plans were postponed along with all commemorative activities and events related to the 400-year anniversary of the original *Mayflower*'s departure.

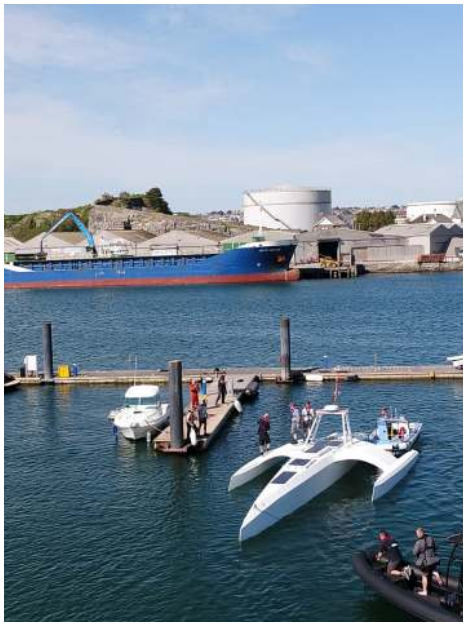
Despite all this, on September 16, 2020, the Mayflower Autonomous Ship was ready for launch from Turnchapel Wharf. The subsequent official naming ceremony organized by Plymouth City Council took place at the "Mayflower Steps," the location of the *Mayflower*'s departure. The event was open to the public and was well attended by Plymothians.

(Facing page) After such a long wait, the MAS team were a little giddy when the ship was finally ready for launch, riding the hull as it emerged from storage.

(Above and right) The MAS was carefully cradled by a large motorized Turnchapel Wharf crane.

Photos courtesy of ProMare/IBM.





A ceremonial bottle of Plymouth Gin was poured on the ship, before the US Ambassador to the UK, Robert Wood Johnson; the Dutch Ambassador, Karel van Oosterom; Andy Stanford-Clarke, Adrian Vinken, Brett Phaneuf, and the First Sea Lord, Admiral Tony Radakin, spoke to the public about the historical significance of this day.

To enable followers around the world to stay updated with the MAS as it undertakes its various missions, IBM and ProMare also launched a new interactive web portal: www.mas400.com

(Top, bottom left, and bottom center) The MAS was gently lowered into the water, the straps were loosened, and the engines were activated for the first time to back it away from the slipstream.

(Bottom right) The MAS started its final journey from land to sea on a gray and overcast morning, but by the end, the skies were blue and the waters were calm.

Photos courtesy of ProMare/IBM.

(Above, clockwise from top left) The Royal Marine Band played; Dutch Ambassador, Karel van Oosterom spoke; First Sea Lord, Admiral Tony Radakin; Brett Phaneuf salutes the crowd.

(Right) The MAS is christened by US Ambassador, Woody Johnson, with a bottle of Plymouth Gin.

Photos courtesy of ProMare/IBM.

Robert Wood Johnson said:

"Four centuries after the famous *Mayflower* voyage across the Atlantic, the US and the UK are once again setting sail from Plymouth to make history. American and British scientists have collaborated to launch a new autonomous Mayflower ship powered by the most cutting-edge artificial intelligence ever known. As we embark on this new era of marine exploration together, it could not be clearer: In America and Britain, the pioneering spirit of the original Mayflower Pilgrims lives on."

Karel van Oosterom commented:

"In the Netherlands, we have always been proud of our maritime history and religious tolerance. The story of the *Mayflower* is part of our history."

Adrian Vinken, Chair of Mayflower 400, added:

"It's fitting that this radical pioneering vessel should receive the Mayflower name 400 years to the day that her namesake left on her original world-changing journey. "

Brett Phaenuf, Director of Mayflower Autonomous Ship Project, added:

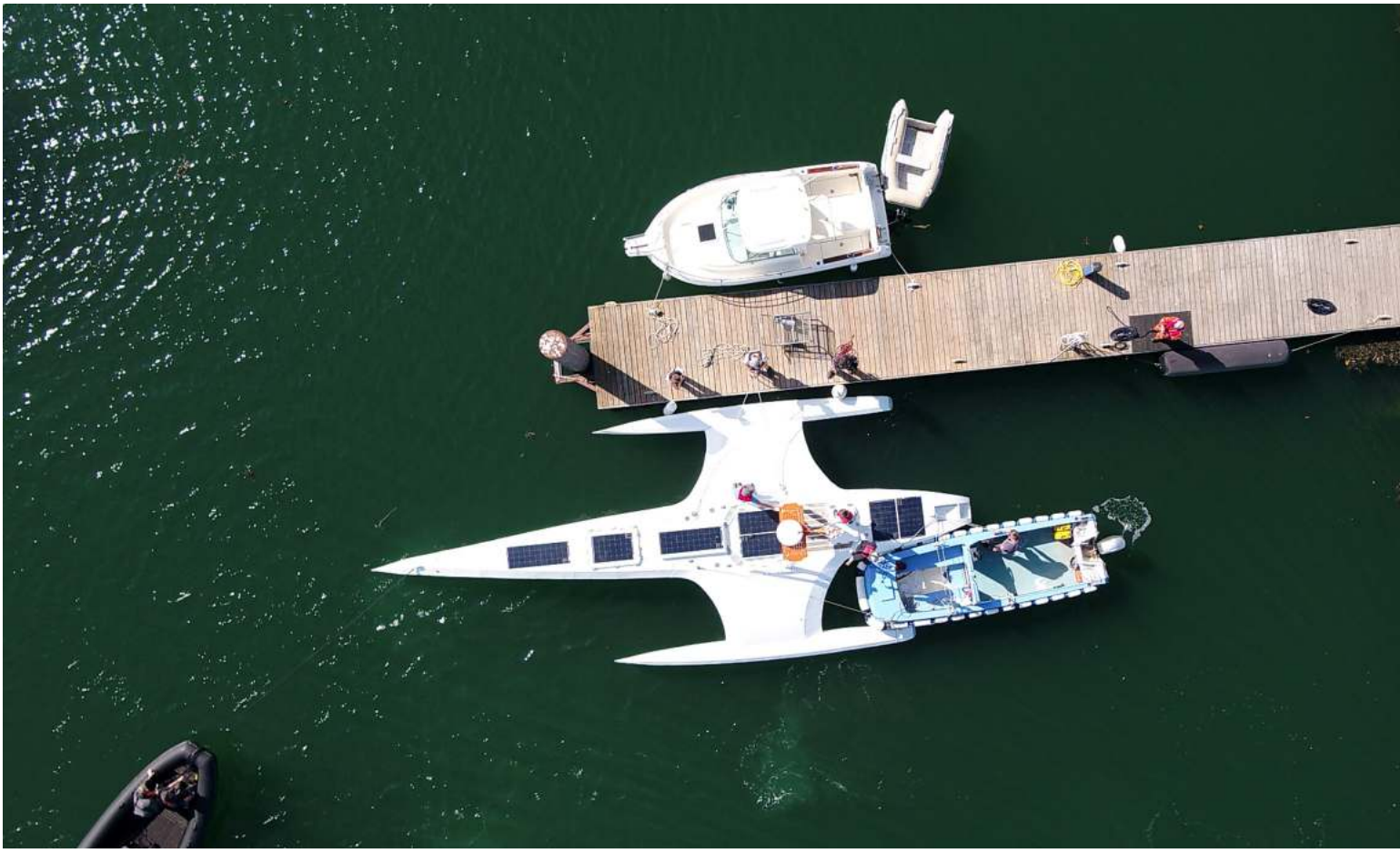
"What I find inspirational, is that people onboard the original *Mayflower* were willing to take an incredible risk to jump off into something new, with not just no guarantee of success, but no guarantee of survival. This project is not about the last 400 years, it's about the next 400 years, it's about the future. Mayflower Autonomous Ship is inspired by the idea of a new beginning, jumping off without a guarantee of success into a new world, in this case, a new world of artificial intelligence and robotic systems that help us."

Scan this QR code to see video of MAS' launch and naming ceremony.

The MAS then crossed the short distance to Turnchapel Wharf in Plymouth. This would be the Mayflower Autonomous Ship's home port during the sea trials in preparation for the Atlantic crossing.

(Below facing page, and following pages) The MAS leaving Plymouth Harbor, heading out to the open ocean, escorted by support craft and media boats.

Photos courtesy of ProMare/IBM.




HARBOUR PATROL


HARBOUR PATROL

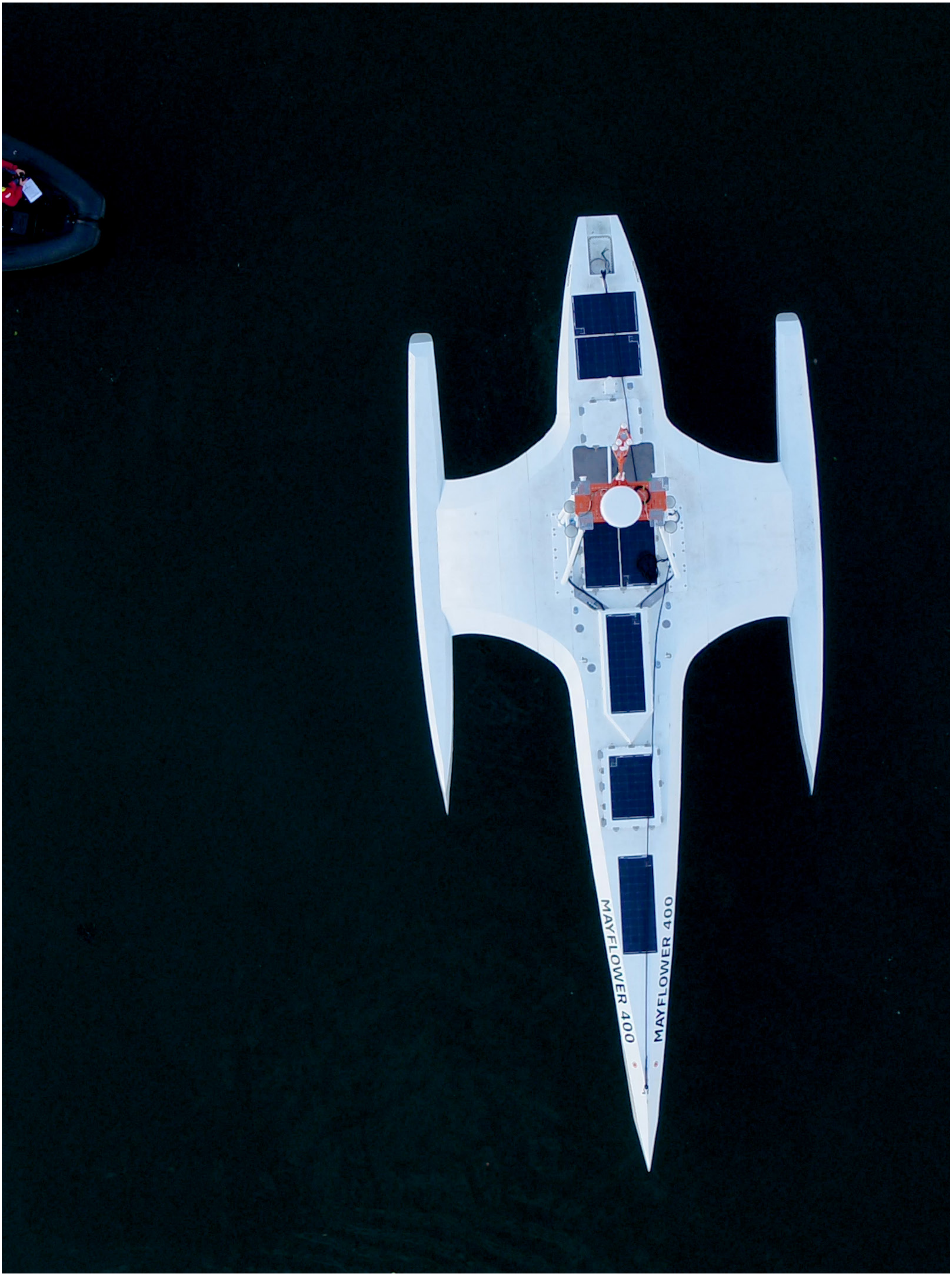
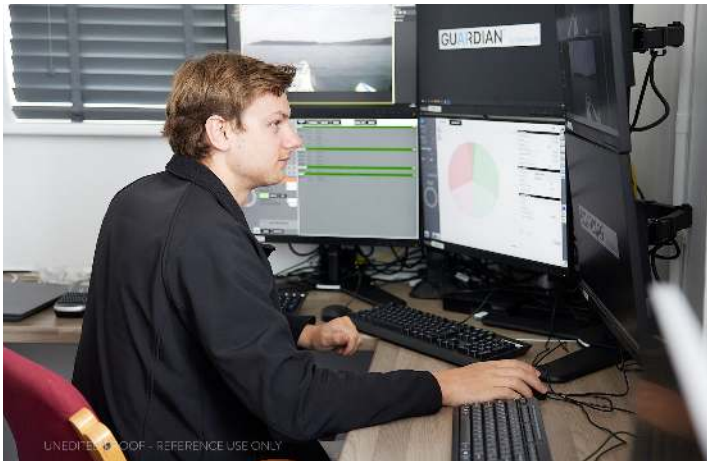

MAYFLOWER 400
MAYFLOWER 400

Photo courtesy of Promare/IBM.

