REx 4 – An Autonomous Surface Vessel for Marine Research

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Abstract

On conclusion of the 2014 Maritime RobotX Challenge, the vessel of winning team MIT-Olin returned to MIT to be modified for marine research. This paper reports on enhancements to the REx 4 vessel by MIT Sea Grant College for a variety of marine missions, including autonomous navigation of confined channels, automated casting of a scientific instrument, deployment of a Remotely Operated Vehicle (ROV), and bathymetric surveys. Results of field trials and lessons learned are discussed.

Introduction

Since 2008, the MIT Sea Grant College, Autonomous Underwater Vehicles (AUV) Lab has produced a series of submarines for remote education and marine research called Reef Explorer ("REx"). These vehicles were hybrid AUV/ROVs, characterized by a vessel-mounted winch connected by tether to a buoy platform housing GPS and radio modem. By 2012, REx I, II, and III had completed many successful missions, including autonomous identification of invasive species, surveys of subaquatic vegetation, and classroom demonstration via internet. All of these vehicles, however, were limited in speed, range, and tolerance to underwater currents. The AUV Lab concluded that an autonomous surface vessel (ASV) that could deploy an ROV would ease these limitations and began to look for a suitable craft.

In October, 2014, the AUVSI Foundation Maritime RobotX Challenge was held in Singapore. The competition consisted of complex autonomy tasks, including navigation of buoy fields, object detection and avoidance, search and report on submerged sonar sources, visual identification of symbols at docking locations, and subsequent docking. All vessels for the competition were based on the Marine Advanced Research, Inc. **16' WAM-V USV** [1], a flexible, modular catamaran of nominal length 4.88 m (16 ft.) MIT entered the competition in partnership with Olin College. Team MIT-Olin received the overall first-place prize as well as awards for presentation and community support. After the competition at the end of 2014, the competition vehicle returned to the AUV Lab and was repurposed as the **Remote Explorer 4** ("REx 4".)

The objectives of the AUV Lab for 2015 were to prepare REx 4 for deployment with an ROV and associated marine research missions. These objectives included:

- Autonomous navigation of a defined nonlinear channel between target sites

- During such navigation, demonstrate automated casting and recovery of a scientific instrument constrained by measured depth at the site
- Demonstrate the ability to deploy a deck-mounted manual ROV from an autonomous platform
- Demonstrate the ability to run missions remotely via Internet
- Empirically determine maximum mission range and duration
- Explore the use of inexpensive “fish finder” sonar as a bathymetric and substrate composition survey tool
- Identify systems in need of reliability improvement

In this paper, we summarize our approach to these objectives, results of our field trials, and discuss lessons learned.

1. Methods

1.1. Areas of Operation

REx 4 preliminary and developmental test runs were performed at the MIT Sailing Pavilion on the Charles River, Cambridge, MA [Figure 1] between June and November, 2015. Field trials were performed on Dorchester Bay, off of the University of Massachusetts Boston, Fox Point Facility, Columbia Point, Boston, MA, in September, 2015.

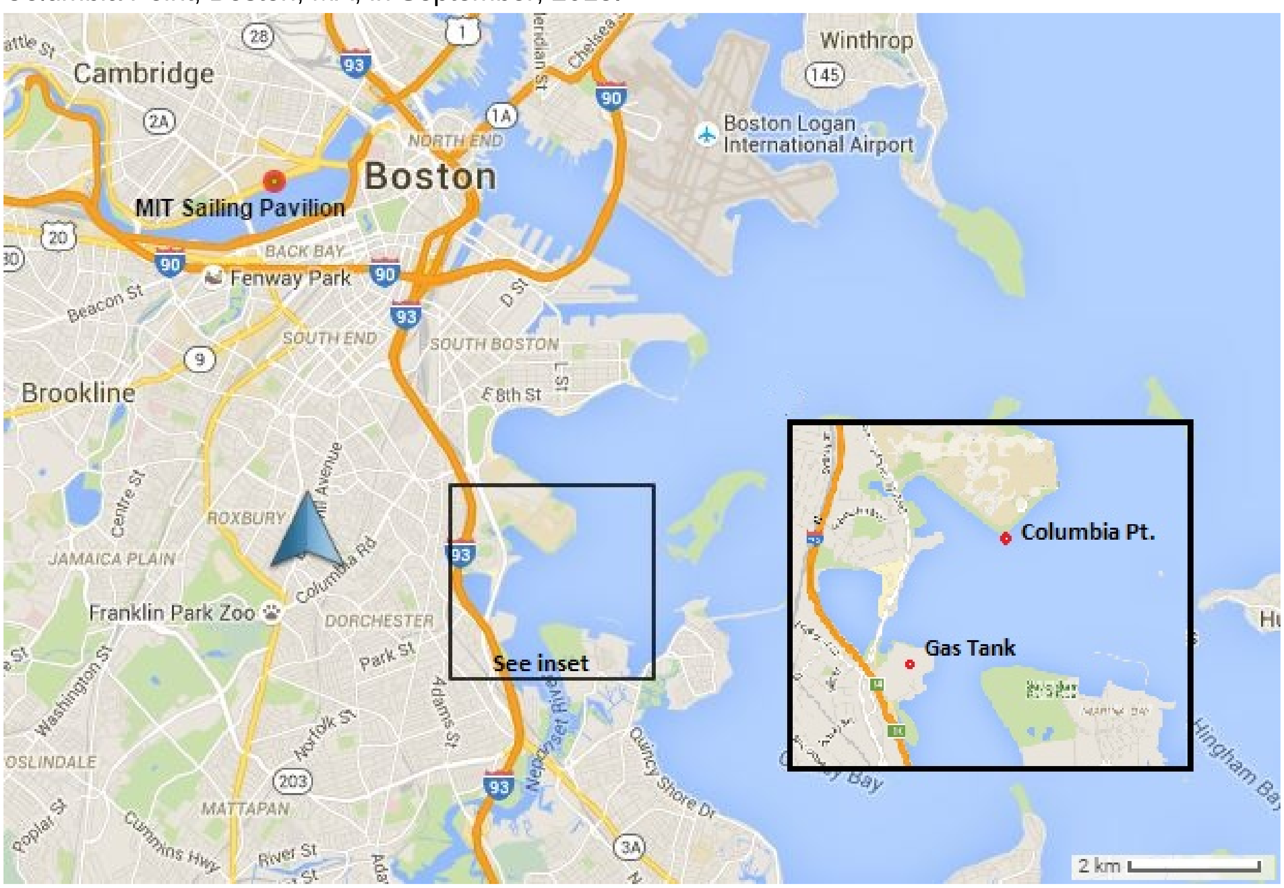

Figure 1: Area of Operations. Map data © Google and © Scribble Maps

1.2. Vessel and Major Components

The Rex 4 vessel and major components are shown in Figure 2.

1.2.1. Vessel and Propulsion

The vessel is a Marine Advanced Research, Inc. **16' WAM-V USV**. As designed by the manufacturer, the craft separates modularly for easy and compact transport. Major components include the upper deck, support cross-bars, and inflatable pontoon components. Hinges and dampers allow the pontoons to pivot independently, improving stability.

As delivered to MIT, the vehicle consisted only of the hull components and did not include propulsion, sensing, computing, or power. The OEM design calls for rear-mounted pontoon extensions that improve keel-line stability and support the weight of electric propulsion and batteries. The selected motors provide minimal thrust for locomotion and, as they are lightweight, do not predicate the installation of pontoon extensions.

The Minn Kota trolling motors are suitable for calm seas and short-duration, low-speed missions. The AUV Lab acquired larger and more powerful Torqeedo Cruise 4.0 motors that will increase the speed and operational distance of the vehicle. For 2015, the objective was to design an interface with the proprietary control system. Installation on the vehicle is intended for future efforts along with the procurement of suitable hull extensions for propulsion mounting.

