REx IV deployed on the Charles River in Boston, MA.

The REx

MIT Sea Grant's autonomous vessel for data acquisition and dissemination

BY MICHAEL DEFILIPPO

There are several limitations to autonomous underwater vehicles (AUVs), including low-bandwidth communication abilities, slow speeds, and limited battery life. The Massachusetts Institute of Technology (MIT) Sea Grant's AUV Laboratory has been working for several years to transfer the high-bandwidth communications and increased power capabilities of remotely operated vehicles (ROVs) to the lab's remotely operated reef explorer (REx) vehicles. The REx suite of robotic submarines provided higher energy capabilities than traditional small AUV systems along with giving the operator the ability to control the ROV from afar via the Web, rather than from onboard a ship. While the first three REx vehicles successfully overcame certain limitations of AUVs, the surface buoy used for communications proved to be a limitation on the maneuverability of the vehicle.

The next iteration of the REx family of vehicles will attempt to address all of these limitations. The REx IV system replaces the former surface expression—a passive high-drag buoy—with a completely autonomous or supervisory-controlled surface vessel, capable of deploying and extracting an ROV or oceanographic sensor suite from the ocean, with the added capability of traversing to a new location efficiently and at higher speeds. The new overall system design will enable a broader range of operation in the littoral regions of the seacoast and into the open ocean. With this new design, we have decided to rename our efforts the Remote Explorer program. This will keep with the REx-class naming convention for the vessels themselves, while indicating that this is a versatile exploration system intended for use in all regions of the coast.

REx I to III

The REx vessels were developed for capability in remote education and remote research. The first REx was built for the Hawaii Institute of Marine Biology with the aforementioned purpose in mind. Over the six months of fabrication, many improvements to the original design were implemented and by the end of 2008, the vehicle was completed in Cambridge, MA and shipped to Hawaii. Once onsite, it was made operational by a technician and deployed by mariners. The vehicle was then operated remotely by MIT staff from the MIT campus for several hours over the course of the next few days.

After this successful trial of the technology, the first educational users—a group of Hawaiian high school students—were brought into the classroom to pilot the

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vehicle and identify potential failures of the missions. These students, with the help of local teachers, operated REx for a dozen hours performing transects of a coral reef while sampling the ocean for temperature and salinity. The students piloted the vehicle successfully and aggregated the data on charts in the classroom and for several months thereafter analyzed their findings to draw conclusions about the state of the ocean.

The student trial demonstrated that this second test of the system was a success, leaving one final systems-level test of the logistics of deployment. REx I weighed 300 pounds and was 3 ft. long. A typical deployment involved hiring a forklift operator and a small boat for the day, along with a navigator and a robot engineer. This team (sans forklift) would transport the submarine to the target reef by motorboat. Once onsite, the navigator would communicate with the classroom indicating all systems were okay to go. When the classroom was ready, they would indicate as much and the engineer would push the reef explorer into the ocean and then dive in after the machine to perform the precise underwater manipulations of the mounting system clamps required to begin a mission. The mission would be executed, and the vehicle recovered through a similar process in reverse. The motorboat would then move approximately one-half mile and the launching process would begin again.

The only conclusion to be drawn from this experience was that the logistics were simply not cost-effective. If the system were left unchanged, it was very unlikely that our target users would be able to handle the necessary logistics, or be able to hire a team for the length of time needed to carry out the tasks. This finding was substantial. It indicated that the concept was sound and worthwhile, but the deployment architecture was unreasonably complex. Everything from the radio modem to the size of the vehicle needed to be rethought. The forklift needed to be eliminated from the launch protocol. The speed of transition between deployment sites required a dramatic increase and the complexity of the process, a reduction.