CHAPTER 6:

THE INTELLIGENT SHIP

Unmanned surface vehicles (USVs) like the MAS fuse artificial intelligence (AI) and automation to navigate the oceans. It's not a simple task. The AI must monitor data feeds coming in from dozens of sensors, compile the data, verify that it's not distorted or faulty, and then perform sophisticated analysis by merging that data to produce new insights.

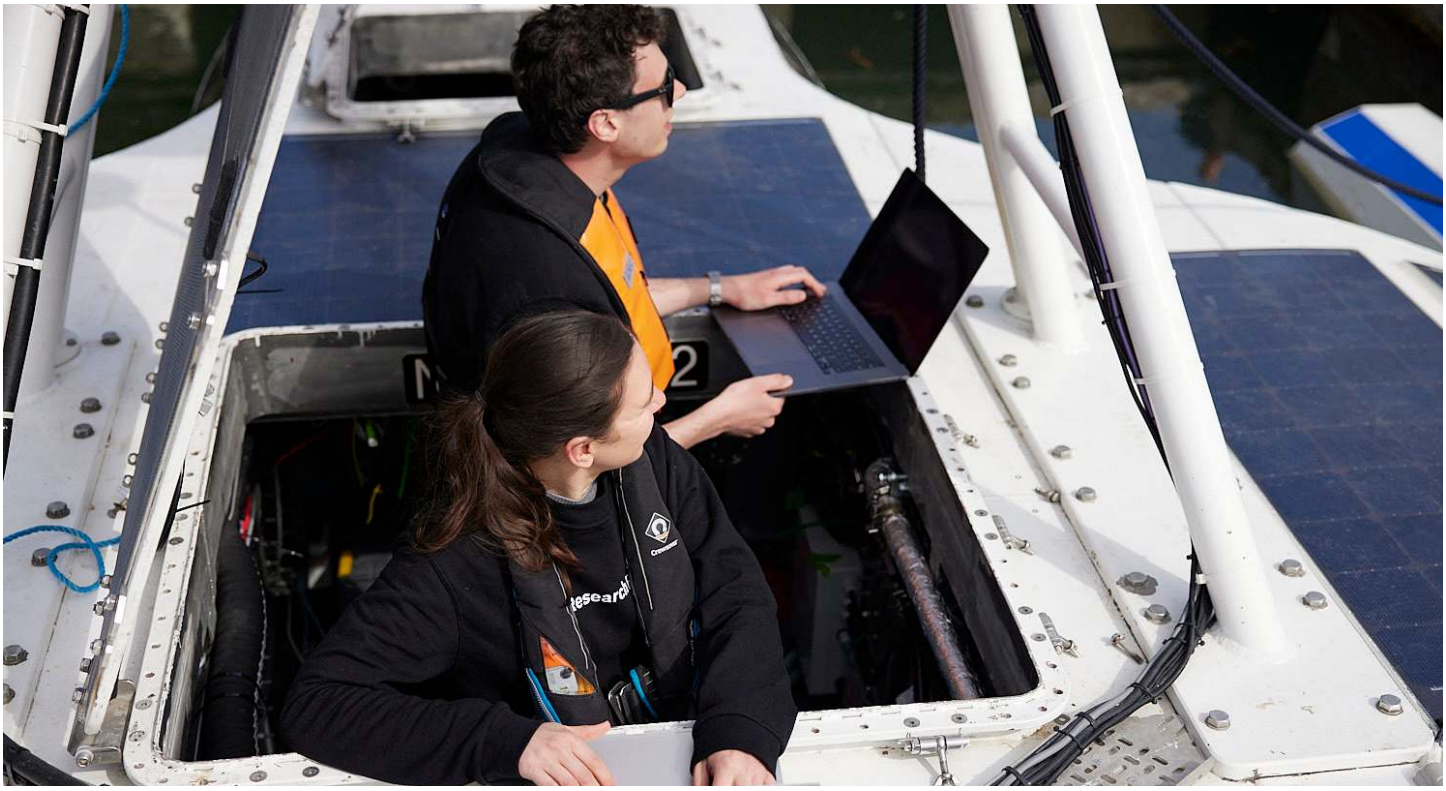


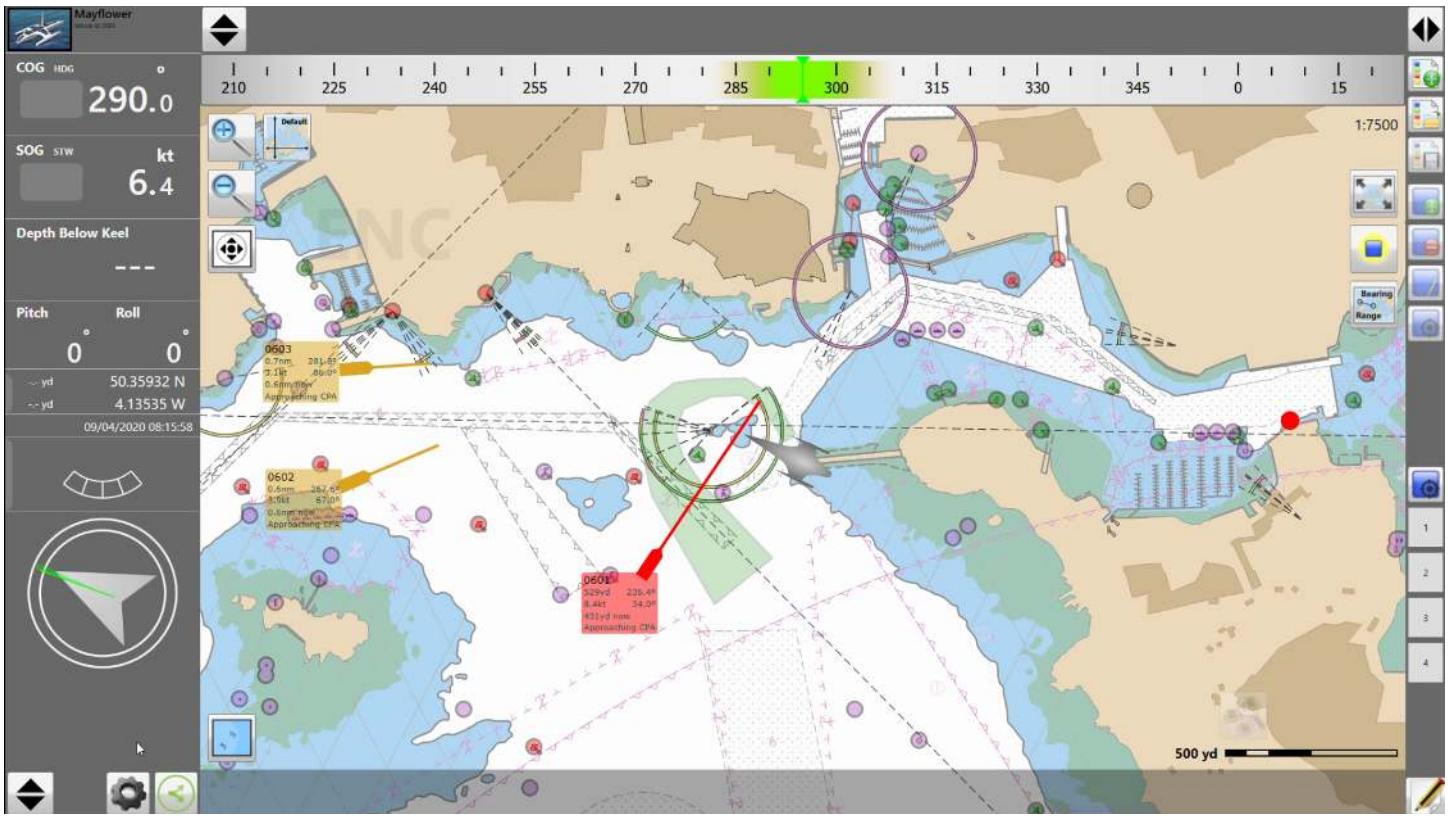
Brett and Don Scott, CTO of Marine AI (the company responsible for designing, building, and refining the software that operates the MAS), were presenting the MAS at a conference, when they ran into Eric Aquaronne from IBM.

Eric took an immediate interest in the project and championed for IBM to support the MAS team. The idea was that the ship could use IBM's Cloud infrastructure, AI, and decentralized computing architecture (also known as edge computing) technologies to develop an "AI Captain" to navigate the vessel and detect and avoid obstacles.

The MAS was therefore built around edge computing, which is essential for enabling the autonomy required for continuous operations. Small, powerful, and lightweight, edge devices provide enough computing power for an uncrewed vessel to operate independently, even without network connectivity.

The resultant AI Captain technology was created by a software company, Marine AI, using some elements of IBM Power System AC922—the same technology that lies behind some of the world's most powerful supercomputers.





(Facing page, top to bottom) The marine AI team were constantly checking and updating the artificial intelligence software that runs the MAS.

(This page) While previous generations of shipbuilders used hammers and saws (or, later, rivet guns and welding torches), the most ubiquitous tool for the MAS team is a laptop computer. In the top photo, scientists are going over last-minute details.

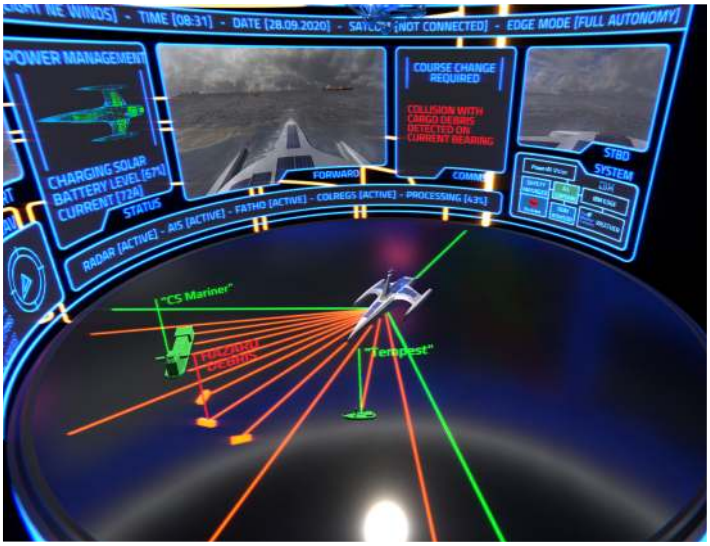
(Bottom) The IBM Maximo systems help the MAS recognize obstacles and other ships, and avoid collisions.

Photos courtesy of ProMare/IBM.

This cutting-edge system helped reduce the time and expense of physical testing, and meant that the AI Captain algorithms could be constantly tweaked and updated by the MAS support team on shore.

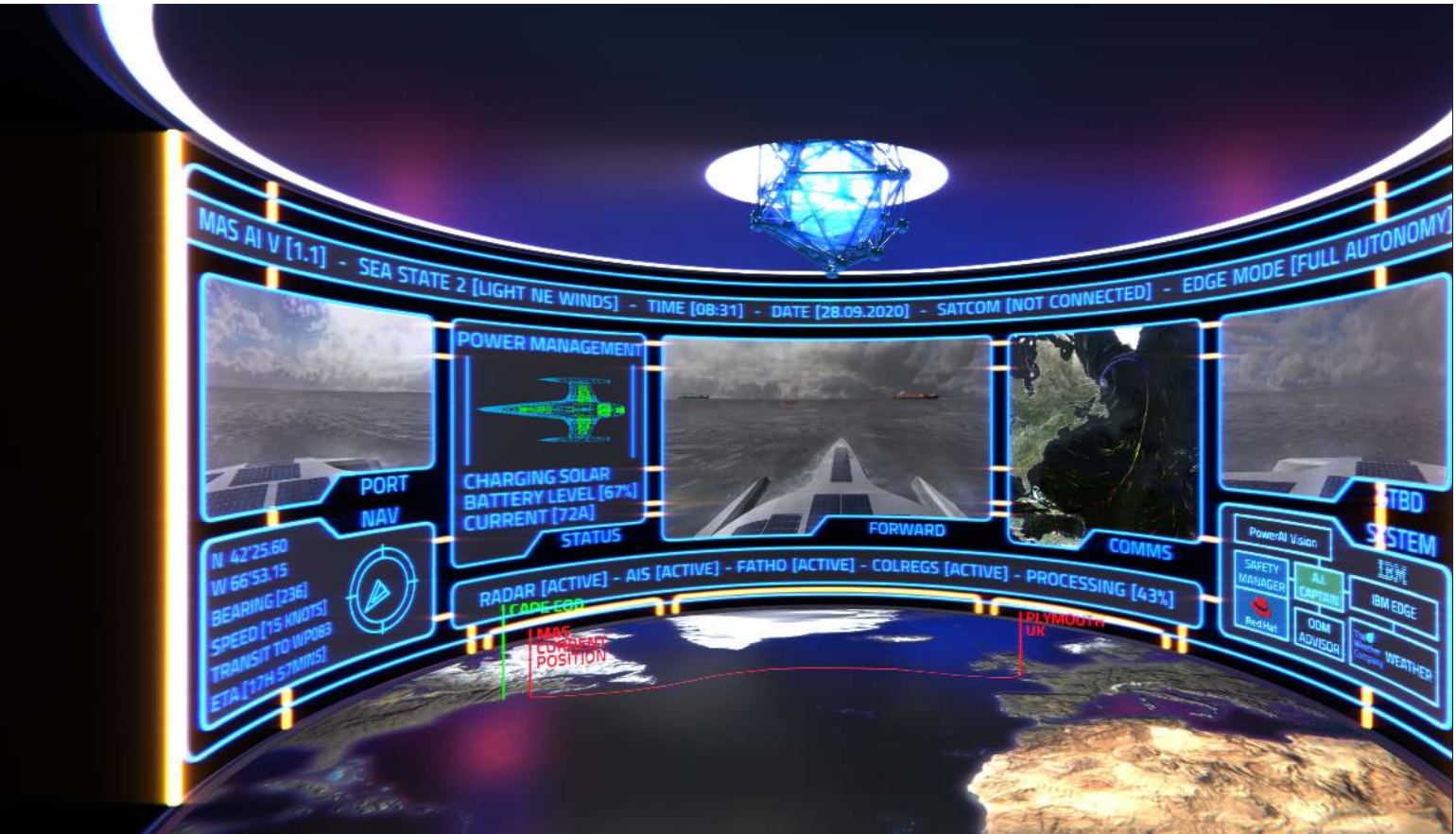
The past few decades have seen amazing advances in image-recognition technology; not only can you unlock your phone by looking at it (as it recognizes your face), but self-driving cars and trucks have been buzzing around the streets of major cities for years, growing increasingly good at navigating urban streets and interstate highways.