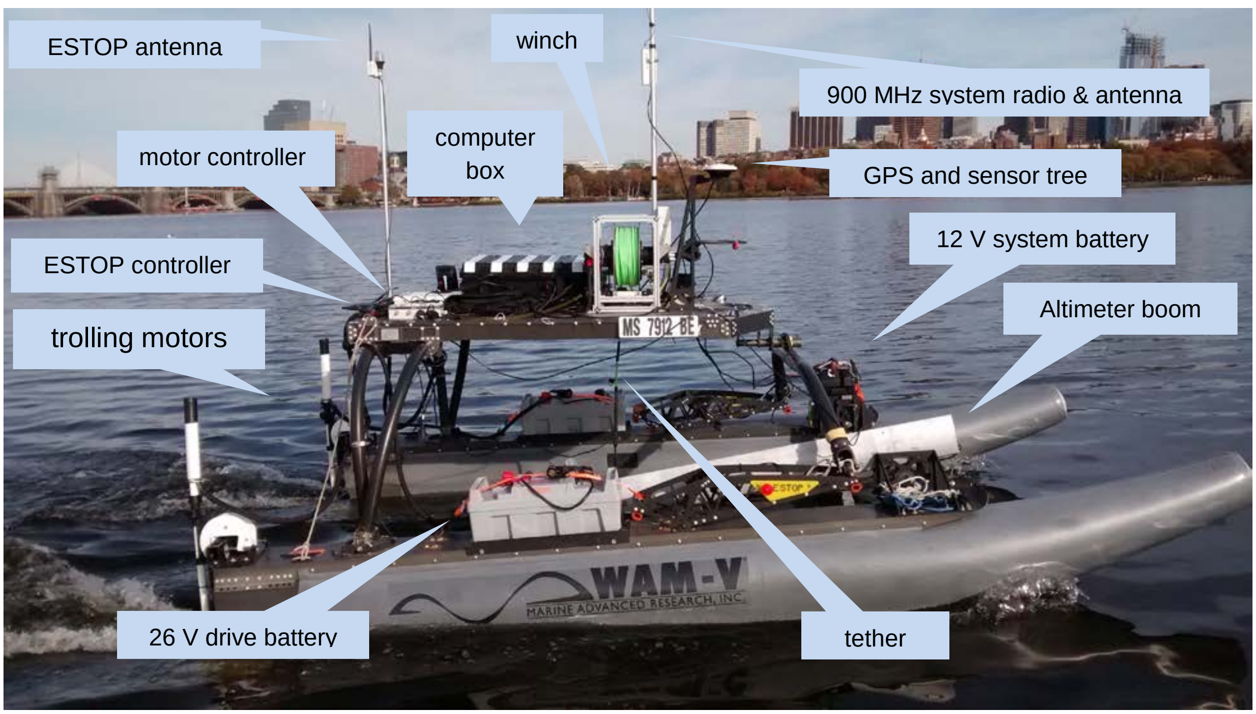

Figure 2: Vessel and Major Components

1.2.2. Batteries

The propulsion batteries are twin Torqeedo 26 VDC, 108 Ah, marine Lithium-Ion cells which are mounted on the pontoons to lower the center of gravity. A separate Optima 12 VDC, 55 Ah AGM battery mounted to the port side pontoon provides power to the computers, radio, GPS, altimeters, and other sensors.

1.2.3. Computer subsystem

A waterproof enclosure contains the computer subsystem, consisting of two Portwell Technology, Nano 6060-E3845 single board computers running Ubuntu 12.04 and connected to a network switch and power distribution panel. The enclosure also contains terminations and adapters for the GPS receiver, ESTOP system, digital camera, multi-beam LiDAR, shore communications radio, winch controller, instrument tether, and water altimeter.

1.2.4. Onboard autonomy software

The REx 4 navigation system is based on the **MOOS-IvP** autonomy software suite. MOOS-IvP is an open-source package currently maintained by researchers at MIT. Historically, components were developed at the MIT Laboratory for Autonomous Marine Sensing Systems (LAMSS) group, the MIT Computer Science and Artificial Intelligence Lab (CSAIL), the Oxford Mobile Robotics Group (MRG), and by various groups at the U.S. Navy. **MOOS** ("Mission Oriented Operating Suite") is a robotic middleware that provides a platform-independent, efficient, and robust architecture for real-time applications components of a robotic system to execute and communicate. The original MOOS design is described here [2] and the main MOOS website here [3]. The MOOS database ("MOOSDB") is central to the architecture, and provides a mechanism for communication between applications. Many REx 4 components are supported by dedicated MOOS applications.

IvP ("Interval Programming") [Figure 3] is a MOOS application designed to provide autonomy on robotic platforms and is particularly well-suited to marine vehicles [4]. IvP **Behaviors** determine how the vehicle responds to its environment in pursuit of some defined goal. Examples include **Waypoint** behavior (traverse a set of given waypoints) and **StationKeep** behavior (maintain a vehicle's position at a given point within a given radius.)

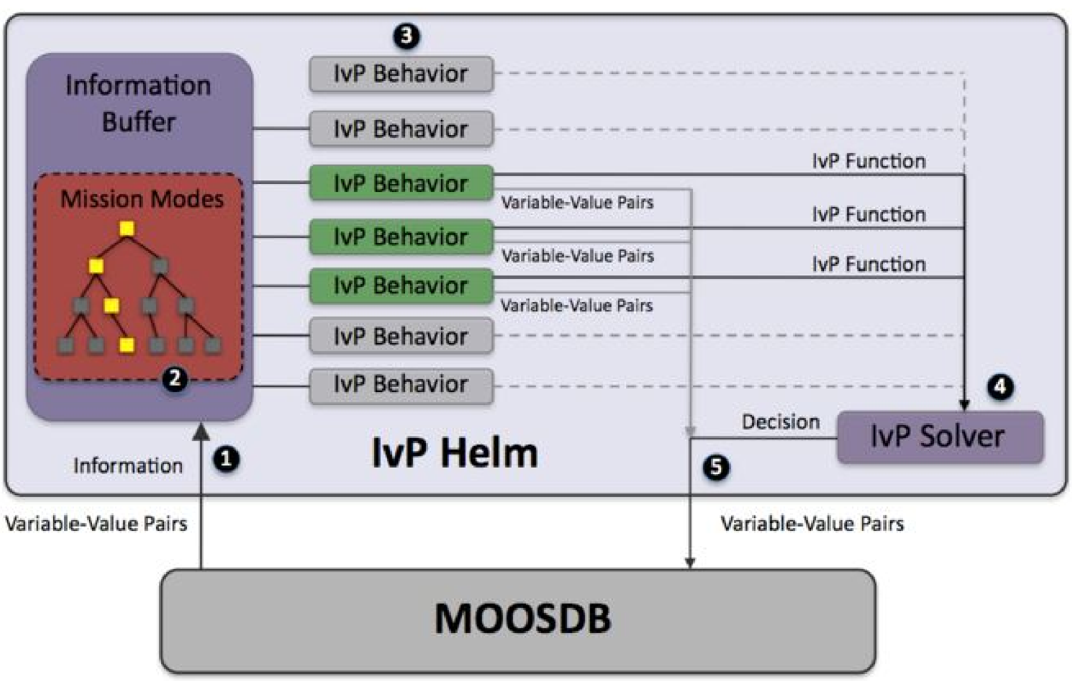

Figure 3: The IvP helm application

1.2.5. Safety and Control subsystem

The Safety and Control subsystem is a critical part of the REx 4. Multiple layers of safety integrate remote and local emergency stops, human control, and when all safety checks are in place, autonomous control of the propulsion system. At the lowest level, clearly marked emergency stop mushroom buttons on port and starboard pontoons are wired directly into the Roboteq VDC 2450 motor controller. Engaging either of the buttons immediately prevents power from reaching the motors. These buttons are tested before every deployment.

An onboard Emergency Stop (ESTOP) system is managed by an embedded microcontroller. System inputs include motor control requests from the remote Operator Control Unit (OCU) [Figure 4] or from the vessel-mounted autonomous control computer system. In normal operation, the desired motor speeds are passed on to the Roboteq motor controller, which manages thrust. Several safety conditions cause the ESTOP to stop the motors, including emergency stop button actuation on the vessel and the OCU and a watchdog that requires 1Hz updates on thrust requests. In manual control mode, the OCU sends these requests. When the OCU permits, the MOOS autonomy subsystem publishes the requests.

Microcontrollers in the remote OCU and the onboard ESTOP systems are linked by 925 MHz X-Bee radios with a range of about 75 m. Longer-range missions require the OCU be mounted on a chase boat. If the OCU and ESTOP controller fall out of radio range, the watchdog triggers and motor actuation ceases.

The OCU provides the following monitoring functions:

- Allows the operator to assert an ESTOP (the large red button)
- Allows the operator to sound the vessel horn
- A physical tether (“deadman switch”) can be connected that engages the ESTOP if the operator is not proximate to the OCU box
- Provides a Manual Control button that takes the vessel out of autonomous control. Pressing this button while moving the OCU joystick drives the vessel ahead, astern, to port, or to starboard
- Provides a MOOS Control Start/Stop button that enables autonomous control as follows:
    - System states not ready for autonomy and/or autonomous control is not cued: Vessel must remain under manual control
    - System states are safe for autonomy and autonomy is ready: Vessel control may be changed into autonomous (MOOS) control
    - System is under autonomous control: Autonomy will be stopped and vehicle will regain manual control

The OCU provides the following monitoring functions:

- ESTOP status:
    - Switch on vessel is engaged
    - Switch on OCU is engaged
    - Local and vessel safety systems are not engaged, motors are free to engage
- Communications
    - If not lit, indicates system is off
    - System on but not communicating with vessel
    - System on and communicating properly with vessel
- Thrust Motor Batteries
    - Batteries capacity in normal operating range

- o Low batteries
- o Batteries at critically low levels

- Manual Control
  - o Vehicle is able to be manually controlled
  - o Manual control is unavailable
- Autonomous Control
  - o Autonomous control can be engaged
  - o Cannot be engaged
  - o Is engaged

During a typical mission, the operator may take the vessel in and out of MOOS control several times in order to, for example, avoid other vessels or perform an equipment check on the vessel. The OCU can be installed in a chase boat to allow single-person operation of the chase boat and the OCU. [Figure 5.]