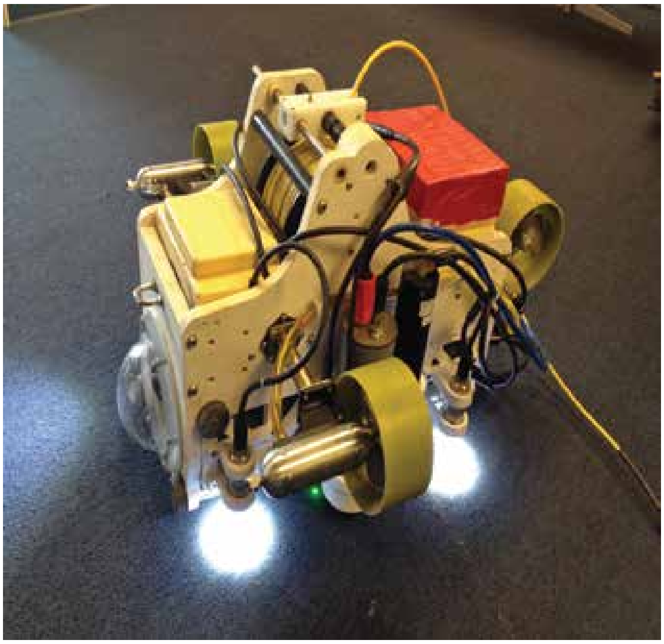
The first target was to reduce the size of the vehicle and, by virtue of material selection, eliminate the need for the forklift and its operator. The Reef Explorer II prototype was designed and fabricated over the course of six months with the goal of a final form that was half the size and half the weight of its predecessor. This was achieved and a similar test to that of the first REx was executed. The vehicle worked well enough and no longer required heavy lifting or tending by divers; however, it still required an engineer onsite in a boat to toggle the vehicle on and off while moving it between mission locations. It became clear that, for maximum efficiency, the vehicle would have to be able to get from the dock to the reef without the aid of a marine operations team and attendant vessel. It also became clear during the student tests, and even more so during the engineer pilot tests, that the vehicle would need an autonomous reef collision avoidance system.

REx I deployed in Hawaii.

From the ground up

Requirements for this research were simple, the general idea being that any mission requiring a human diver should be possible using a Reef Explorer. With this in mind, the vehicle was equipped with the sensors required for species identification and water quality analysis; better cameras were installed and reliability was improved. In winter 2010, the REx II suffered an unrecoverable failure

The REx *continued*



REx III during mission preparation.

REx IV obstacle detection sensor suite.

with the winch and tether and was disassembled and rebuilt from the ground up. The batteries were improved with a new packing design and expanded with a power distribution board; the computer was replaced with a better processor and network interface; and all of the communication ports were broken out into a custom expansion board. The hull was redesigned to include a robust but lightweight general-purpose mounting bracket, and LED lights were added. The winch was redesigned and rebuilt to enable simple field repair. After four months of work, the Reef Explorer III had been developed into a powerful and serviceable machine.

In 2011 and 2012, the REx III was used for several missions in collaboration with the University of Maine with the goal of autonomous identification of Didemnum vexillum by REx III equipped with an appropriate sensor, the hyper spectral radiometer (HSR). Although it was difficult to find the species at sea, after months of searching the combination of REx III and the HSR proved that it was possible to autonomously identify growths of Didemnum vexillum. That same year, REx III was tasked with surveying local eelgrass beds for damage from anchors and identifying the outer perimeter of the fields. Regrettably, the research team was unable to find eelgrass in low-current areas of the Massachusetts Bay and the missions were mildly successful at best. Regardless, the REx III had proved amazingly successful and adaptable in the field based on approximately 200 dives with a team of fewer than three during that one year of operation.

With a reliable vehicle and a long list of successful missions, our goal of offering every student the opportunity of diving remotely on a reef required us to solve the remaining logistical challenges. The REx I, II, and III had certain serious limitations. The vehicles were slow, comparable to a human swimmer; and they all shared a particular design feature: the surface buoy required for transmitting communications. These features required a trained team to handle the delicate connection between buoy and vehicle and, in addition, a marine deployment team was needed to expedite the process of moving from the dock to the target site. Our solution was to replace the buoy with an autonomous surface vessel (ASV) equipped with a winch capable of extracting the vehicle in its entirety from the ocean; this would enable high-speed translation. An ASV has additional benefits, most notably a large surface area and positive buoyancy that allows for a large payload of energy storage.