An even more sophisticated version of this computer vision technology deciphers images streaming in from MAS's six onboard video cameras. The system aboard the MAS was trained on millions of maritime images gathered by Marine AI since 2016. This vigilant AI-powered system is now able to recognize a wide range of threats in the vicinity of the ship—whether physical outcroppings of land, floating debris, marine life, other vessels, or other potential perils, even paddle boarders!



Live weather data is downloaded from IBM's The Weather Company to optimize the performance of the AI Captain. When network connectivity isn't available, the MAS has an onboard weather station that monitors and analyzes weather data, feeding it to the AI Captain, where it is combined with all the other datasets being gathered in real time, to make rapid and informed decisions.

MAS needs to be able to operate independently through its own decision automation system.



This system is called the Operational Decision Manager (ODM).

The ODM accesses a broad range of data sources—including the ship's onboard computer vision system, weather data, radar, sonar, and other marine navigation systems—to better understand the surrounding environment. And because it is trained on two key sets of marine rules—the International Regulations for Preventing Collisions at Sea (COLREGS) and the International Convention for the Safety of Life at Sea (SOLAS)—the ODM helps the MAS follow maritime regulations, while considering real-time data to optimize its decision making.

Navigating an ever-changing seascape depends on this ability to collect and process data locally, so that mission-critical decisions can be made rapidly and accurately. The MAS is breaking new ground (or sailing uncharted seas, to use a more appropriate metaphor) each time it sets out on its own; and each time, the team learns a little bit more, and makes incremental progress.

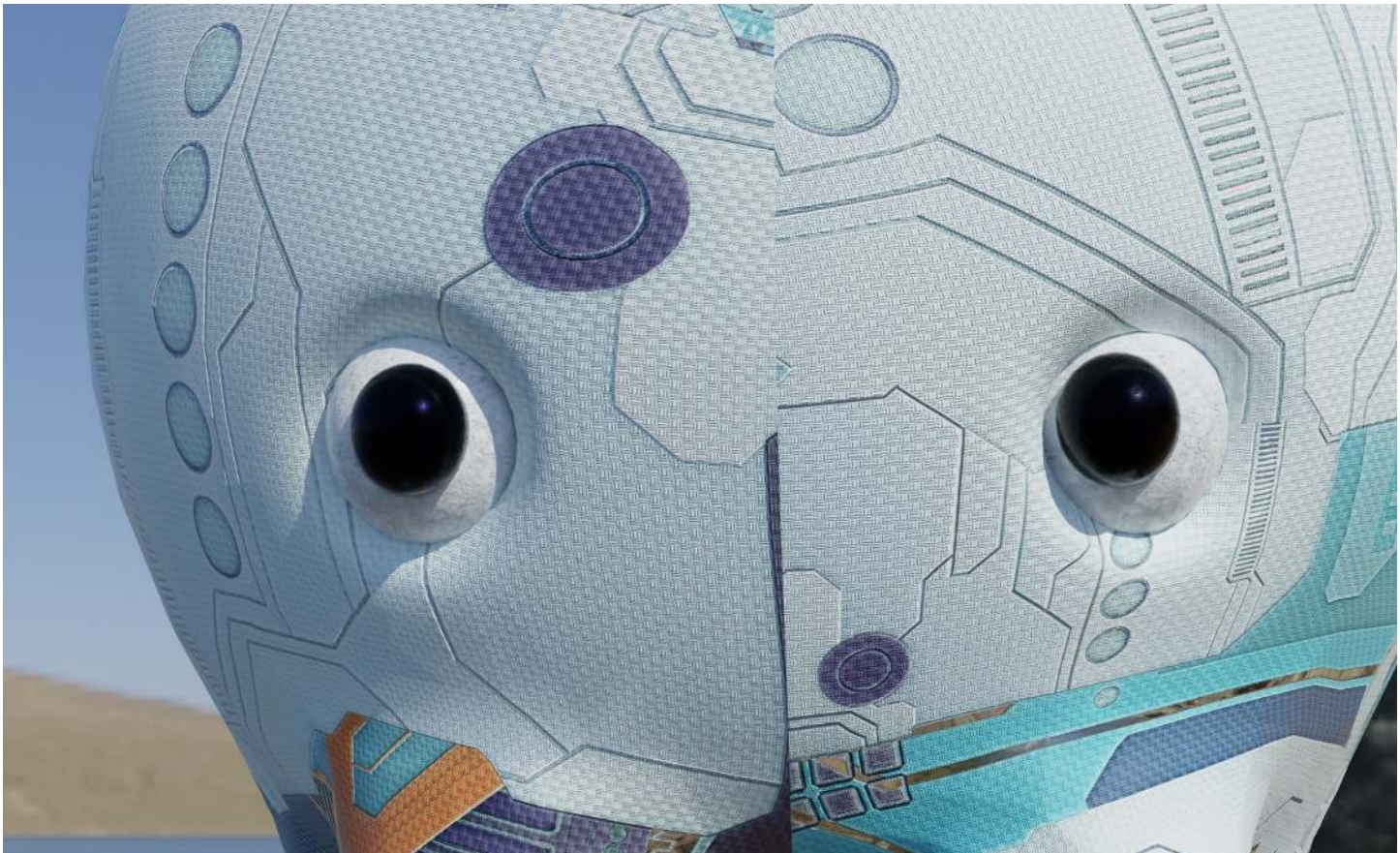
(Facing page, top to bottom) The AI Captain is able to combine inputs from a wide variety of sensors—ranging from cameras and GPS systems, to battery power and engine condition monitors.

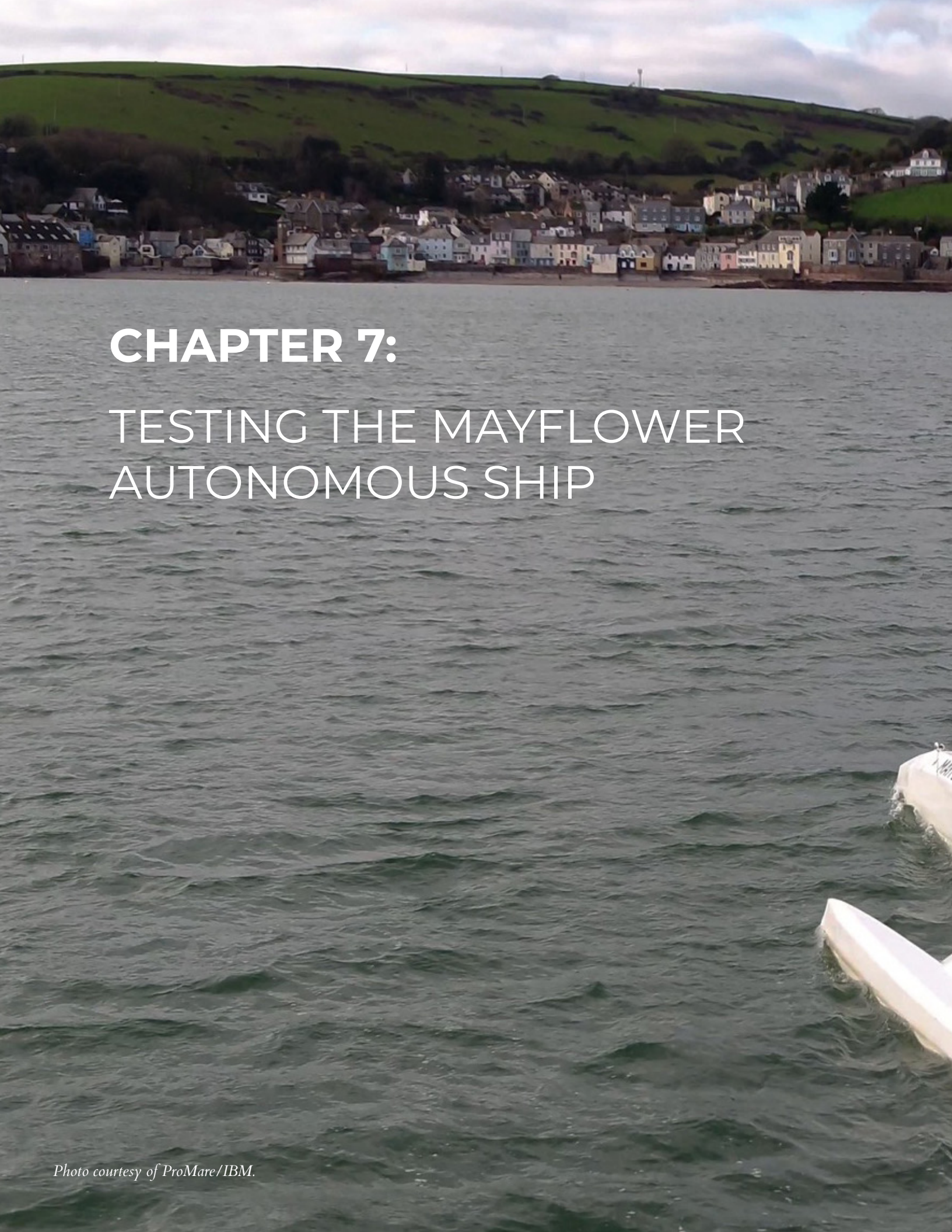
(This page, top to bottom) The unofficial mascot of the MAS is Artie the Septapus—a chatbot on the mas400.com website that can answer questions, and has been playfully adopted by the ProMare team.

Artie even appears in an illustrated children's book, *Artie's Ocean Adventure*, to help explain how AI works to the thousands of schoolchildren around the world who are fascinated by the MAS.

Photos courtesy of ProMare/IBM.

Scan this QR code to see video explaining the AI Captain concept that guides the mind of MAS.





CHAPTER 7:

TESTING THE MAYFLOWER AUTONOMOUS SHIP

Photo courtesy of ProMare/IBM.


PLYMOUTH

After the naming ceremony in September 2020, the MAS team completed the installation of the remaining equipment. The power and propulsion system is the largest item on board, consisting of a diesel generator and solar panels. Both charge a battery bank, which provides power to the ship's systems. The ship's electric motor is connected to the propeller.

Scientific instruments were installed in the science bay, and hundreds of meters of electric and control cables had to be pulled between the various instruments, the battery bank, and the onboard AI Captain control system.

(Previous page) The MAS was tested over several months and in various weather conditions in and around the Plymouth Sound, UK. An escort vessel carrying several engineers closely monitored the vessel at all times.

(This page and the facing page) The engineering team at work through the sea trials.

Photos courtesy of ProMare/IBM.

Once these final installations were complete and had been tested (well, tested under the controlled conditions of a ship in port), the MAS team started the next stage of testing: sea trials off the south coast of England. The first short excursions were just brief tethered cruises around Plymouth Sound, but as the MAS kept performing as it was designed to do, the team grew more and more confident that the ship could indeed sail autonomously.

The MAS team told the ship where they wanted it to go, and then it would figure out on its own how to get there, taking into consideration the weather, ocean currents, COLREGs, and other variables. The MAS reacted to ocean traffic in real time, using a combination of radar, cameras, and the Automated Identification System (AIS), which transmits information such as the MAS's latitude and longitude to other boats.

Like a child learning how to walk, the MAS started to go on longer and longer journeys away from the safety of port, but always in the company of an escort vessel.

Through the winter of 2020/21, several test runs of about 50 nautical miles were performed inside the testing area assigned to the MAS team outside the Plymouth Breakwater—a massive stone and sand reef built during the Napoleonic Wars to absorb the energy of waves and provide a safe harbor for the Royal Fleet.