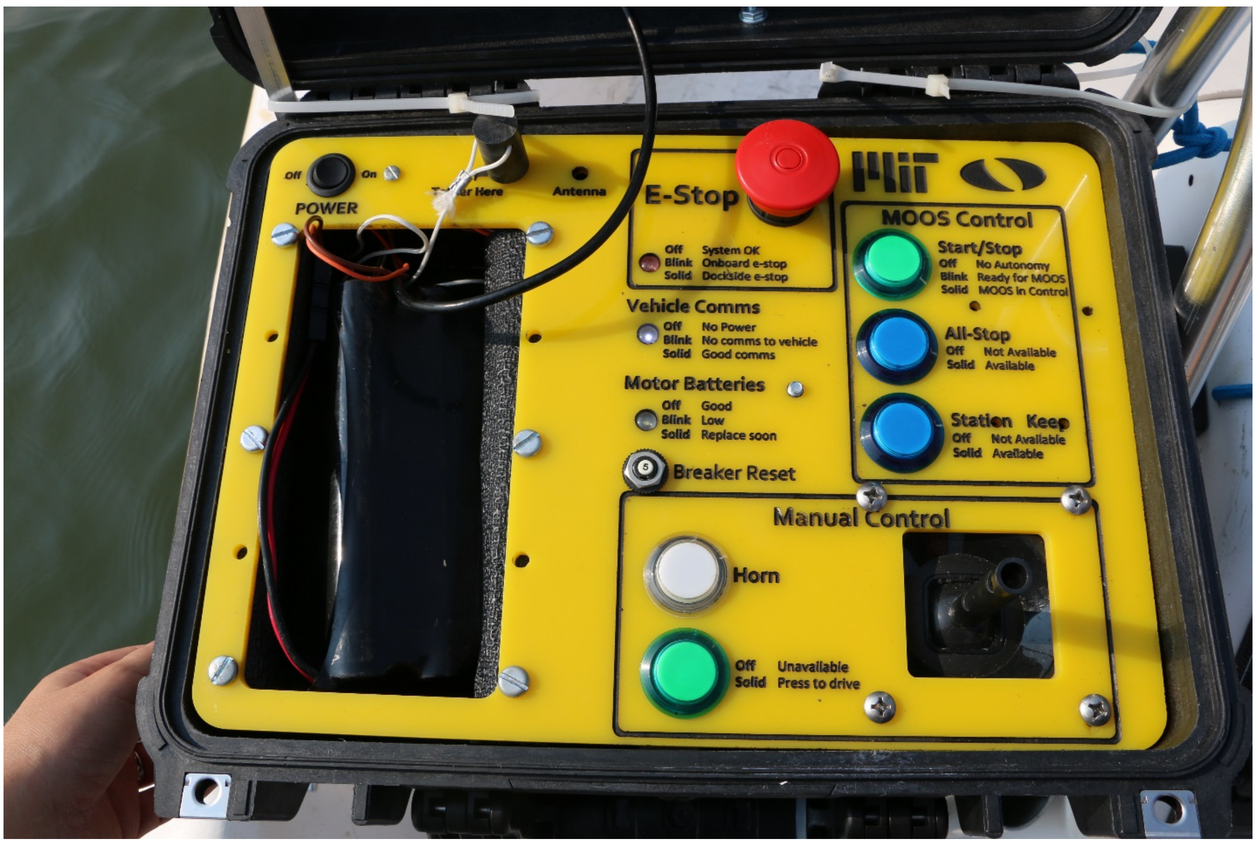

Figure 4: Operator Control Unit (OCU)

Figure 5: Driving REx 4 by OCU while underway on a chase boat

1.2.6. GPS

The Hemisphere Vector 102 GPS receiver is mounted to the forward sensor tree and provides vessel latitude, longitude, heading, yaw, pitch, and roll. The Vector 102 is a dual-antenna receiver that in typical conditions can measure sub-meter position, as well as yaw and heading, even while not underway.

1.2.7. LiDAR

The Velodyne Lidar HDL-32e sensor is mounted to the forward sensor tree and produces a three-dimensional point cloud of the environment. Laser returns are reliable up to 80m. Conveniently, water absorbs the IR radar returns, which helps to declutter obstacle information.

1.2.8. Camera

A Logitech c920 webcam is mounted to the forward sensor tree and provides forward-facing video. For the initial iteration of the vessel, it was decided that a single video channel was sufficient for sensing in the direction of movement. A polarizing filter was added to reduce glare.

1.2.9. Winch subsystem

The winch subsystem includes motor controller, motor, drive chain, gearbox, reel, fairlead, and tether, all repurposed from earlier REx models and mounted to a custom, 8020 (“t-slot”) frame [Figure 6.]

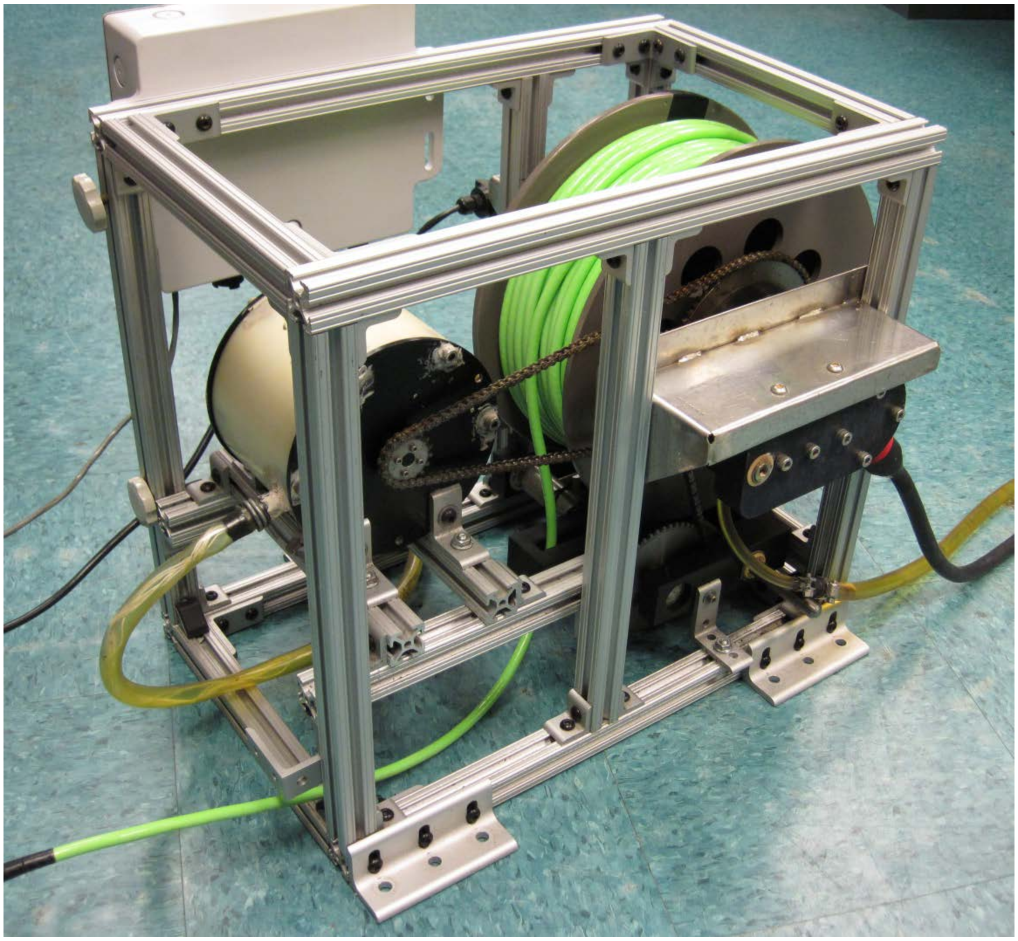
Figure 6: Winch subsystem

The motor is 3-phase, brushless model, immersed in oil, in a custom housing. The motor controller is a J.R. Kerr PIC Servo SC 3PH board. It was originally installed in a submersible encslosure as part of an earlier version of the REx platform. For REx 4, it is remounted in a new enclosure rated for IP68 (submersion only for brief periods). The installed reel holds approximately 25 m (82 ft.) of Falmat Inc. *Xtreme CAT* CAT5e Ethernet tether, and is connected to surface cabling via eight-contact slip ring. The existing spool and slip ring can be fitted with other cables that do not exceed the spool's retainment volume. Larger spools can be installed with minor reworking of the 80-20 superstructure, lengthening the drive chain, and refitting the fairlead. A rotary encoder was installed that senses angular movement of the spool in both directions.

A custom MOOS application (iJRKerr) was developed to interface with the JR Kerr control board. Basic winch monitoring and controls are managed using a hierarchical state machine.

Messages published to the MOOS community include:

- Report winch position (based on encoder readings)
- Report winch state (e.g. traveling, at soak depth)
- Report winch electrical current (as percentage of full scale)

Commands that can be received from the MOOS community include:

- Travel to fully submerge instrument ("soak" position)

- Retract winch until limit switch actuates (“stow”)
- Travel at specified speed
- Travel to specified position
- Pause
- Emergency stop

A user interface application called iWinch running on the shore side computer provides supervisory monitoring and control of the winch. This allows operators to, for example, see the status of the travel limit switch, observe internal winch state, and drive to specified positions. This was especially helpful dockside while loading and unloading the CTD.

Preparing the winch subsystem for field trials presented many challenges. Table 1 shows some of the problems encountered in development of this part of the system and how they were resolved.

Problem	**Root cause and solution**
Oil leaking from motor enclosure	Drain oil. The original purpose of the oil was for pressure equalization when running submerged. Since the winch runs above deck, oil maintenance is unnecessary.
Shaft optical encoder exposed to weather	Design and print 3D top and bottom housings
3D printed bottom housing cracked at bolt sockets	Weakness of ABS plastic • Redesign and machine housing from aluminum
Erratic winch motion	Water intrusion into top housing of shaft encoder • Reprint housing and seal by wiping with acetone • Install winch ESTOP mushroom button
Erratic winch motion	Optical encoder slipping from winch shaft • Attach encoder more securely
Chain loosens and can slip off gear	By design, attachment points allow motor to pivot • Improved motor connection to frame and increased tightening of set screws • Add software to monitor winch travel and assert fault if target position not achieved when expected
Insufficient winch power	Install new power supply with greater input voltage

Erratic winch motion if powered up under load	Motor PID changes during initialization • Reset integration error on start-up • Enhance software functionality to de-energize winch on excessive current

Table 1: Winch problems and solutions

1.2.10. CTD sensor

The primary scientific payload used in this study was a SeaBird Electronics SBE 49 FastCAT CTD Sensor with built-in pump, providing real-time conductivity (salinity), temperature, and depth data. The sensor has an overall length of 62 cm (24.4 in) and weight in-air of 2.7 kg. The communications protocol is RS-232.