REx IV

Remote Explorer IV is the fourth robot in the REx series designed for remote research. This vehicle's design includes innovative use of a tether, winch, and GPS device, coupled with an autonomous surface vessel. The current vessel has the ability to collect samples or deploy an ROV at a depth of 30 m, but with a simple tether upgrade would be able to reach depths of up to 100 m. This combination enables sampling of the local underwater environment at depth with various marine sensors and high definition video. The data collected is streamed in real time through a radio modem onboard the ASV to a nearby relay station and then to the Internet. This architecture enables two-way, real-time communication between a user on land and the robot.

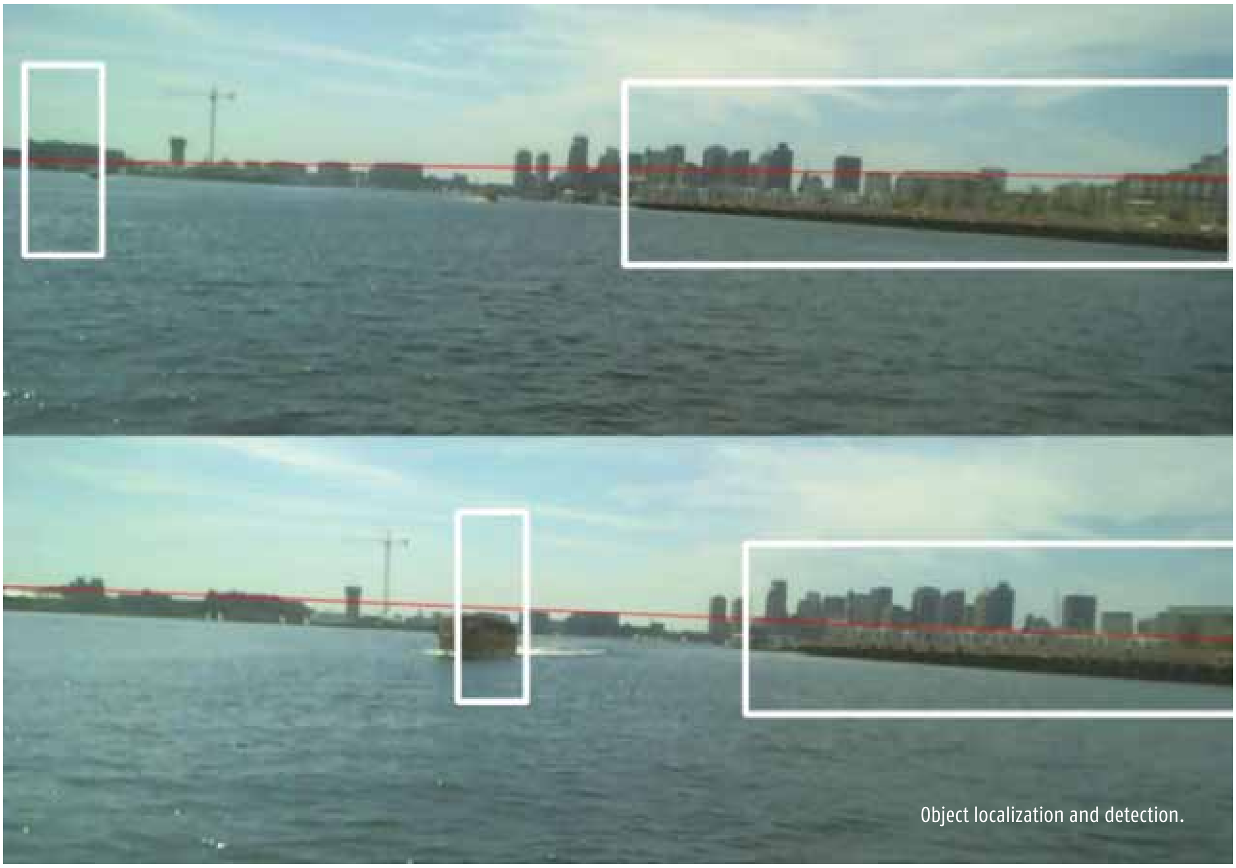
> *A typical deployment involved hiring a forklift operator and a small boat for the day, along with a navigator and a robot engineer.*

The REx IV vessel consists of an ASV with a sensor suite or an ROV attached to a winch/tether module onboard the vessel. REx IV will now autonomously navigate from waypoint to waypoint using the MOOS-IvP programming architecture. When the ASV reaches the waypoint of interest, REx will autonomously lower the sensor suite or ROV into the water column and dynamically station keep at the location while the tether is deployed. Once the mission is complete, the tether will be retracted and the ASV will navigate to the next location of interest and repeat the deployment.