Gradually, the little ship ventured east, west, and south, running stress tests on all the systems, and traveling as far as weather conditions and daylight permitted the team following along in the escort vessel to keep pace.

Scan this QR code to watch a video showing our teams' efforts in 2020 and 2021 to test the MAS' AI software and seaworthiness.

(Facing page, top) An engineering team inside the escort vessel during testing.

(Facing page, bottom) MAS in Cawsand Bay during the early stages of testing.

(This page, top) MAS engineers Rob Shaw and Paul Barretto.

(This page, left) Chief Engineer Matt Shaw and Meirwen Jenkins getting the MAS ready for a test run.

Photos courtesy of ProMare/IBM.

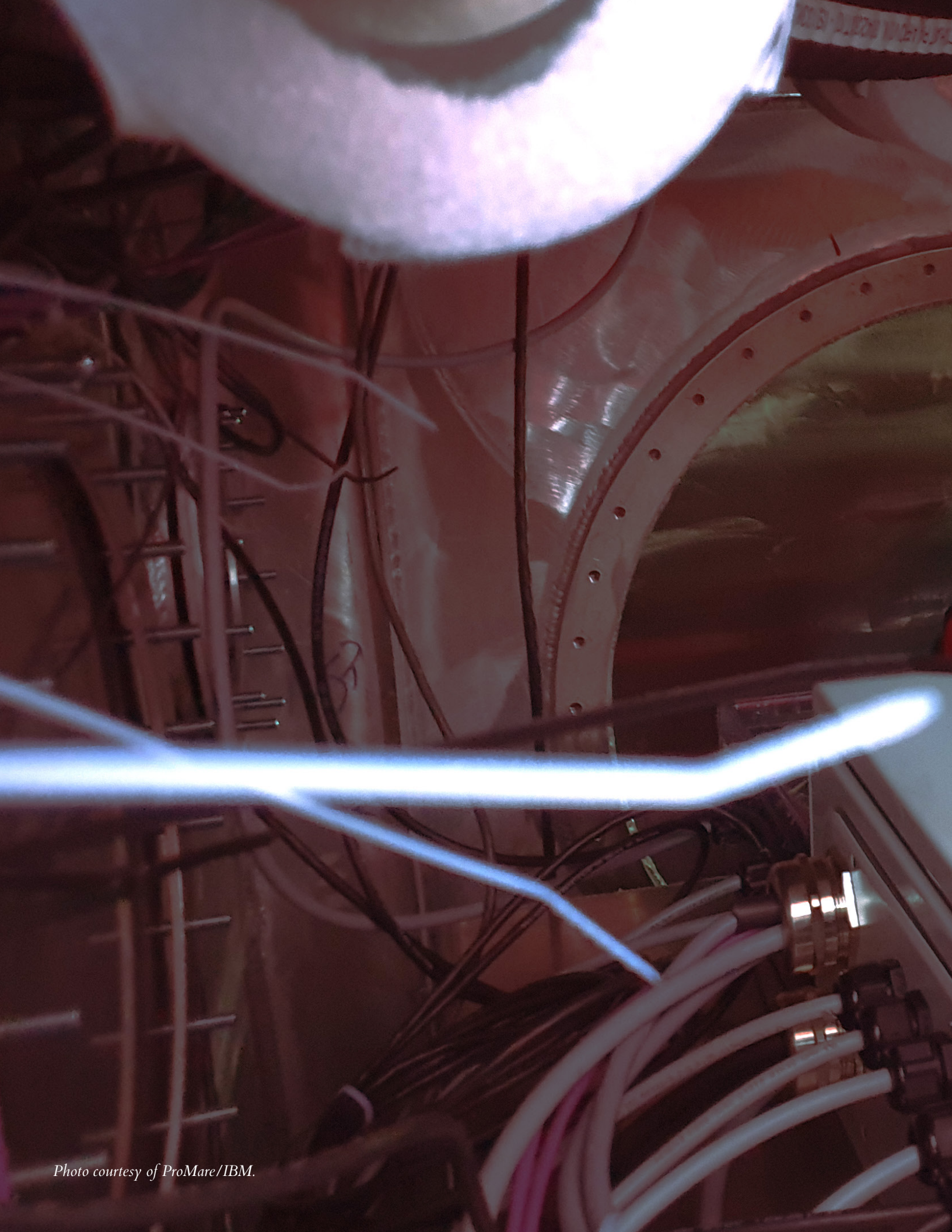
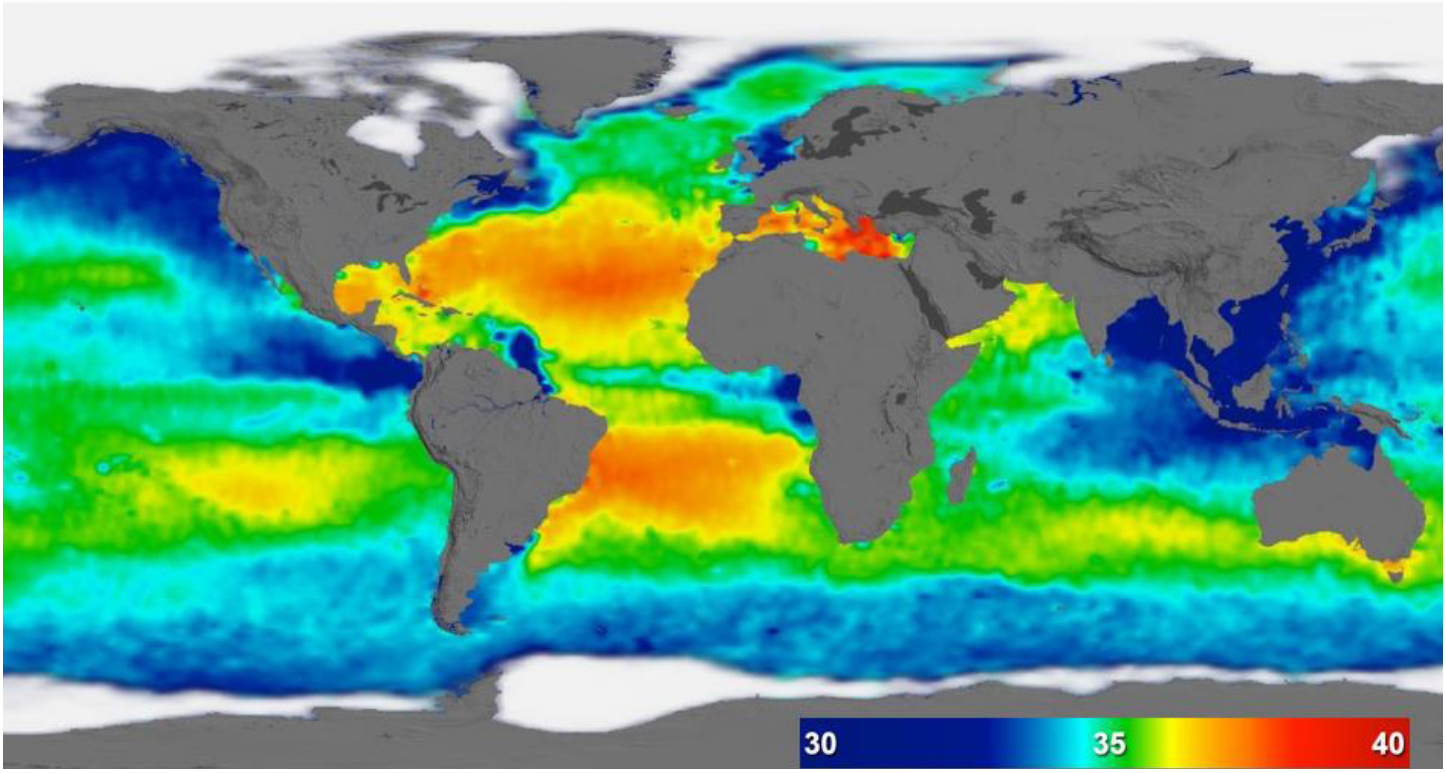


Photo courtesy of ProMare/IBM.

CHAPTER 8:

A NEW KIND OF RESEARCH VESSEL

The Mayflower Autonomous Ship is a research vessel. After the initial crossing from Plymouth UK to Plymouth USA, it will continue to collect data to help monitor and protect our oceans. This is the main motivation for our project, as we believe autonomous research vessels will be able to collect more data more efficiently and at a lower cost than manned research vessels.



The MAS is equipped with an array of scientific equipment. For the initial Atlantic crossing, the science projects on board focused on the following main topics: ocean health; marine mammals; open ocean tides and waves.

OCEAN HEALTH

Temperature, salinity, oxygen (O2), and pH:

These important indicators of ocean health and condition are monitored constantly using a CTD (a device that measures conductivity, temperature, and depth) provided by Valeport (uvSVX), and an O2 sensor provided by Aanderaa Data Instruments. Some of this data is available in real time on the MAS dashboard.

PCO2:

This instrument is used to measure the concentration of carbon dioxide (CO2) dissolved in seawater.

(This page, top) NASA's Aquarius mission performed an analysis of sea surface salinity patterns, demonstrating the wide variations along the proposed path of the MAS from the UK to the USA across the Atlantic Ocean.

Photo courtesy of NASA, Public Domain license via Creative Commons.

(Facing page) The HyperTaste system. Special tubing draws the water from the ocean into the MAS, then divides the flow between the various scientific instruments for analysis.

The jugs of reagents for the HyperTaste. Above them is the transponder listening for marine mammals. (More about that in the next section.)

Photos courtesy of ProMare/IBM.

HYPERTASTE:

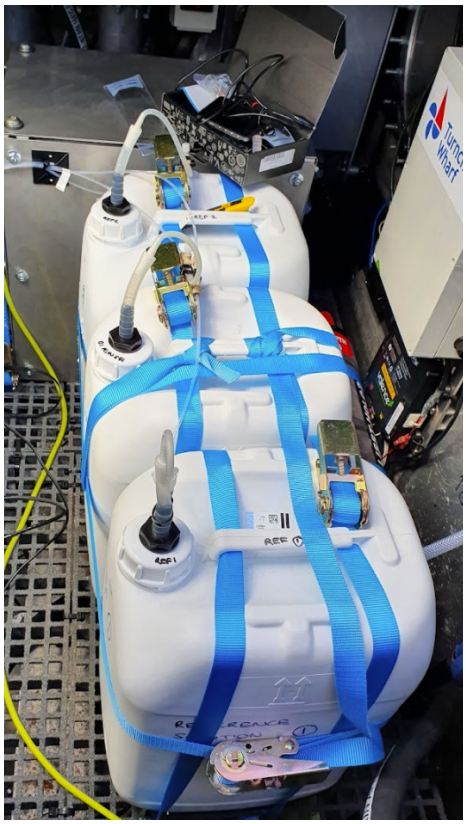
HyperTaste is a technology developed by IBM for AI-assisted rapid chemical testing of liquids. Inspired by the sense of taste, it uses an array of electrochemical sensors that react to a wide range of molecules and ions in liquids.

A pattern consisting of a set of voltages produced by the sensor array represents the digital chemical fingerprint of the liquid.

On the MAS, HyperTaste is used to help study the chemistry of the ocean. The ocean plays a key part in absorbing much of the world's CO2, trapping it in the deep ocean. However, too much absorption can lead to harmful effects, such as ocean acidification, damaging vulnerable ecosystems like coral reefs.

Measuring O2, pH, and the concentrations of ions such as calcium (Ca2+) and carbonate ion (CO32-) helps us to understand the rate of ocean acidification in different parts of the ocean. Moreover, assessing the magnesium:calcium (Mg+:Ca2+) ratio will be useful in identifying bio-geochemical processes such as precipitation, dissolution, or consumption that alter the physico-chemical properties of seawater.

The ratio reflects the dynamic exchange of important elements between the earth, ocean, and atmosphere. HyperTaste is able to automatically track such changes in ocean chemistry along the route.



MICROPLASTICS:

An increasing concentration of microplastics poses a risk to all life in the marine environment and is one of the most urgent issues threatening the ocean.

A microscope developed by Sequoia and image analysis software developed by the University of Plymouth will attempt to detect microplastics in real time, while a robotic water sampling array delivered by Teledyne ISCO takes water samples in selected areas. Collected data and the water samples will be analyzed by the University of Plymouth labs for microplastics. Additionally, plankton, algae, and other tiny sea creatures will be collected and studied.