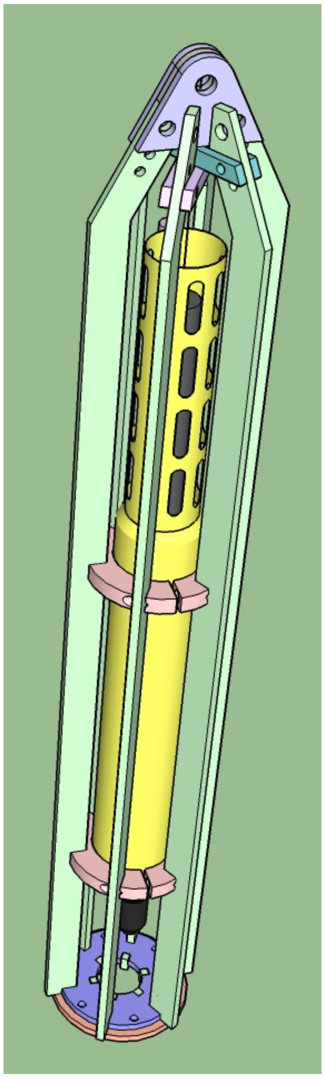

Figure 7: Prototype CTD enclosure

The Lab worked through several designs for how best to deploy, recover, and protect the CTD. A cylindrical encasing frame for the CTD [Figure 7] and slanted, tubular silo to be mounted under the deck were both prototyped with intention that these would shield the sensor and reduce swing motion while in transit. This approach, however, would not scale well to an ROV payload and was ultimately abandoned for simplicity. Figure 8 shows the CTD as it was in trials, in a simple frame consisting of two aluminum channel beams. Also shown are the supporting bolt, tether, paddle, and winch limit switch. Two cast rubber junctions take the eight conductor tether down to the four conductor connector of the CTD.

A MOOS application written for the CTD provides an interface to control the pump, start/stop sampling, convert pressure readings to depth, and publish results to the MOOS database.

Figure 8: CTD sensor and tether detail

1.2.11. Altimeter

Our objectives included surveys of shallow water with features such as sand bars. We added an altimeter to the sensor suite to help avoid collisions between CTD and bottom features. The altimeter, a Teledyne Benthos PSA-916 Programmable Sonar Altimeter, was mounted by custom Delrin fitting to the end of a hydrophone strut mount used in the RobotX competition (background of Figure 20.) When lowered into position, the altimeter head was about 1 m under the water surface. The unit was protected by being recessed into the strut body. The strut itself is protected from forward collision by a breakaway spring mechanism at its upper mounting point.

A MOOS application publishes altimeter water depth to the MOOS database about twice a second.

1.2.12. Single-beam “fish finder” sonar

Another of our objectives was to explore the application of inexpensive, consumer-grade, single-beam, “fish finder” sonar in bathymetry, bottom composition, and subaquatic vegetation mapping. We purchased a Lowrance Mark 4 Chirp fish finder/chartplotter with HST-WSBL depth/temperature transducer for this purpose for approximately $200. The transducer was mounted to a 6.4 mm (1/4 in.) thick aluminum arm marked with distance from the transducer face [Figure 9] allowing operators to read transducer offset from waterline. The arm was mounted on the port pontoon, near the system battery. We experimented with several different mounting locations for the Mark 4 GPS/display unit. The final mounting location was directly over the sonar transducer.

We configured the device to provide depth over its NMEA 0183, RS-232 output, and made this compatible with to the altimeter input of the computer box. A MOOS application publishes water depth to the MOOS database, allowing the Mark 4 to serve as an alternative altimeter during CTD casts and in transit. The Mark 4 also supports logging broadband sonar to SD card, in this case of 32 GB capacity.

Figure 9: Lowrance Mark 4 sonar and mounting arm

1.2.13. System radio network

A wireless connection to shore allows convenient access to the vessel for updating software, configuring missions, downloading data files, and for real-time monitoring of autonomous operations. The wireless network was provided by a pair of Ubiquiti Rocket M900, 900 MHz Ethernet radios. The vessel antenna was an omnidirectional, 5 dbi, 900 MHz antenna attached to a mast fashioned from a telescoping aluminum pole. Measured from the water's surface, the center of the antenna was approximately 3.4 m (11.2 ft.) high. The shore side antenna was a Hyperlink Technologies, Hypergain HG908U omnidirectional 8 dbi antenna attached to a 7.6 m (25 ft.) telescoping mast.

Various shore mounting locations were attempted. Due to a massive construction effort along Columbia Point, few positions afforded a completely uninterrupted line-of-sight view of the operating area. Permission was gained to place the Sea Grant truck on the Columbia Point seawall that would offer adequate coverage. When mounted on the Sea Grant truck [Figure 10], this resulted in a mid-antenna height of approximately 11.5 m (37 ft.) above the low-tide water surface.

Figure 10: Radio shore station, Columbia Pt.

Antenna heights were determined experimentally by use of the built-in Ubiquiti Speed Test tool. The Lab desired a vehicle-to-shore side speed of at least 2 Mbps at a distance of 1500 m. With antennas at about 1 m over waterline height and a few meters apart, receive speeds in excess of 13 Mbps were observed. However, this dropped to less than 1 Mbps at 400 m distance, even though endpoints were in clear line-of-sight. Raising vehicle and shore side antennas restored performance to above 2 Mbps at 1100 m and gave us the confidence to proceed to field trials. Based on the improvement in speed with antenna height, we believe the speed drop was due to water obstructing the radio Fresnel Zone [5].

The Lab also created a custom "ping" utility to help determine the latency of MOOS communication packets between the shore and REX 4 network nodes.

1.2.14. Shore side equipment

The shore side equipment included shore side radio, MacBook Pro running MOOS-IvP with pMarineViewer UI application, and network router. When mains power was not available, the shore side station was powered by batteries and a 12v inverter.

1.2.15. pMarineViewer application

pMarineViewer is a MOOS UI, shore side application that renders an overview of real-time vehicle and mission status and provides real-time mission control. For Columbia Pt. trials, an image of the area was exported from Polar Navy LLC, PolarView NS [6], based on NOAA chart US5MA12M. This image served as a background for field trials [Figure 11.]

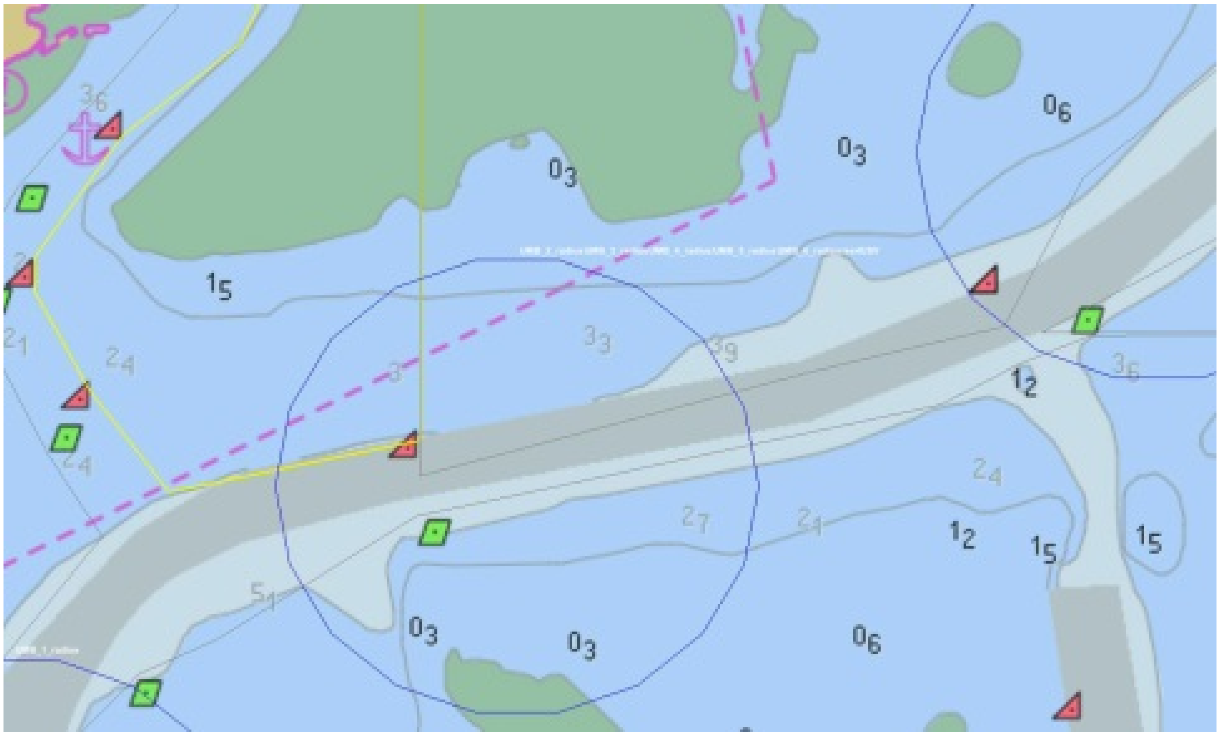

Figure 11: pMarineViewer detail

1.2.16. Highest-level application and behaviors

pRex4 is a custom application written to control the REx4 USV for casting missions. The application is based on a hierarchical state machine that ties together navigation, casting waypoints, winch, and CTD control.