REx is a completely electric vehicle and is intended for day-long studies, and to be used as a force multiplier. If multiple REx vessels are deployed for mundane or dangerous tasks, this can significantly free up researchers' time. REx IV will have the ability to travel autonomously up to 5 nautical miles to reach its study area, 10 nautical miles round trip. Deployment range is limited by radio communications and battery load, and can theoretically be extended with a satellite uplink as well as by adding power. The ASV, having deployed the tether, can either send data collected with a sensor suite back to shore, or allow real-time command and control of an ROV through a video uplink.

The ASV will be operating in areas with navigation buoys, small recreational vehicles, and large oceangoing vessels, as well as natural obstacles. This means REx will inevitably encounter static obstacles along with maritime traffic.

The REx *continued*



Object localization and detection.

Human-in-the-loop monitoring is possible, and will be required to meet all current International Regulations for Preventing Collisions at Sea (COLREG) conditions. We are creating software for a suite of sensors that can enable the vessel to avoid hazards while transiting to the target site.

The ASV will host a suite of onboard sensors with data processing capability to support autonomous collision detection and avoidance. Software to support avoidance in non-COLREG situations is currently available. The MOOS-IvP autonomy suite provides standard avoidance and safety behaviors for use onboard the vessel. These behaviors, coupled with the onboard sensor suite, will provide the backbone of the navigation and autonomy system.

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The ASV has been developed to be used as an ocean science data collection platform as well as a communications platform to allow for supervisory control of an ROV from any Internet connection. The primary navigation and object avoidance software was developed in conjunction for use in open water applications. The ASV accomplishes this by taking advantage of the MOOS autonomy software package that was developed here at MIT Sea Grant. With applications created specifically for each sensor, the ASV will be able to safely traverse the open ocean.

Stringent requirements

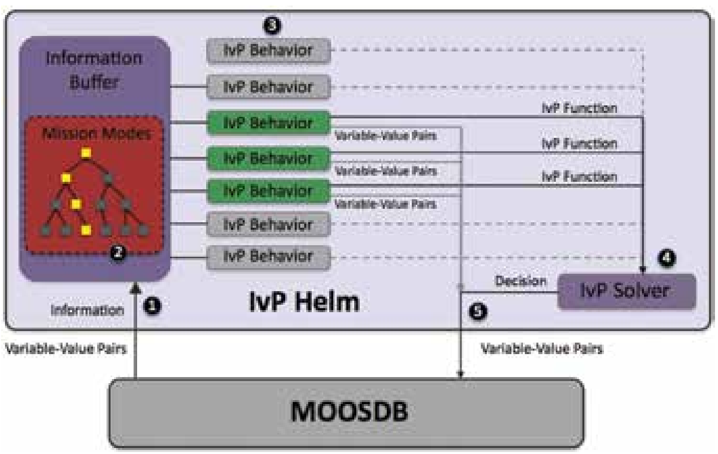
Marine sensing requires sensors that are capable of identifying hazards while countering environmental factors such as precipitation, temperature, visibility interference, sunlight/

glare, sea state, vehicle speed, and the corrosive effects of saltwater. Sensor processing is accomplished by onboard embedded computing systems. The onboard embedded computers will handle the processing of sensor data and decide how to best react to the ocean environment. Sensor data currently includes raw GPS data, Velodyne light detection and ranging (LiDAR) data, and camera data. Other obstacle avoidance and navigation sensors, such as an additional LiDAR unit, automatic identification system, and an IR camera will be added in the future.

As noted earlier, there is no all-in-one sensor available for safe navigation, so many sensor options must be employed in order to navigate safely in an ocean environment. Multiple requirements must be met and each sensor plays a different role in meeting these requirements. At short and medium ranges (<100 m) the Velodyne LiDAR and the camera are the main sensors for object detection and recognition. Because the vessel is not moving at high speeds, these sensors suffice for safe navigation. Future iterations may include smaller LiDAR units for enhanced short range (<10 m) detections, as well as an IR camera for long range detections (>100 m). The IR camera is versatile and can be used for short, medium, and long-range detections. For long range missions, the surface vessel must be able to let other boats know of its location through multiple communications (navigation lights, AIS, pose/position) in order to avoid being run down. All of this sensor data must be processed in real time so that it can make decisions and react on the fly.