FLUOROMETER:

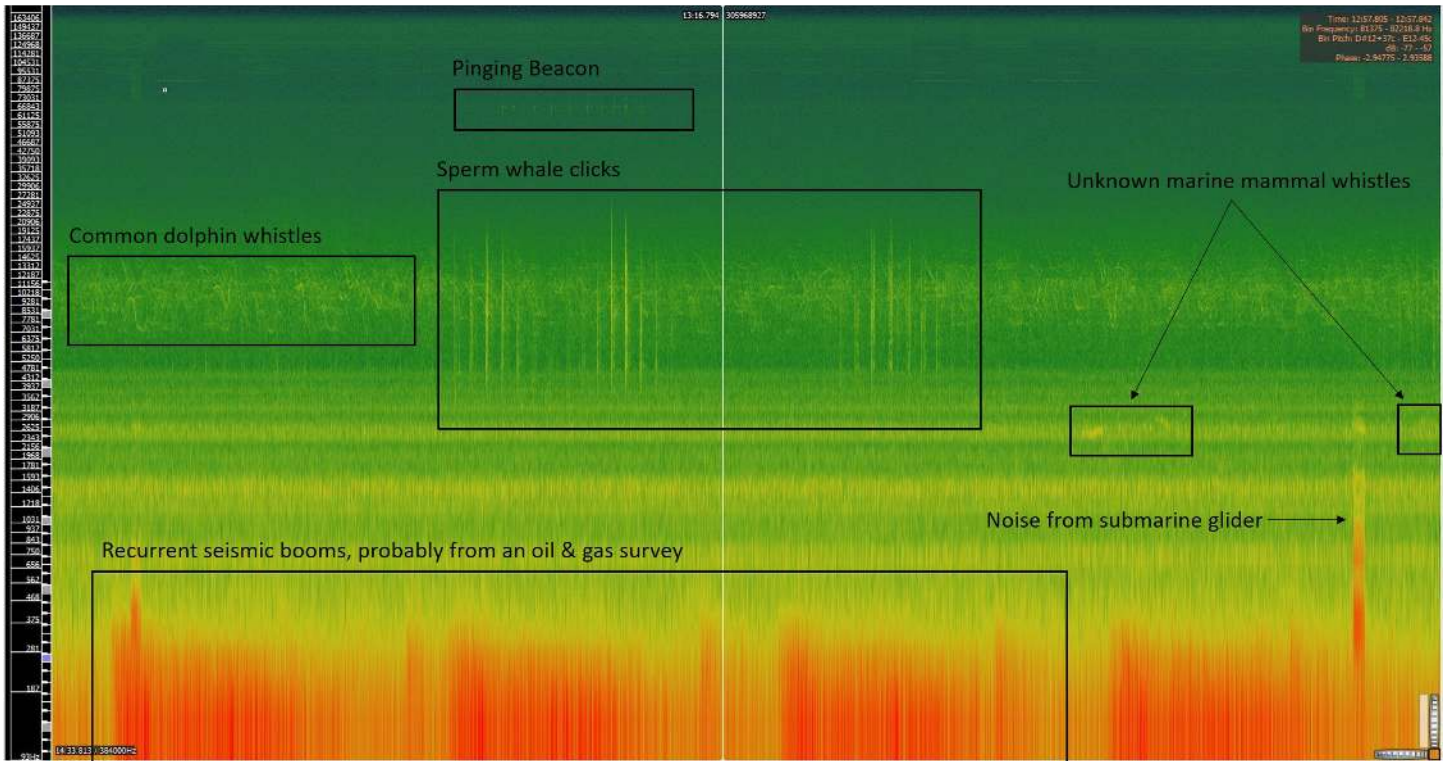
A fluorometer provided by Chelsea Technologies measures the fluorescence of algae, dyes, and pollutants in the water. These measurements can be used for dye-tracing studies, pollutant tracing, or estimating the concentration of phytoplankton and cyanobacteria (blue-green algae) for bloom predictions. Algae blooms are sometimes deadly to marine life and are increasingly common, closing beaches around the world and making people who live near shore sick from the awful smell.

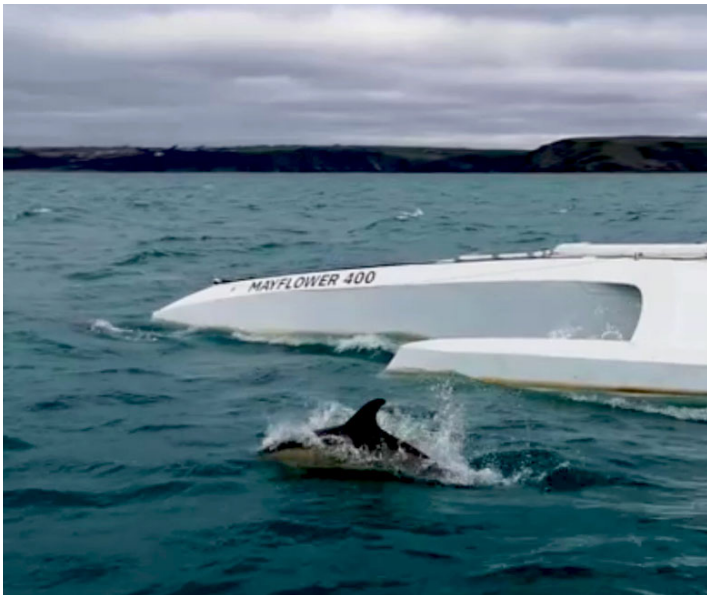
(This page, top) Microplastics concentrations are generally determined by sieving samples from ocean water.

(Facing pag, top) A sample of tagged acoustic data that shows the signatures of a variety of sources, such as marine traffic, equipment and marine mammals.

(Facing pag, bottom) Certain types of porpoise likes to approach and ride along the bows of ships. MAS was approacked by dolphins several times.

Photos courtesy of ProMare/IBM.





MARINE MAMMALS

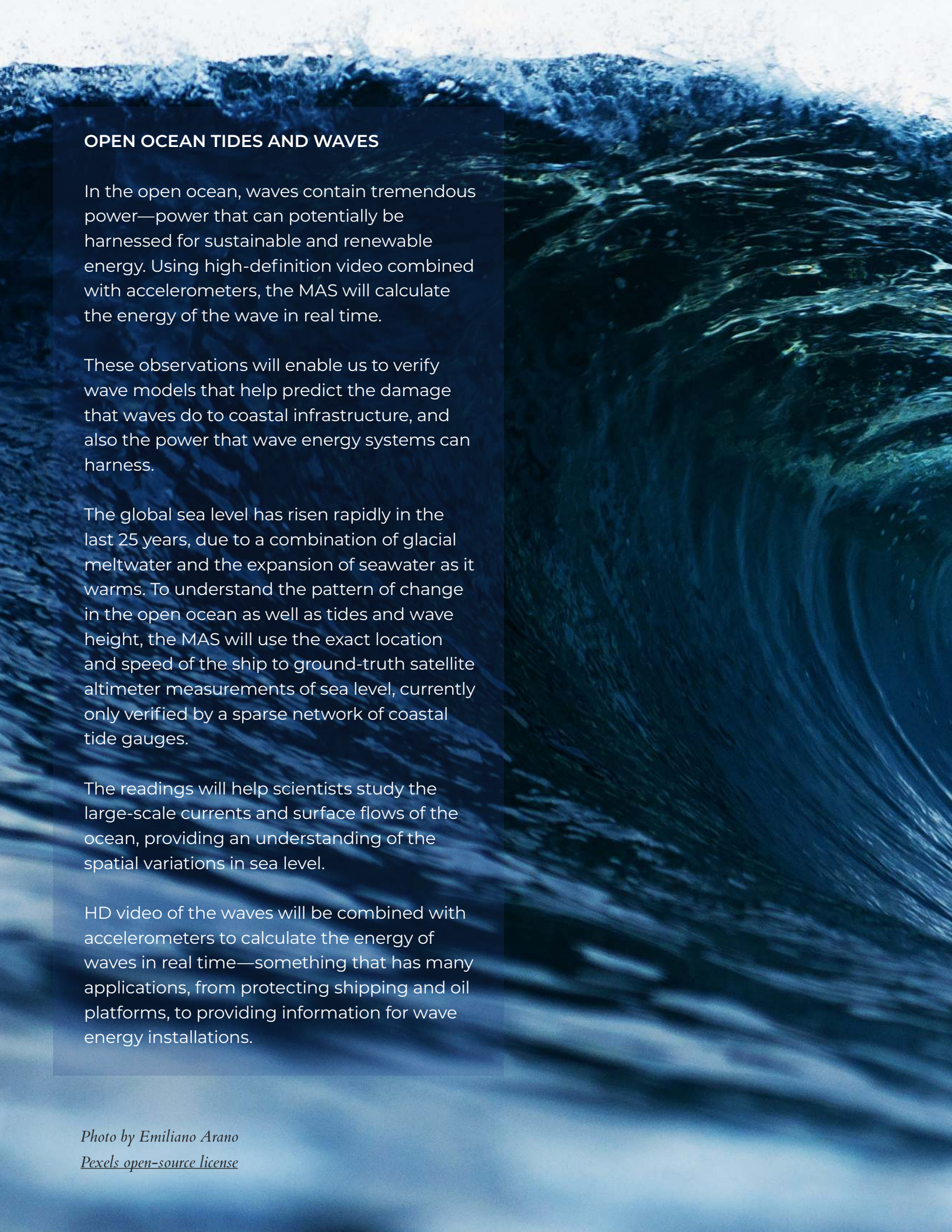
Marine mammals (in particular, whales) play a vital role as ecosystem engineers, supporting a healthy marine food chain. However, scientists know very little about their population distribution in difficult-to-reach locations such as the middle of the Atlantic.

The Mayflower Autonomous Ship carries a RS Aqua (Porpoise) Passive Recorder. As it name suggests, this device listens for marine mammal activity within range of the instrument and processes the data using AI models developed by IBM for the project.

Using many hours of carefully labeled ocean sounds contributed by the project's research partners (IBM Research, University of Plymouth, RS Aqua, and the Jupiter Research Foundation), a machine learning model deployed to one of the ship's science pods analyzes the acoustic data for signatures of marine mammal vocalizations.

Much like visual recognition, the model uses patterns in the frequencies to distinguish a dolphin whistle from a passing boat. A team of marine mammal experts helps to validate the model. This is necessary since sounds not present in the training data are likely to emerge throughout the ship's journey and require human interpretation.

With no humans on board, the MAS can more easily access regions that scientists rarely get the chance to visit, helping to further their understanding of the distribution and health of marine mammal populations.



OPEN OCEAN TIDES AND WAVES

In the open ocean, waves contain tremendous power—power that can potentially be harnessed for sustainable and renewable energy. Using high-definition video combined with accelerometers, the MAS will calculate the energy of the wave in real time.

These observations will enable us to verify wave models that help predict the damage that waves do to coastal infrastructure, and also the power that wave energy systems can harness.

The global sea level has risen rapidly in the last 25 years, due to a combination of glacial meltwater and the expansion of seawater as it warms. To understand the pattern of change in the open ocean as well as tides and wave height, the MAS will use the exact location and speed of the ship to ground-truth satellite altimeter measurements of sea level, currently only verified by a sparse network of coastal tide gauges.

The readings will help scientists study the large-scale currents and surface flows of the ocean, providing an understanding of the spatial variations in sea level.

HD video of the waves will be combined with accelerometers to calculate the energy of waves in real time—something that has many applications, from protecting shipping and oil platforms, to providing information for wave energy installations.

Photo by Emiliano Arano
Pexels open-source license

OCEAN TWILIGHT ZONE PROJECT WITH WOODS HOLE OCEANOGRAPHIC INSTITUTION

The MAS's mobility, autonomy, endurance, large payload, energy supply, and connectivity to researchers ashore can enable a variety of scientific observations. The Ocean Twilight Zone (OTZ) project at the Woods Hole Oceanographic Institution (WHOI) plans to utilize the MAS's unique capabilities to make observations about the midwater ocean that existing technologies cannot. OTZ is a six-year multidisciplinary, privately funded project that seeks to answer fundamental scientific questions about the midwater ocean and to develop technologies to support midwater exploration and science.

The midwater ocean, or "twilight zone," extends from depths where sunlight is too dim to support photosynthesis (200 meters/656 ft) to depths where sunlight is almost undetectable (1,000 meters/3,280 ft). It is home to a vast community of animals that likely play a major role in regulating the Earth's climate.

(This page) Mayflower Autonomous Ship arriving in WHOI after the final short passage from Plymouth MA to Falmouth.

(Facing page) Mayflower Autonomous Ship at its temporary place while engineers and technicians install the required equipment for the upcoming scientific cruise.

Photos courtesy of ProMare/IBM.

In the OTZ project's first use of autonomous surface vessels, the MAS will survey the midwater using several sonar devices called broadband echosounders. These provide an overview of midwater animal life. From the MAS, they can be operated at low cost with great mobility and endurance, and on flexible schedules, enabling them to complement corresponding measurements made from fixed moorings and research vessels.

The OTZ project has deployed similar sonars on an up-looking bioacoustics mooring off the New England Shelf break, about 240 km (150 miles) from Woods Hole. Acting as a mobile down-looking version of the mooring, the MAS will be able to carry out a variety of complementary surveys. In addition to being highly mobile and directed interactively by researchers ashore, the MAS will provide significant data in real time. Researchers will be able to make adjustments to the sonars and survey plans as they see fit, adding valuable spatial coverage around the mooring.

The midwater ocean is vast and many of the most interesting phenomena are concentrated in specific spots that are hard to find. In the summer of 2022, the OTZ team tagged a number of large apex predators such as tuna, swordfish, and sharks, allowing researchers to track them. Those fish travel over hundreds or even thousands of miles, seeking out the most productive areas in which to feed.