A control file for pRex4 determines CTD casting parameters (how long to hold station before starting a cast, how long to soak the CTD under water before sampling, how far the vessel can drift during a cast, etc.) and the actual cast positions. Cast positions, defined by name, latitude, longitude, and target depth, are also specified in this control file. For example, this line defines a cast position with a target depth of 20 meters:

Cast_Pos   = 2, UMB_2, 42.30655, -71.03766, 20.0

The system is designed to prevent motor spin-up when the CTD is not securely in its stowed position. When the CTD is stowed, the vehicle is free to travel between casting locations and to position in preparation for a casting. The behavior-based helm application pHelmIvP includes several behaviors that control vehicle motion. Individual behavior parameters (such as the location of the next cast point) are updatable by the pRex4 state machine, based on the next casting waypoint. The three main behaviors include:

- BHV_Confines: Defines the operating area by preventing actuation of the vehicle outside of the defined boundaries.
- BHV_Waypoint: Used to set target locations for CTD casting. Reaching anywhere within a small buffer zone surrounding the exact lat/lon position satisfied the condition of arriving at the casting location.

- BHV_StationKeep: Used for multiple purposes:
  - At any time, temporarily hold current location at command of operator
  - Keep the vessel near a CTD cast position while preparing to cast
  - Return to survey start location

Simplified vessel operation during a casting survey is as follows, in pseudo-code with typical deployment values:

```
Initialize system, stow the winch (retract completely)
When the user starts the survey
      If winch is stowed
            While avoiding confined regions
                  Transit to first cast location
When within capture radius of cast location
      Stationkeep for 30 seconds while determining minimum
            altimeter depth
      Disable vehicle propulsion
      Drive winch to CTD soak depth for 30 seconds
      Turn on CTD pump for two seconds
      Start sampling CTD
      Start paying out winch
      If CTD depth exceeds (target depth or minimum altimeter
            Depth) or depth stops increasing
                  Reverse winch
      If at CTD soak depth
            Stop sampling
            Stop CTD pump
            Stow winch
If winch is stowed
      Enable propulsion
      Start transit to next cast location
```

The Lab originally sought to hold position dynamically during casting to keep the CTD on the target location. This, however, would require a physical restrain to prevent the tether from interacting with the propellers or getting caught in the pinch-point between motor and transom. The effort to design, build, install, and maintain such an apparatus is non-trivial. The decision was made to simply disable propulsion during winch deployment, with the downside that the vessel would be able to drift during CTD casting.

Another objective was to lower the CTD to the target depth without contacting the bottom, as this could damage the sensor or allow mud and debris to be ingested by the CTD pump. For this reason, the vehicle determines maximum depth by altimeter before casting. CTD depth is monitored throughout the cast by parsing the live data stream (D in CTD stands for “depth”) and comparing against the maximum allowable depth. Preliminary testing revealed a problem: if the CTD never reaches this minimum depth, the winch will simply continue to pay out. This can occur if the vehicle drifts into an area that is shallower than the depth found before casting. An additional test, essentially a bottom detection scheme based on CTD speed of descent, was added to prevent this.

1.2.17. Vessel registration, required equipment, and general safety

Any vessel that is powered by a motor and operated on Massachusetts public waterways must be registered [7] and the Lab therefore went through the process of registering REx 4 with the state of Massachusetts. While there are exceptions to this law, none applied to our vessel. For example, there is no stated minimum size for registration. Although small, “toylike” autonomous boats are probably not commonly registered, REx 4 weighs around 220 kg and is almost 4 m in length, and is therefore not “toylike”. Getting the vessel properly registered required three trips to the State Registration and Titling Bureau and a visit from the Environmental Police to resolve title, determine length, and assign a conforming hull identification number. In addition to registration placards, REx 4 was outfitted with all the safety equipment (paddle, day/night flares, etc.) appropriate for a manned vessel of this length, as required by federal and state law [ibid.] We reasoned that it was better to conform to the spirit and letter of the law than risk a citation from authorities.

The Lab also considered the level of immediate supervision required to operate the vessel safely, regardless of whether in autonomous or manual mode. The MIT Sailing Pavilion area is highly congested with sailboats, racing shells, kayaks, power boats, tour boats, and even other robotic vehicles. The Columbia Pt. area contains traffic from numerous marinas and an active channel. In both locations, REx 4 often attracted the attention of operators of other vehicles, complicating our efforts to maintain a safe buffer zone.

Our decision on supervision was informed by the Navigation Rules, especially RULE 5 “Look-out: Every vessel shall at all times maintain a proper look-out by sight and hearing as well as by all available means appropriate in the prevailing circumstances and conditions so as to make a full appraisal of the situation and of the risk of collision.” [8] and RULE 8 “Action to Avoid Collision: (a) Any action taken to avoid collision shall be taken in accordance with the Rules of this Part and shall, if the circumstances of the case admit, be positive, made in ample time and with due regard to the observance of good seamanship” [ibid].

The vehicle was always operated with the OCU nearby and a staff member watching the operations. Note that for safety, when out of OCU range, the onboard e-stop system forced the vehicle to stop. When deployed in a fixed area such as the Charles River immediately in front of the MIT Sailing Pavilion, the OCU was situated on a dockside platform. With larger river operations or at Columbia Point, REx 4 was accompanied by a chase boat equipped with the OCU, hand-held radio, cell phone, and means to tow the vessel.

1.3. “Wide” survey

When considering field trial locations, the Lab sought an area that could provide dynamic temperature and salinity contrasts over a winding channel. The Columbia Pt. region was selected, as it included a fresh/salt water mixing zone at the mouth of the Neponset River. The channel is as narrow as 50 m and close to an extensive mooring field. It also contained two existing water chemistry monitoring buoys of the Coastal Environmental Sensing Networks (“cesn”) [9], funded by MIT Sea Grant and maintained by UMass Boston. We designed a survey (“wide survey”) off of Columbia Pt. starting at the cesn “C” buoy and ending at the cesn “B” buoy 2.4 km distant, with cast points each 600 m [Figure 14.]

Cast points were selected using PolarView NS software [6] based on soundings shown on the US5MA12M NOAA electronic navigational chart. These latitude-longitude pairs were named with unique identification numbers then entered into the pRex4 control file. A private vessel mooring field was marked on the chart as spanning the region between the UMass Boston dock and the main channel. Publicly available aerial imagery demonstrated that the moorings extend farther into the channel than marked. Polygons demarcating navigable portions of channel were provided to the confines behavior to both restrict vehicle movement and for display in the user interface.

Historical cesn data [9] indicated that the highest difference in salinity between "B" and "C" buoys occurs at low tide. For this reason, REx 4 surveys were scheduled at low tide, recognizing that survey transit time and other delays would affect comparisons. Also, we tried to perform surveys before and after a rainfall event of at least 2.5 cm (~1 in.) to provide further temperature and salinity contrast.

For these surveys, the shore station antenna was located on the southern promontory of Columbia Pt. as described above [1.2.13.] Shore station equipment was located nearby under a pop-up tent.

At the completion of each survey, log files were transferred from computers onboard REx 4 to shore side laptops then archived. Generally, data could be transferred during the transit back to the UMass Boston dock at the end of a run. Conductivity (salinity), temperature, and depth data were extracted via MOOS aloggrep utility and processed in Microsoft Excel. Vehicle position node reports were also extracted via aloggrep and then converted to csv files via Excel. In ArcMAP, the **Create Feature Class from XY Table** tool was used to create vehicle track lines.

1.4. "Intense" and "endurance" surveys

An additional set of tests was designed to demonstrate rapid casting in a small area over a sustained period. For this "intense" survey, we selected the mouth of the Neponset River [Figure 12], near the cesn "C" buoy and just off of the National Grid "rainbow" gas tank, a local landmark. Our intent was to capture the dynamism of fresh/salt mixing over approximately half of a tide cycle. We created a grid of cast points, with three rows approximately 65 m apart and columns between 25 and 30 m apart. The time between casts was set at ten seconds, with 15 seconds allowed for the CTD to soak before start of sampling.

For this survey, the shore station antenna and equipment were located at the UMass Boston, Fox Point dock, approximately 200 m NW of the wide survey shore station site. This shore station location is preferred because of access to shore power, indoor spaces for the shore crew, and increased security for unattended equipment. Radio coverage was adequate for the testing field near the National Grid gas tank.

An "endurance" survey was designed to further define REx 4 endurance limits and explore its use as a "mobile data buoy". Our goal was to perform CTD casts every 900 seconds for at least four hours. This testing occurred at the MIT Sailing Pavilion. Results from the wide, intense, and endurance surveys are discussed in the Results and Discussion section.