The 16 ft. wave adaptive modular vessel (WAM-V) functions as the platform around which the ASV is built. According to specifications, this vessel can safely operate in up to sea state 4. This enables a more flexible deployment schedule, without the need to wait for ideal weather conditions. The ability to handle such elevated sea state is due to the WAM-V's articulating pontoon design. For open ocean conditions, the vessel has recently been slightly modified to accommodate larger electric motors. The modifications come in the form of articulating motor pods that move in concert

The REx *continued*



MOOS and the IvP helm architecture.

REx IV's autonomous sampling path in Boston Harbor.

with wave action to keep the motors in the water, thus ensuring maximum thrust and vessel stability.

Object localization and identification

To achieve truly autonomous navigation, we will need REx to localize and identify objects on the water. The goal is to give REx the ability to use sensor data from the onboard camera and LiDAR to avoid collisions; recognize possible threats and avoid them; predict and plan a trajectory; and to generally navigate safely. Our steps are to first detect objects using sensor data using horizon line detection algorithm and background subtraction algorithm to help make object localization and identification faster. The second step is to identify what these possible objects are (for example, rocks, vessels, or buoys). We are using convolutional neural networks for object identifications, used in many machine learning applications.

The software architecture system used by this vessel is MOOS-IvP. The MOOS part stands for mission oriented operating suite, and the IvP part stands for interval programming. The system is developed jointly by the MIT Laboratory for Autonomous Marine Sensing Systems (LAMSS), MIT Computer Science and Artificial Intelligence Lab (CSAIL), and the Oxford Mobile Robotics Group (MRG). The AUV Laboratory at MIT Sea Grant has been a MOOS-IvP developer and user for past and current autonomous vehicle designs. Overall, MOOS-IvP is a set of open source C++ modules with a mathematical programming model for multi-objective optimization that provides autonomy to robotic platforms, and in particular autonomous marine vehicles.

One focus of the MIT Sea Grant college program is healthy coastal ecosystems. In particular, we are directing our efforts into mapping and understanding the effects of coastal ocean acidification, particularly the effects on local species (scallop, oyster, lobster, and so forth) in Massachusetts Bay. We envision autonomous data collection missions within Boston Harbor and extending into Massachusetts Bay, and eventually into the Gulf of Maine. REx IV is currently equipped with multiple sensors for both surface and water column data collection. We have demonstrated REx IV's ability to travel to pre-selected waypoints within Boston Harbor to gather multiple water quality measurements.

These measurements can be taken at precisely the same location once per week for the summer, or can be taken

Deeper Dive

To learn more about the MIT Sea Grant program, visit **seagrant.mit.edu** multiple times in a single day over a tide cycle. We demonstrated this autonomous measurement capability during summer 2016 in Boston Harbor. REx was able to autonomously navigate the mouth of the Mystic River to the mouth of the Charles River, to Inner Boston Harbor. While navigating across the river mouths, REx stopped at multiple waypoints to cast a multi-parameter sonde through the water column, all while dynamically keeping position.

The way forward

There will be a time where fully autonomous surface vessels (cars, planes, and so forth) are the norm. There is much more research needed to fully realize this goal, and the path that it takes is still very open. At MIT Sea Grant, we envision fleets of ASVs collecting data for weeks to months at a time, enabling ocean exploration and research that is currently unaffordable. Continuous data collection is the dream of all oceanographic scientists. ASVs will become a less expensive and highly adaptable alternative to deep water moorings.

REx IV has been proved to be highly adaptable and will be used for several different missions over the next year. With an integrated off the shelf sonar, we will continue to use REx IV to autonomously map the bathymetry of the Charles River in Boston, MA. We will continue to autonomously collect data within Boston Harbor and plan to venture into the open ocean conditions of Massachusetts Bay as well. We also will integrate an ROV onboard REx to provide real-time control through a remote Web link for researchers and students alike. **MT**

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