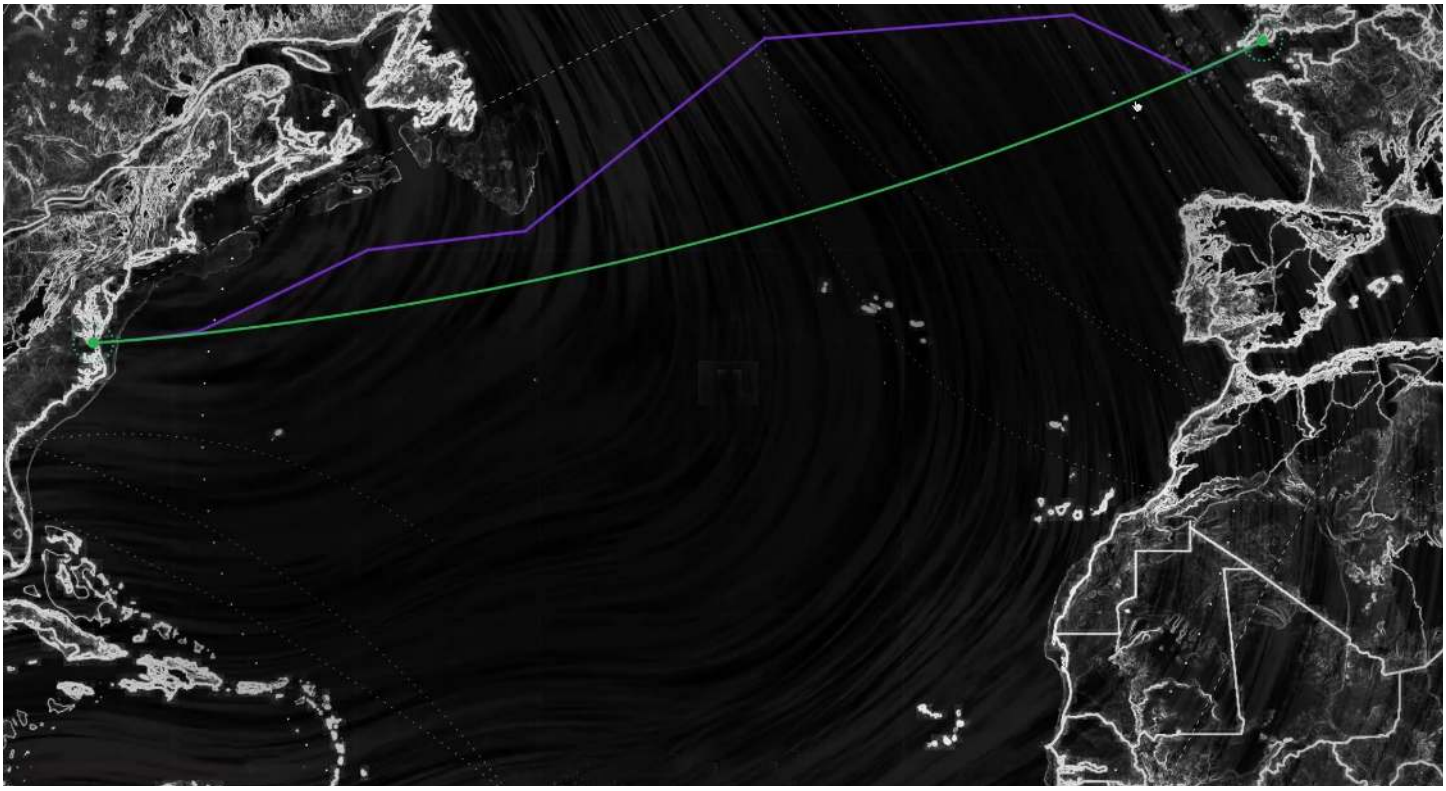
Much as hounds lead hunters to foxes, WHOI hope to use those tagged apex predators to lead the MAS to some of the most biologically interesting places in the twilight zone. The sonar surveys should provide critical details about these biological “hot spots” not available through conventional vessel operations.

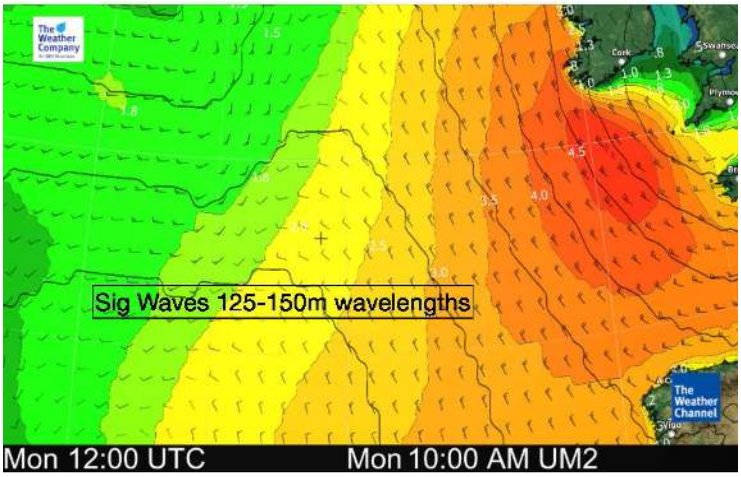
CHAPTER 9:

THE FIRST ATLANTIC CROSSING ATTEMPT

By the spring of 2021, everything on the MAS had been rigorously tested. Everything looked good. In order to give the MAS the best chance of a successful crossing, the team wanted to find the optimal route and the least dangerous weather conditions for the little ship.

Photo courtesy of IBM/Promare.





(Above) Possible routes likely to be followed by the AI Captian, depending on how the Gulf Stream behaved at the time.
Image courtesy of ProMare/IBM.

(Left) The weather forecast for the first crossing showed conditions as good as they were likely to get.
Image courtesy of IBM The Weather Company.

(Opposite) Numerous volunteers from a variety of organisations, watchkeepers, monitored the MAS and the AI Captain 24/7 to ensure the safety of the operation.
Image courtesy of ProMare/IBM.

While studying weather patterns, it was determined that a ship that sails at about 7–9 knots could not cross the Atlantic Ocean in late spring/early summer from Plymouth, UK to Plymouth, USA without encountering at least one storm in the north Atlantic. The timing of the attempt to cross would therefore be crucial.

There were many factors to take into consideration, and the ProMare team pored over charts, weather forecasts, and endless scenarios. Ultimately, it was concluded that if the MAS launched early enough in the spring season to avoid running into a storm during the first half of the journey, then should a developing storm from the south move along the eastern coast of America, it might be possible to avoid encountering the worst part of any storm.

However, weather patterns are extremely difficult to predict with precision, especially two to three weeks in advance. The ProMare team relied on expert advice from the IBM Weather Company (a service that also uses the Watson AI to crunch data). Eventually, after a long wait in May 2021, weather conditions looked optimal to make an attempt.

Before the launch, the team met regularly with Leon Brown, Head of Global Meteorological Operations for The Weather Company, who provided advice. Nevertheless, as Brett said before the attempt: “It [a successful crossing] just comes down to, if the sea is kind to us.”

On Tuesday, June 15, 2021, the MAS started its nearly 3,220 nautical mile transatlantic crossing. The ProMare team and thousands of followers watched as live-streaming video feeds showed the ship departing the harbor, as the original Mayflower had done 400 years previously. The seas were calm and the ship was behaving perfectly. It encountered other vessels a few times, but the AI Captain followed all the laws and rules concerning navigation and collision prevention and navigated safely around these ships to continue the journey.

The ProMare team monitored the MAS 24 hours a day, and verified that all the decisions made by the AI captain were correct and in accordance with the programming. To help with this vetting process, ProMare had a master mariner on site; even when he needed to sleep, he remained on call and ready to respond at a moment’s notice.

For the first three days, everything went exactly as planned: The weather was perfect, the AI was making sound decisions, and enthusiasts and followers all over the world were watching the live feed along with the ProMare team in the monitoring station. The team began to relax a little, getting used to the rotation of “watching the Mayflower,” and monitoring all the data that was flowing back from the many and various sensor arrays and diagnostic systems on the ship.

Then, unfortunately, on Friday June 18, those systems reported a fault. Something was very wrong aboard the MAS.

he ship was 350 nautical miles out of British territorial waters, a tenth of the way to the United States, when it reported that it had insufficient battery power to cruise at its optimum speed of 7 knots. Through internal cameras and other indicators, the ProMare team quickly realized that there was an issue with the generator.

The MAS has a hybrid system that uses solar panels to draw as much energy as possible from the sun. The diesel generator switches on automatically to charge the battery when required (much as hybrid cars operate). The problem with the generator meant that the MAS had to rely solely on solar power, but it was not generating enough solar power to continue its journey.

It was decided that the safest option was to direct the vessel to return to port. At about 100 nautical miles from shore, the ship signaled that its batteries were running low and that it still lacked sufficient solar power to fully charge the battery.

With a heavy heart, the MAS team ordered the ship to power down all nonessential systems and wait for a tow. “We had to wait for the towboat to get to it and get a line on it. But the Mayflower was really stable and waiting. This is why we build these sorts of things. They’re not afraid, they’re not tired, they’re not distracted, they’re not lonely,” Brett noted.

Upon the ship’s return to her homebase in Turnchapel Wharf, the ProMare team investigated the issue and determined that the fault was caused by a fracture in the flexible

coupling between the ship's generator and exhaust system, making it unable to deliver the required electric energy for the journey.

For the next few months, ProMare engineers worked on fixing the issue, designing and manufacturing a new custom exhaust system. They also updated and upgraded all the other digital and mechanical systems while they were at it. It was a great relief that all the systems worked well, and that the small mechanical issue, even though it had led to the cancellation of the first crossing attempt, was relatively simple to fix.

There is always a huge risk of failure involved in developing pioneering technologies, and overcoming difficulties and solving problems is part of the job. Luckily, because the MAS is unmanned, no human was ever at risk of harm—well, other than the stress and anxiety experienced by team members!

(Facing page, top) The Marine AI/MSubs/ProMare team monitored the MAS at all times while it was unescorted outside the EEZ (exclusive economic zone), i.e. 12 nautical miles away from the closest land mass.

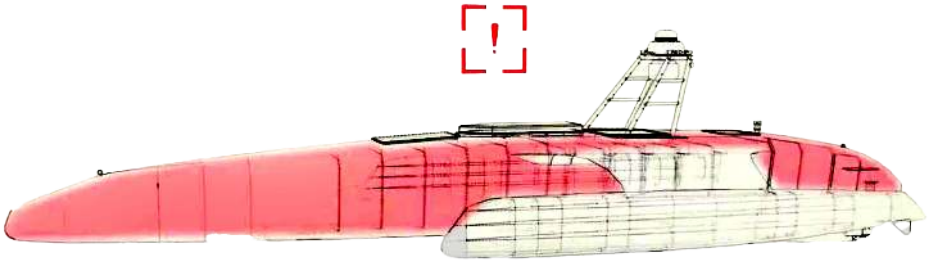
(Facing page, bottom) IBM's The Weather Company provided continuous custom weather forecasts and analysis while the MAS was at sea. It also supplied data daily prior to departure, when forecasting is crucial in deciding the date for the crossing.

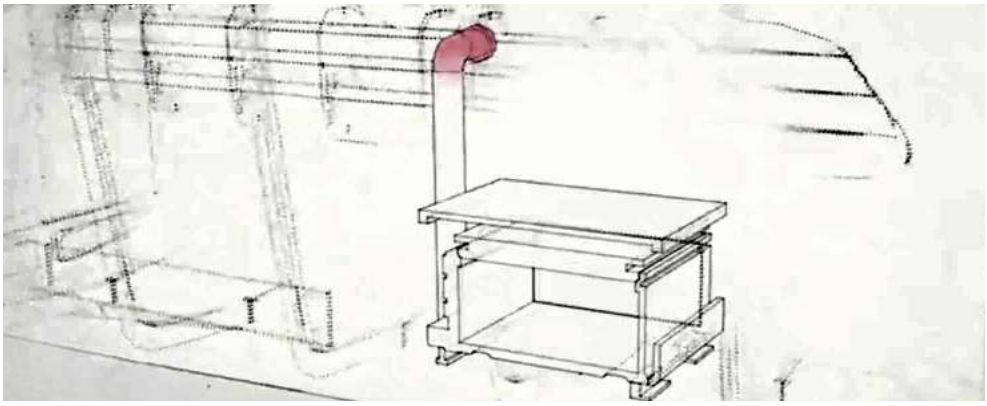
(This page) Illustration showing the location of the mechanical issue that caused the MAS to return to Plymouth in 2021.

Photos courtesy of ProMare/IBM.

"Despite the setback, we've learned a lot and we're more encouraged than ever that the Mayflower will safely navigate the world's oceans in the future," said Brett.

The MAS began a new series of sea trials in December 2021, getting ready for a new crossing attempt.