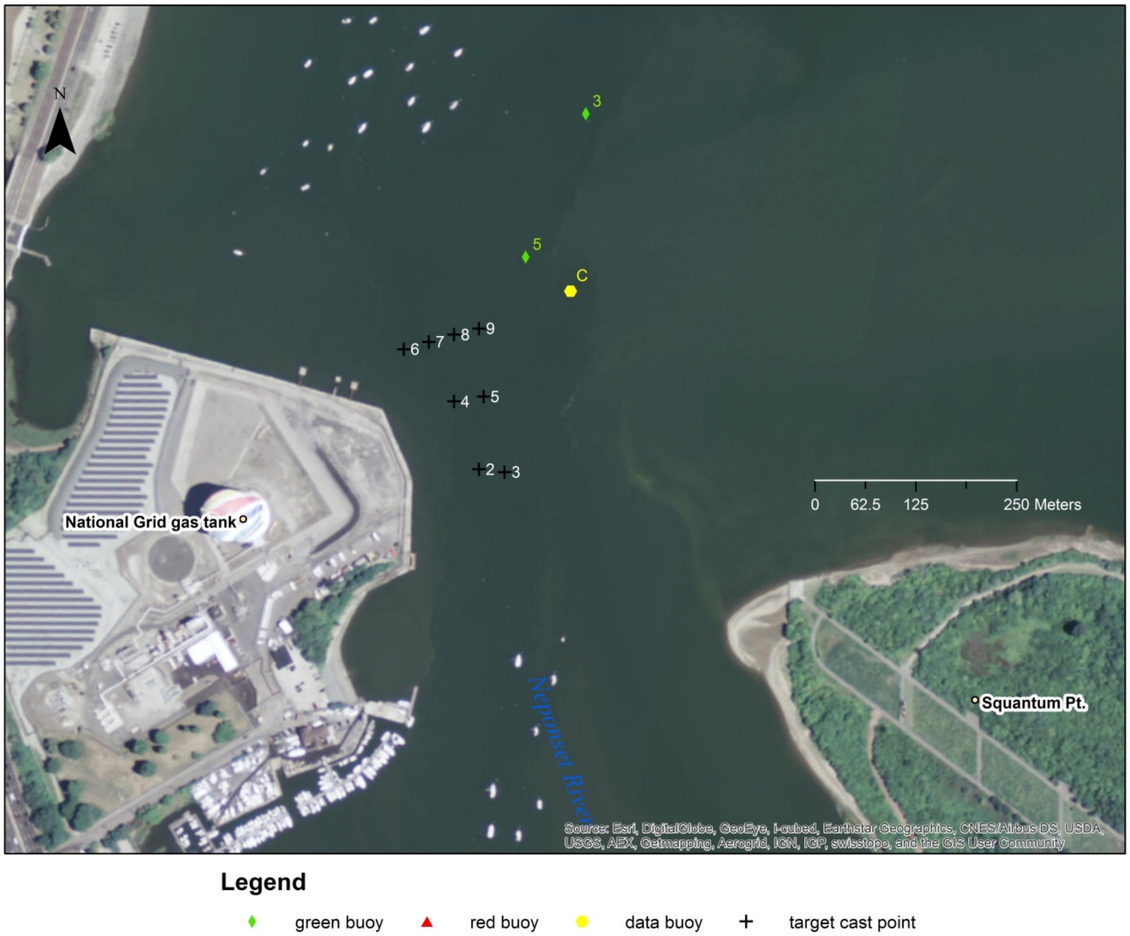

Figure 12: Area of "intense survey". (Map courtesy of © Esri, et.al. [10])

1.5. ROV deployment

The original REx 4 concept was to deploy an ROV from an autonomous surface vessel and the vehicle was prepared accordingly. The winch system, power subsystem, and data pathways to the onboard computing all were capable of connecting with an ROV. While a suitable ROV was not available for the initial field trials, system flexibility allowed for any submergible sensor to be connected with only minor modifications to the electrical connectors. Therefore, integrating the CTD was, in some sense, a “placeholder” for an ROV. While the Lab was developing the REx 4 system, however, a connection was made to an ROV development team in the MIT Marine Robotics Group [11]. Their “Njord” ROV was potentially a good fit for REx 4 and the teams planned a combined trial.

The flexible connection arrangement inside the computer box to provide network access was able to support the Njord. Compatibility was confirmed through preliminary network and system testing at the MIT Sailing Pavilion. Field trials were planned to confirm that:

- The integrated system (vessel and ROV) was stable while underway
- REx 4 radio network supported Njord telemetry and video while underway
- REx 4 could cast and recover the Njord to depth

1.6. Remote Internet demonstration

Classroom access has been a persistent design goal through the history of the REx program. Our objective for REx 4 was to demonstrate monitoring and control of REx 4 via internet from the MIT Sea Grant facility in Cambridge, MA. Preliminary demonstrations at the MIT Sailing Pavilion demonstrated that control may be given across the internet. However, construction at the UMass Boston deployment location had cut off internet access to the dock area and operations there were unable to demonstrate remote control.

Investigations done on the river showed that remote control requires a significant development effort. In particular, safety concerns and situational awareness are not completely conveyed to a remote operator. As described above in 1.2.5, safety dictates a chase vehicle or dockside operator to be present. Therefore, it may be easier to provide control via human communications. Even in this case, it is still useful to provide a live data stream so that remote data consumers can fully participate.

1.7. Single-beam sonar trials

The Lab planned several bathymetric surveys to test the single-beam sonar unit. We set sonar configuration as follows:

- Auto sensitivity: ON
- Range: Auto
- Frequency: 200 KHz
- Ping speed: Normal [10 Hz]
- Keel offset below waterline: As read from sonar transducer arm

Because this sonar unit does not support sonar configuration electronically, sonar logging was started and stopped manually. After each run, the SD card containing the sonar files were manually transferred to the shore computer and archived.

The logged sonar data format (Lowrance .sl2) is compatible with several mapping and analysis programs. We analyzed sonar data using Insight Genesis [12] and ciBioBase [13], two cloud-based services of the Navico Company, manufacturer of the Lowrance brand. We also analyzed sonar data in ReefMaster Pro 1.8, a PC application produced by ReefMaster Software Ltd. [14] .

2. Results and Discussion

Figure 13: CTD casting, Columbia Pt.

2.1. Wide survey results

REx 4 ran several successful wide surveys in September, 2015. Figure 14 depicts an example of one of these surveys.

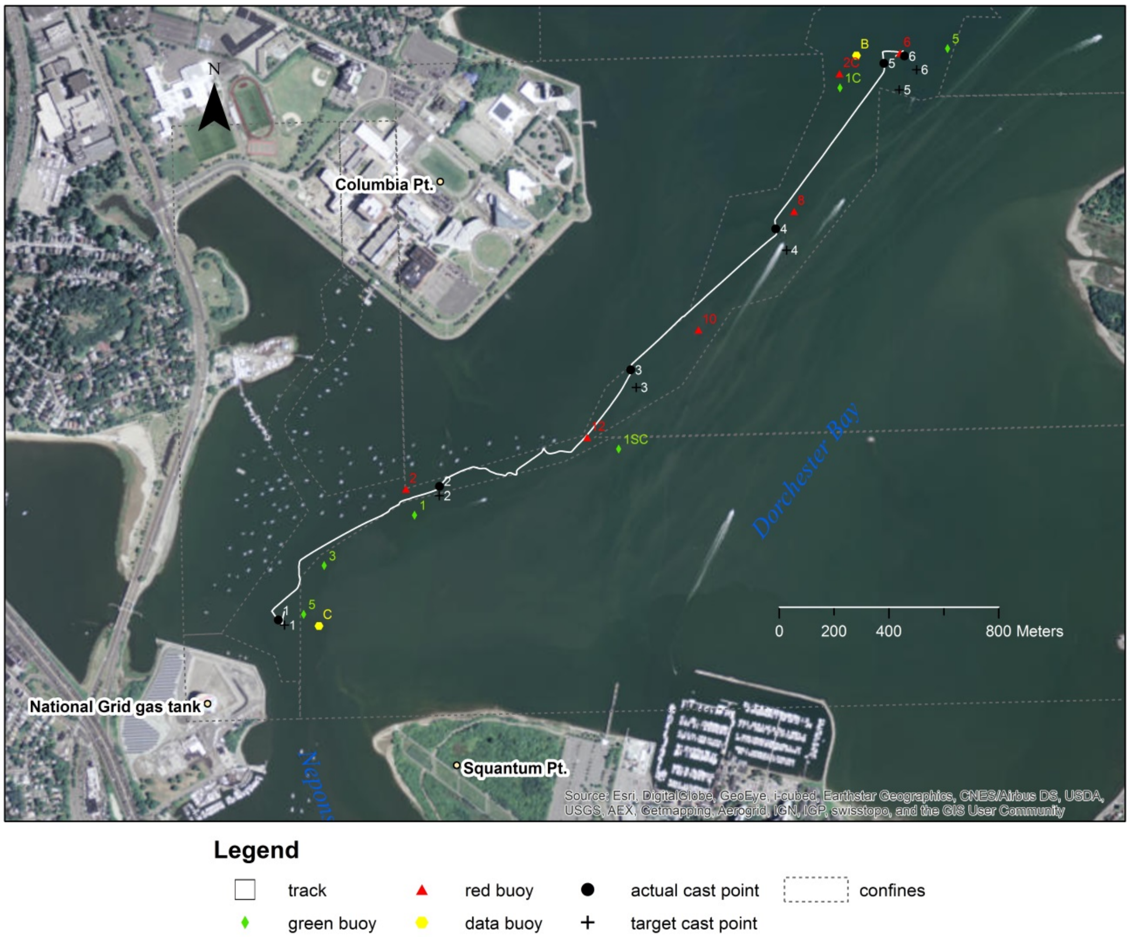

Figure 14: Wide survey. Dotted lines define 'Confines' behaviors, used to restrict the vessel to a narrow channel. The background photograph is correct for the area but not specific to the time of the survey. (Map courtesy of © Esri, et.al. [10])

Surveys were conducted before and after a rainfall event that followed ten precipitation-free days [15]. The "before" survey started about 1.5 hours after low tide. The "after" survey started about .3 hours before low tide. 1.8 cm (.70 in.) of rain fell within 40 hours of the "after" survey, the majority of which occurred within 17 hours of the survey [ibid and direct observation]. Although the "after" survey was incomplete, it was the survey closest in tide cycle to the "before" survey.

Review of the “before” salinity curve for cast point 1 [Figure 15] at the mouth of the Neponset River shows fluctuating salinity between 1.8 and 4.5 m. Our interpretation of this is that the river mouth is a mixing zone of salt and fresh water. Curves become progressively more saline and smoother as casts proceed into Dorchester Bay.

The “after” salinity curve for Cast Point 1 [Figure 16] shows less saline water at shallower water and a pycnocline at 2 m. All of these and subsequent curves are from the downward (“downcast”) portion of the cast data.

“Before” temperature curves [Figure 17] show fluctuations at cast point 1 and overall decrease in temperatures into Dorchester Bay. The “after” curve for cast point 1 [Figure 18] shows a thermocline at 2 m and cooling of about 1° C.

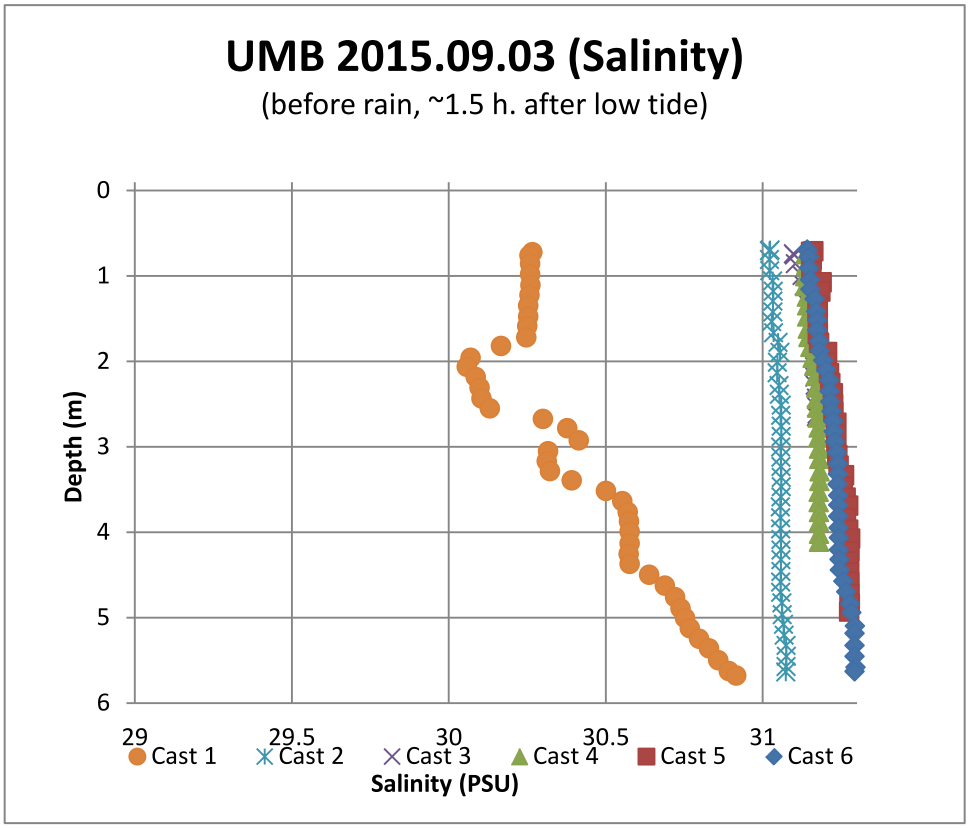

Figure 15: Salinity (before rain)

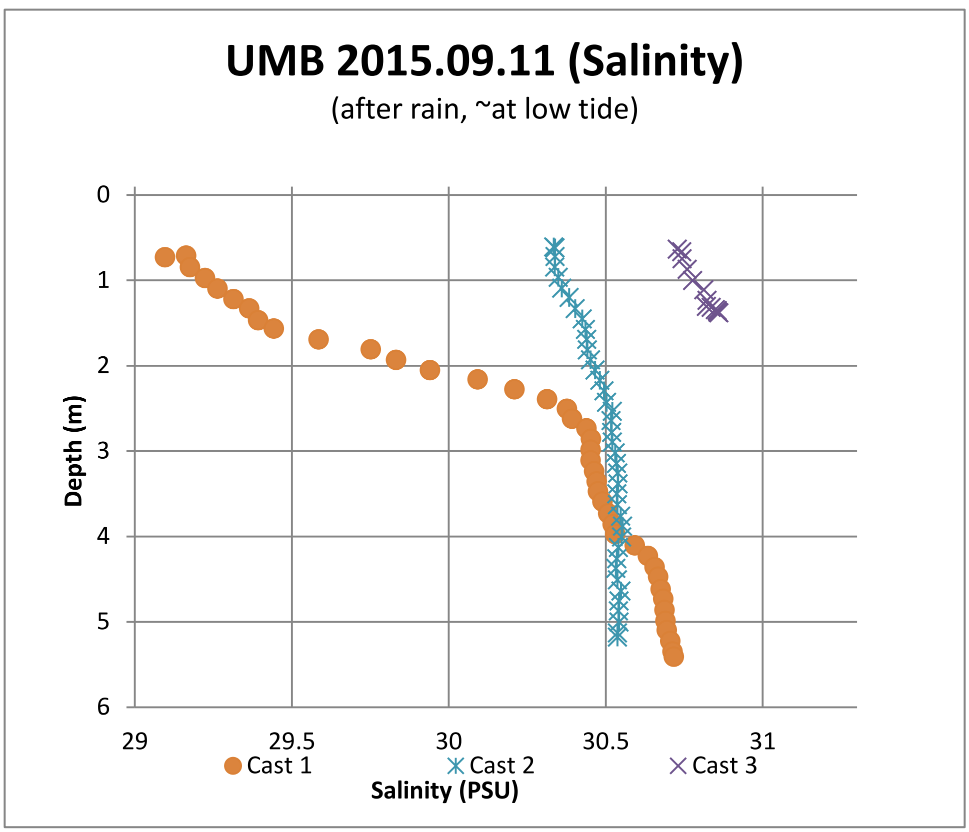

Figure 16: Salinity (after rain)

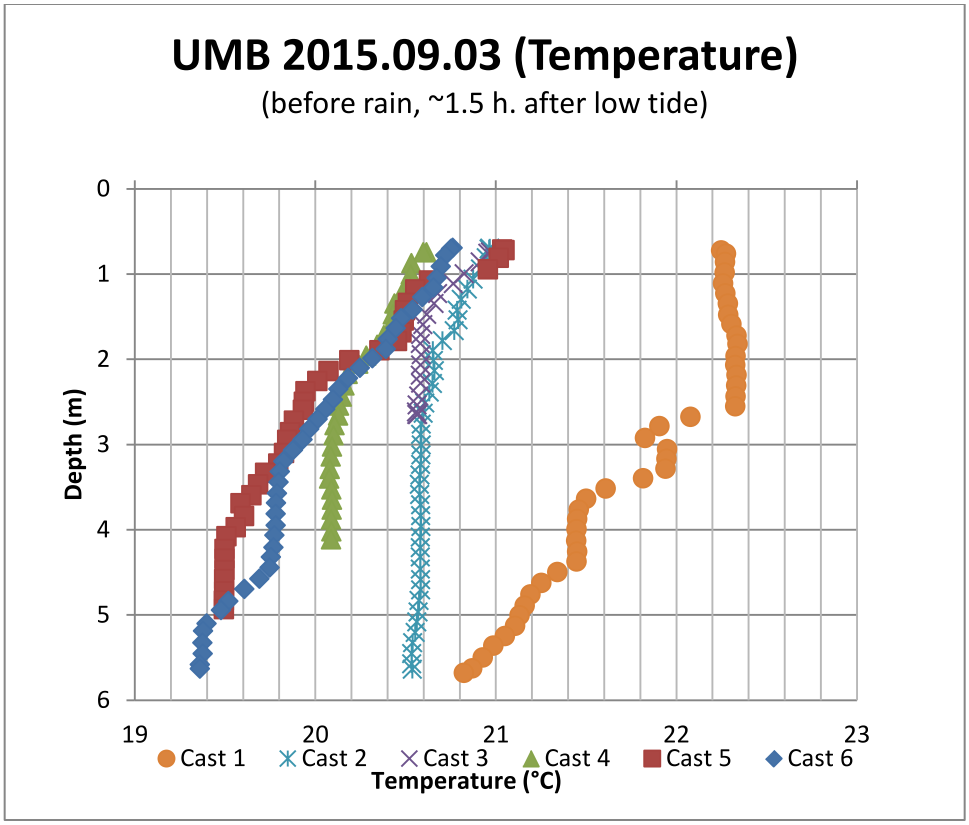

Figure 17: Temperature (before)