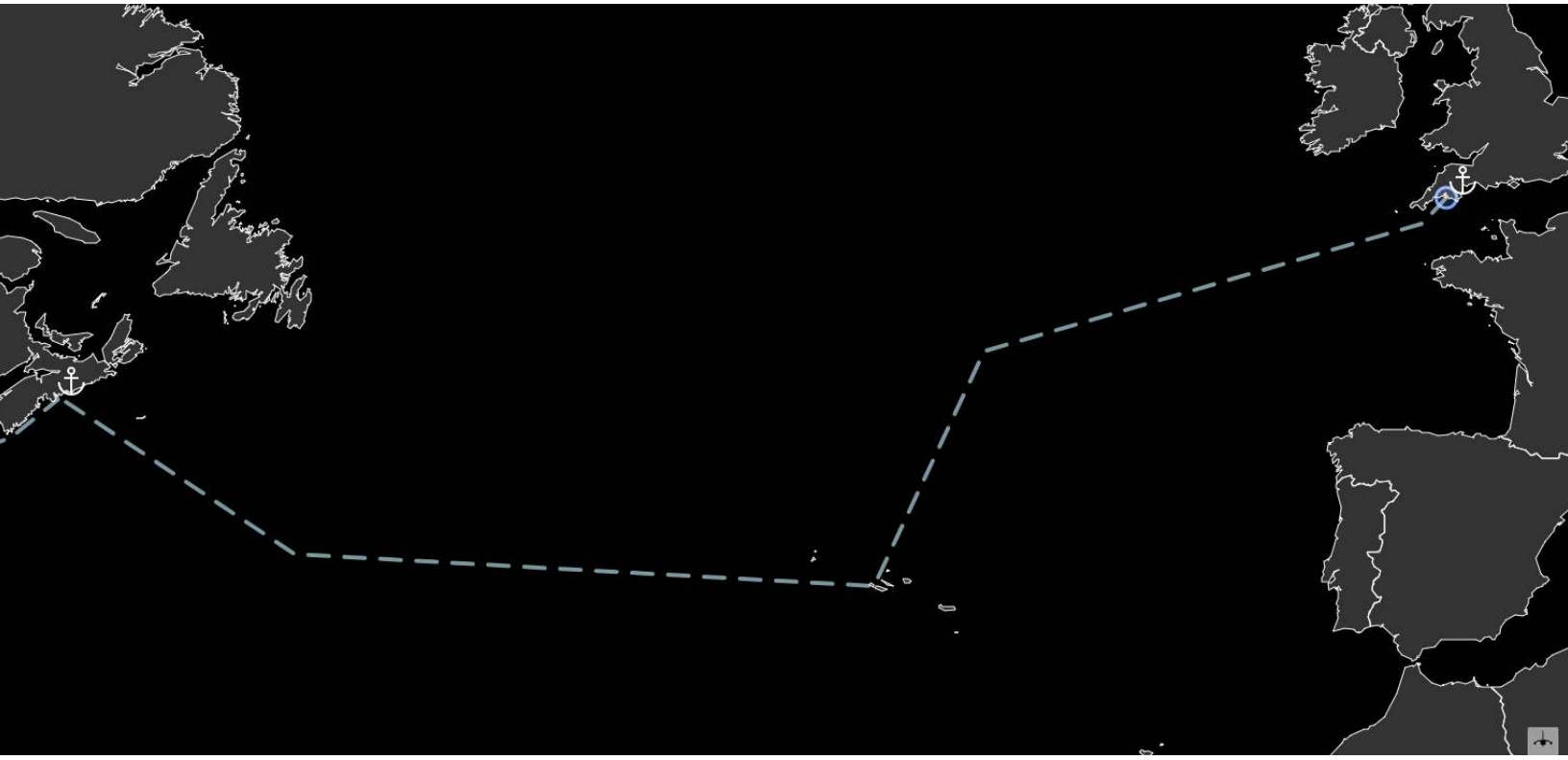
Scan this QR code to see footage of MAS' departure for the first transatlantic crossing attempt.

CHAPTER 10:

THE ATLANTIC CROSSING 2022

The Mayflower Autonomous Ship embarked on its journey across the Atlantic Ocean on April 27, 2022. The systems had been updated and tested and the weather forecast was looking very promising. The MAS was escorted to the 12 nautical mile limit and then started on the 3,220 nautical mile journey.

Photo courtesy of ProMare/IBM.



For the first week, everything looked good. The team were monitoring the journey from the control room in Plymouth, UK. After a few days, the vessel had travelled further than it had during the first attempt. Then several small error messages were detected. One of four batteries on board appeared to be out of balance and while this was a manageable fault, having a look at it was the better option.

The ProMare team had already identified the harbor of Horta (Faial Island, Azores) as a contingency pit stop and established contacts there prior to departure. A decision was made to sail to the Azores and the ship was instructed to turn south after contacts in Horta had been informed of its impending arrival. However, after another day, the ship's generator failed to restart at the beginning of the charge-cycle. In order to preserve the charge left in the batteries, replenished to some extent by solar charge during daytime, the monitoring team turned off all nonessential functions and let the ship remain in standby mode. After another day of sailing south, the ship's generator stopped suddenly and completely, requiring a recovery to be organized. Three members of the MAS team jumped on to the first plane to the Azores. Luckily, a local company experienced with rescues, Mid Atlantic Yacht Services from Horta, was available to take the team to collect the ship and tow it back to a safe harbor.

This was a very simple and quick fix—the ProMare team simply removed the failed switch. This was safe since nobody would be inside the hull until the ship landed in the USA. The MAS was ready for departure within a few hours.

(This page, top) The MAS route across the Atlantic included the stop in the Azores, ending in Halifax.

(Facing page) The MAS in open waters off the Azores.

Photos courtesy of ProMare/IBM.

This break luckily coincided with a major storm, which the MAS waited out in harbor before heading out for the second leg of the crossing. On May 5, 2022, Mid Atlantic Yacht Services sent a small rib to untie and tow the MAS into open water. The MAS team were then able to drive the ship via remote control from the monitoring center in Turnchapel Wharf. Then, once it was safe to do so, the team turned the autonomy on and the MAS sailed back into the Atlantic Ocean.

Having missed the 400-year anniversary of the original *Mayflower* crossing in 2020, the team were keen to celebrate another milestone: the 150th anniversary of oceanography and ocean science, which had begun with the Atlantic crossing made by HMS *Challenger* in 1872.

(This page, top) The MAS at sea.

(This page, bottom) The MAS being towed out of its mooring in Horta, Azores.

(Facing page, top) The control center readouts kept the MAS team apprised of the crucial data, such as heading, speed, position, and all other variables.

(Facing page, bottom) People on ships that stop at Horta before crossing the Atlantic Ocean leave a painting or message on the harbor sea wall. Tradition has it that this ensures a safe return home. The MAS is now among those paintings.

Photos courtesy of ProMare/IBM.

Scan this QR code to see footage of MAS' departure for the transatlantic crossing, and the arrival in Halifax and ultimately, in Plymouth, Mass.

HMS *Challenger* left Portsmouth on its groundbreaking expedition on December 21, 1872 and returned to Spithead, Hampshire on May 24, 1876. The voyage lasted 1,000 days and covered more than 68,000 nautical miles. It is generally considered the first oceanographic expedition since it gathered data on temperature, currents, and water chemistry at 362 oceanographic stations, and discovered 4,717 new species of ocean life. It also sounded the ocean bottom to a depth of 8,183.88 meters (26,850 ft), which is why the deepest point in the ocean is called the Challenger Deep.

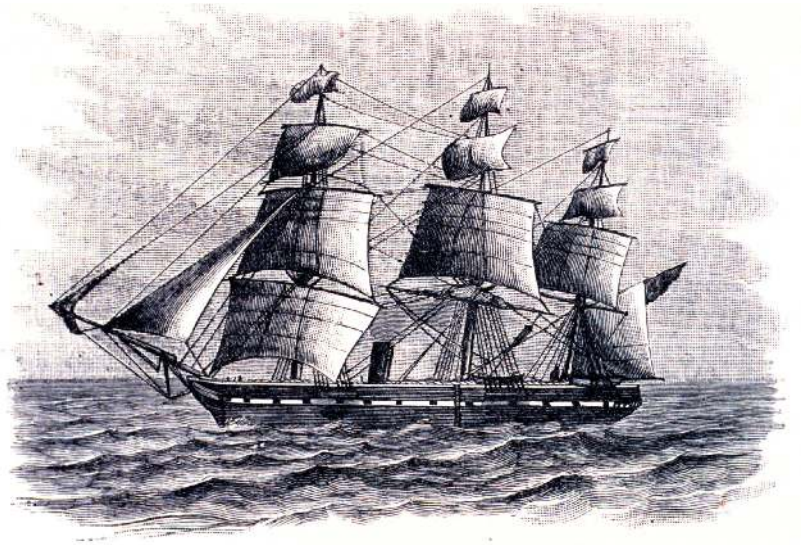
Like the HMS *Challenger*, the MAS crossing was also an oceanographic expedition. However, whereas the HMS *Challenger* had to spend months and even years at sea to gather a few hundred temperature soundings, the ProMare team could simply log on to observe both live images and collect scientific data as their ship sailed in the Atlantic Ocean.

To commemorate the achievements of the *Challenger* expedition, on May 20, 2022, the MAS was sailed to two of the *Challenger* science stations, numbers 73 and 74, in the vicinity of the Azores, before it continued its voyage to America.

(This page, below) HMS *Challenger*.

(This page, bottom) The MAS moored in Halifax for inspection and repairs.

Photos courtesy of ProMare/IBM.



H.M.S. Challenger preparing to Sound, 1872.

(Facing page, top) A screen capture showing the sea state during the storm approaching Halifax. The MAS, being a trimaran, is unable to right itself if it is flipped, so these waves were quite worrisome.

(Facing page, bottom) A screen capture showing the MAS website dashboard.

Photos courtesy of ProMare/IBM.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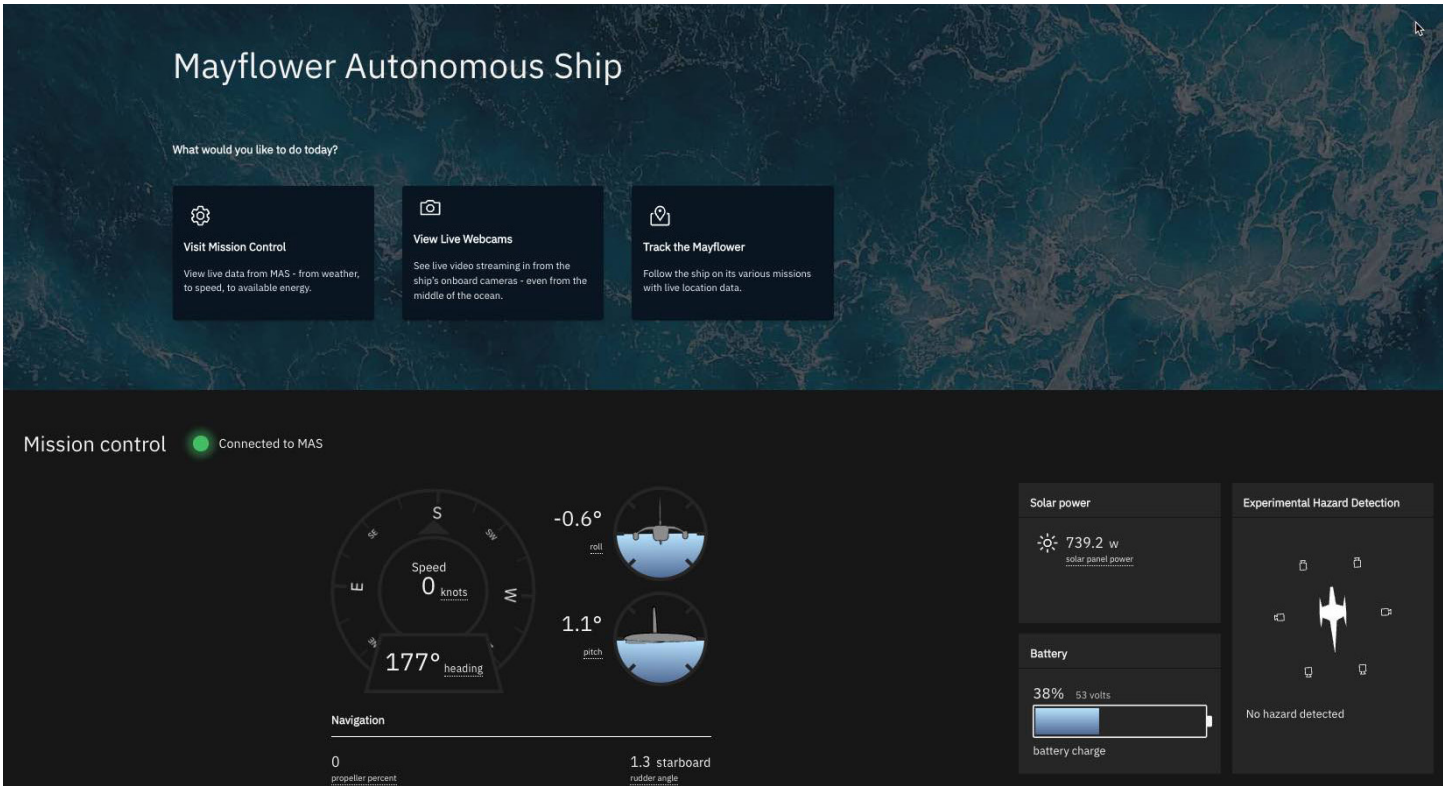
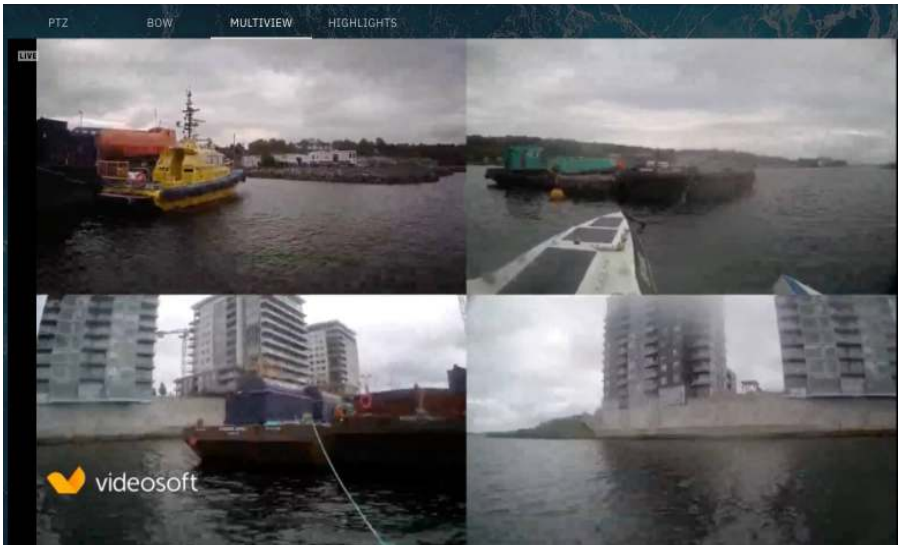

Mayflower Autonomous Ship
What would you like to do today?
Visit Mission Control
View live data from MAS - from weather, to speed, to available energy.
View Live Webcams
See live video streaming in from the ship's onboard cameras - even from the middle of the ocean.
Track the Mayflower
Follow the ship on its various missions with live location data.
Mission control
Connected to MAS
S
E
W
Speed
0 knots
177° heading
-0.6°
roll
1.1°
pitch
Navigation
0
propeller percent
1.3 starboard
rudder angle
Solar power
739.2 w
solar panel power
Battery
38% 53 volts
battery charge
Experimental Hazard Detection
No hazard detected

(This page, top) The MAS sails through the harbor in Halifax.

(This page, right) The cameras on the MAS transmitted live images of the ship as it was moored in Halifax harbor.

(Facing page) The MAS next to the Mayflower replica ship in Plymouth, Mass.

Photos courtesy of ProMare/IBM.



On May 27, 2022 the weather began to turn against the MAS and within a day or so, the ship was in a substantial storm. A combination of slowing down a couple of knots coupled with the effects of the storm, which intensified and resulted in increased swell, waves, wind, and currents all coming against the ship, meant that progress was diminished.

So, on May 30, 2022, the team took the decision to divert to Halifax, Nova Scotia, which was at that time only 500 nautical miles away, and the closest harbor in America. After a few days, the MAS reached the meeting point and hooked up with a towing vessel sent from Halifax. Thus the MAS arrived at the harbor on June 5, 2022, completing the Atlantic crossing. The ship had been out at sea for a total of 31 days, and covered 3,500 nautical miles.

In Halifax, the ship underwent basic maintenance before setting out on the last leg of the journey on June 27. The voyage took three days, and the MAS arrived in Plymouth, USA on the morning of June 30, 2022.

The city of Plymouth, Massachusetts, had been waiting for this moment since 2020. The Mayflower Autonomous Ship was welcomed and placed next to the *Mayflower 2*, a replica of the original that had also sailed across the Atlantic Ocean, in 1957 (see photo below and next page).

The MAS was subsequently the centerpiece of the 4 July celebrations and will now stay in America to do oceanographic research.

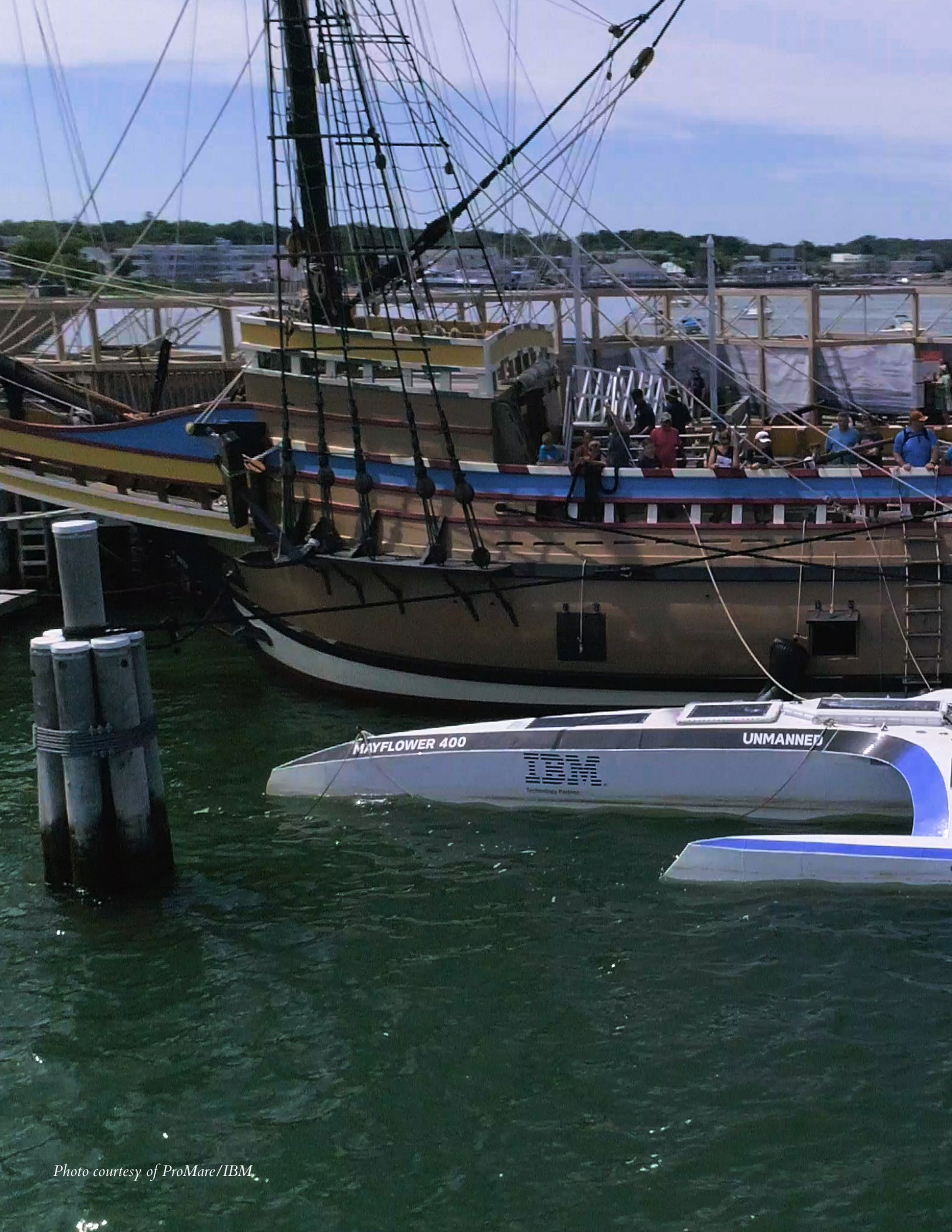


Photo courtesy of ProMare/IBM.

CHAPTER 11:

THE MAYFLOWER AUTONOMOUS SHIP'S CREW

This project is the result of years of hard work and contributions by our brilliant, dedicated team. The majority of the "people of Mayflower" have put considerable time and energy into this project just because they found it interesting and the work fun. We were so very lucky to gather this team and have this adventure together.

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Beth Goodwin (Jupiter Foundation)
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J. E. Higham (Liverpool University)
Miguel Morales (Newcastle University)
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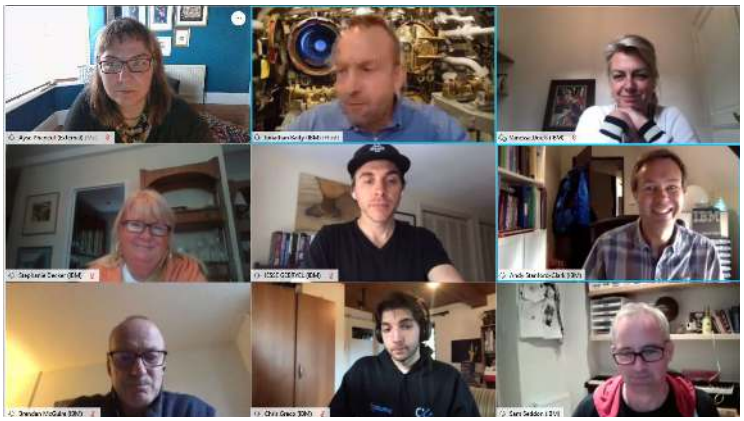

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Emma Sullivan (Plymouth Marine Laboratory)
Georgina Ramn (Plymouth Marine Laboratory)
Sarah Breimann (Plymouth Marine Laboratory)
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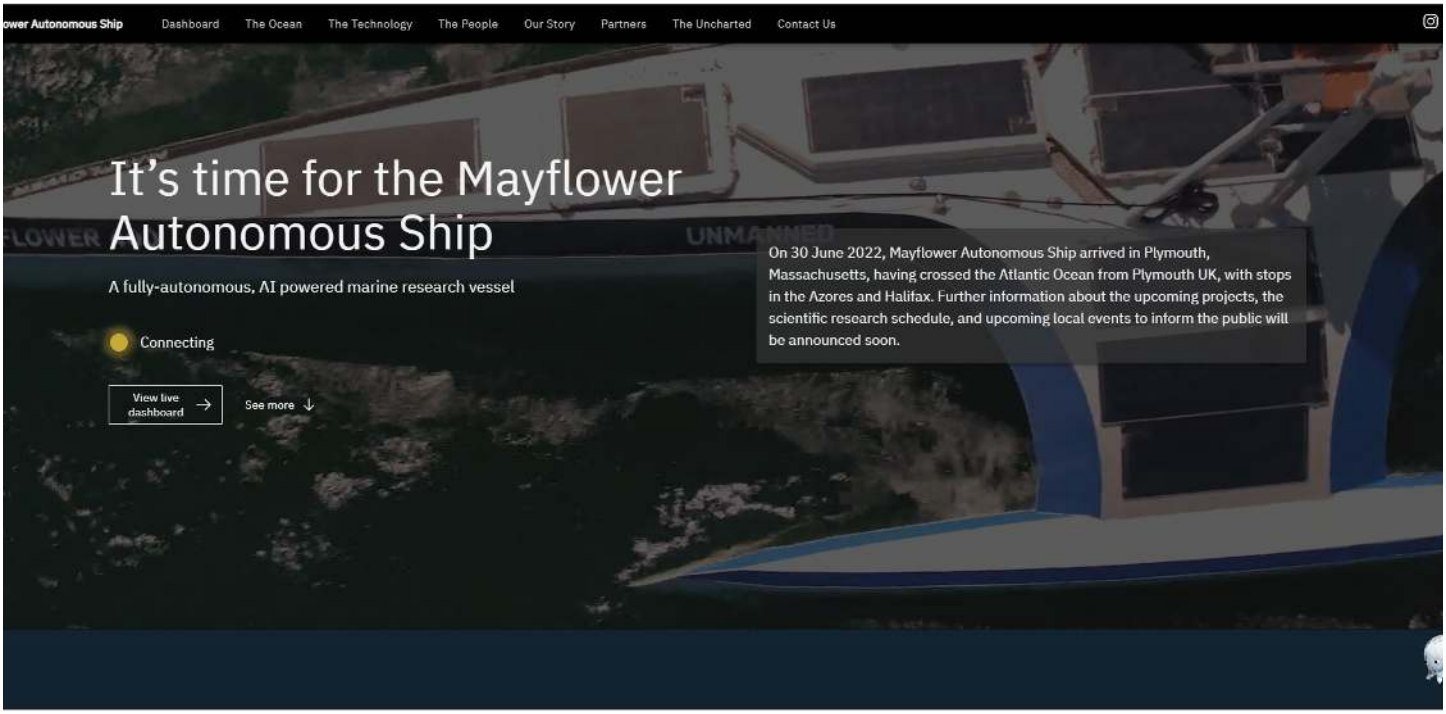

PROMARE

MAYFLOWER AUTONOMOUS SHIP

IBM Technology Partner

This is the story of Mayflower Autonomous Ship (MAS). In 2022 it became the first autonomous ship to cross the Atlantic Ocean, after several years of trials and development.

With no human captain or onboard crew, MAS uses the power of AI and automation to traverse the ocean in its quest for data and discovery.

The ship's AI Captain performs a similar role to a human captain. Assimilating data from a number of sources, it constantly assesses its route, status, mission, and makes decisions about what to do next. Cameras and computer vision systems scan the horizon for hazards and streams of meteorological data reveal potentially dangerous storms. Machine learning and automation software ensure that decisions are safe and in-line with collision regulations.

This peopleless ship will continue to bring people together to define a new era of shipping and ocean research.