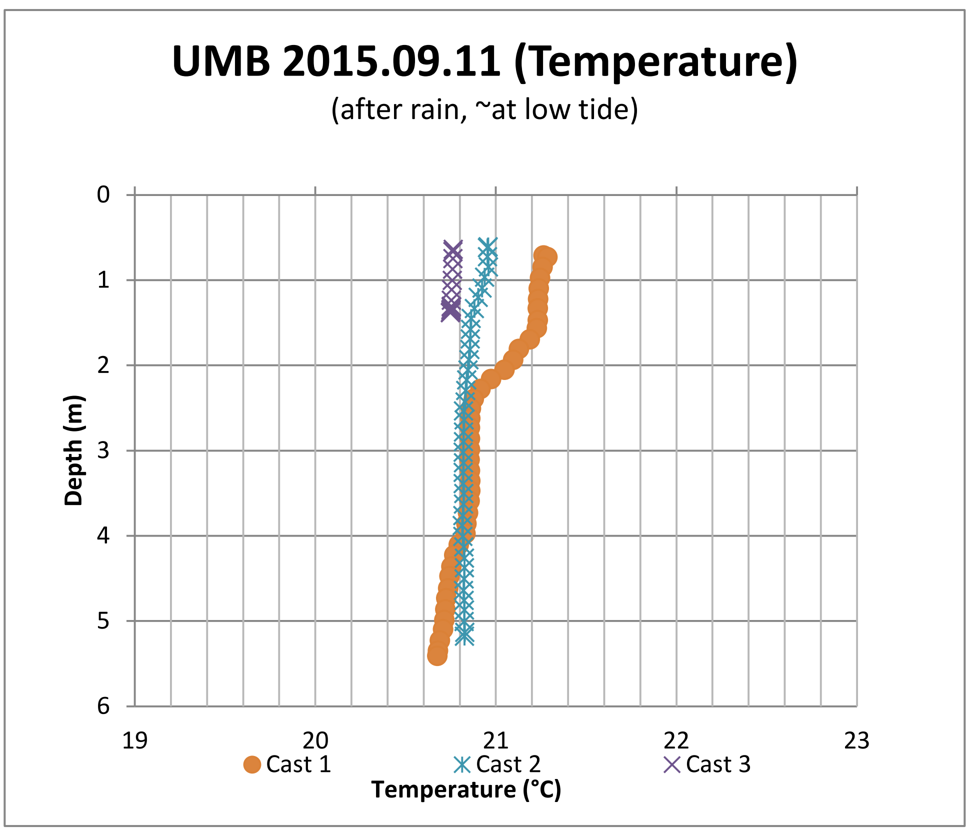

Figure 18: Temperature (after)

Although data are presented in the context of the impact of a rainfall event, additional factors influencing salinity and temperature include:

- Temporal changes over the tide cycle: We did not perform casts at each point at exactly the same phase of the tide cycle.
- Temporal changes over the season: The before and after surveys were separated by eight days, during which time there could have been seasonal effects on temperature.
- Small rainfall event: Only 1.3 cm.
- Small changes in measured parameters: Salinity changes were on the order of 1 PSU.
- River flow caused by the event was not directly gauged.

Position Error Discovery

Field operations at Columbia Pt. covered areas several times larger than the Charles River tests. Although data acquisition and operations appeared adequate at the time of the Columbia Pt. tests, survey post-processing revealed positional discrepancies. In particular, cast points 5 and 6 occurred in different locations than pre-mission planning intentions. The problem became apparent due to the proximity of navigational aids (buoys) to these points; other casting locations were in open water with no local basis for comparison. The cast locations were offset 20-80m to the west-northwest from the latitude/longitude specified during pre-mission planning.

The problem was traced to inconsistent use of methods that convert between latitude/longitude and the X,Y grid, local coordinate reference system. Recent changes to the underlying MOOS-IvP architecture introduced options for an improved geodesy component for calculating geographic transformations. The REx 4 software, written entirely after the changes to MOOS-IvP, applied legacy transformations and newer methods inconsistently. The vehicle would have positioned as accurately as the GPS allowed (90% confidence to sub-meter accuracy) if either method had been applied consistently. However, with local-tangent-plane calculations used for preprocessing and UTM-coordinate transformations used for live transit, a 20-80m error was introduced.

While the position error was significant, the practical implications to the research were minimal. CTD measurements would have been similar at the errant or precise sampling locations, considering the large expanse of Dorchester Bay. In-field operations were disturbed because the errant positions brought the vessel too close to moorings, which then required human intervention to prevent collisions [Figure 19.] Investigation of the position error benefited the MOOS-IvP project, as it resulted in enhancements to the best practices geodesy document and improvements to the code base to prevent future errors.

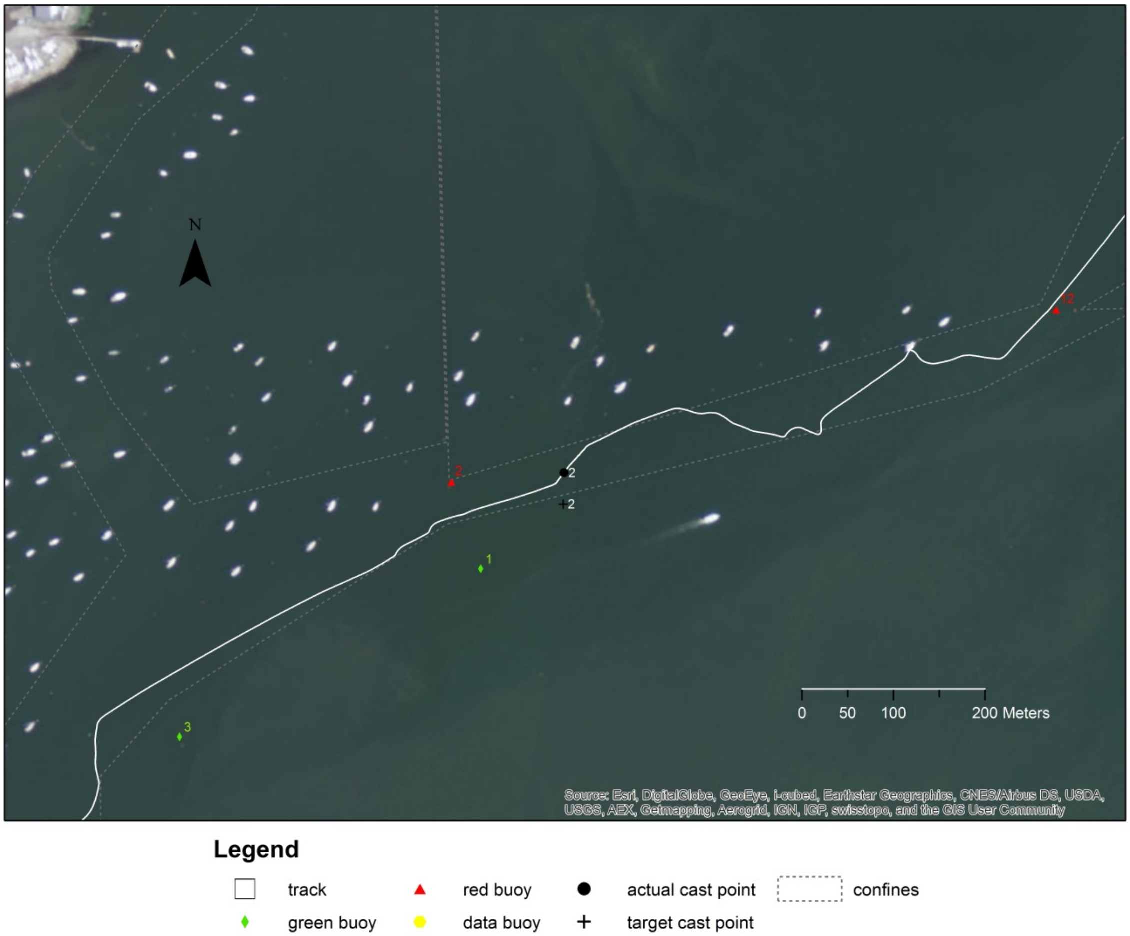

Figure 19: Wide survey (detail) showing difference between target and actual cast point locations and interference with mooring field. (Map courtesy of © Esri, et.al. [10])

2.2. Intense and endurance survey results

The wide survey casts for point 1 sparked our interest in the salt/fresh mixing zone at the mouth of the Neponset River. We intended to start the “intense” survey before low tide, but were delayed by poor system radio performance between the Fox Point shore side station and REx 4. (This was surprising, given our good radio results during all wide surveys.) Following speed and ping tests, our analysis indicated that this was due to Fresnel Zone interference, likely a large vessel docked at Fox Point and possibly the thicket of masts from sailboats moored nearby. Our in-field solution was to temporarily replace the 900Mhz radios with 2.4 GHz radios and ultimately moved our shore station onto the chase boat. Unfortunately, we missed our tide window and instead casted mid-tide.

We ran subsequent “endurance” tests at the MIT Sailing Pavilion, casting every 15 minutes. Our longest endurance run was 5.3 hours, during which Rex 4 performed well.

2.3. ROV deployment results

The combination of Rex 4 plus Njord ROV [Figure 20] performed well during several system integration trials. The Rex 4 system radio supported Njord telemetry and video throughout. Movement of the ROV while in the stowed position and while Rex 4 was underway was modest and smooth. Transport of the ROV to and from the water surface was also well-behaved. Deployment of the ROV to depth is planned in a future integration phase.


Figure 20: Njord ROV suspended under REx 4

2.4. Remote Internet demonstration

Our difficulty in attaining a reliable internet connection in the field is described in section 1.6. Ultimately, we were able to demonstrate starting and monitoring a REx 4 casting survey from the MIT Sea Grant facility. Although operational safety considerations will likely necessitate chase boat support, this remote capability could be extended to classrooms or other remote locations accessible by internet.

2.5. Single-beam sonar trials

We performed several single-beam sonar trials off of the MIT Sailing Pavilion in the lower Charles River “boat basin” [Figure 21] and uploaded the files to Insight Genesis and ciBioBase online sites. The track lines of one survey, spaced at 10 m, are shown in Figure 22 and the resulting bathymetry is shown in Figure 23. Note the prominent 10 m (33 ft.) deep depression on the lower portion of the figure. Bottom composition, from hard to soft, is seen in Figure 24. In all images, North is at the top of the figure.

Figure 21: Bathymetric survey, Charles River

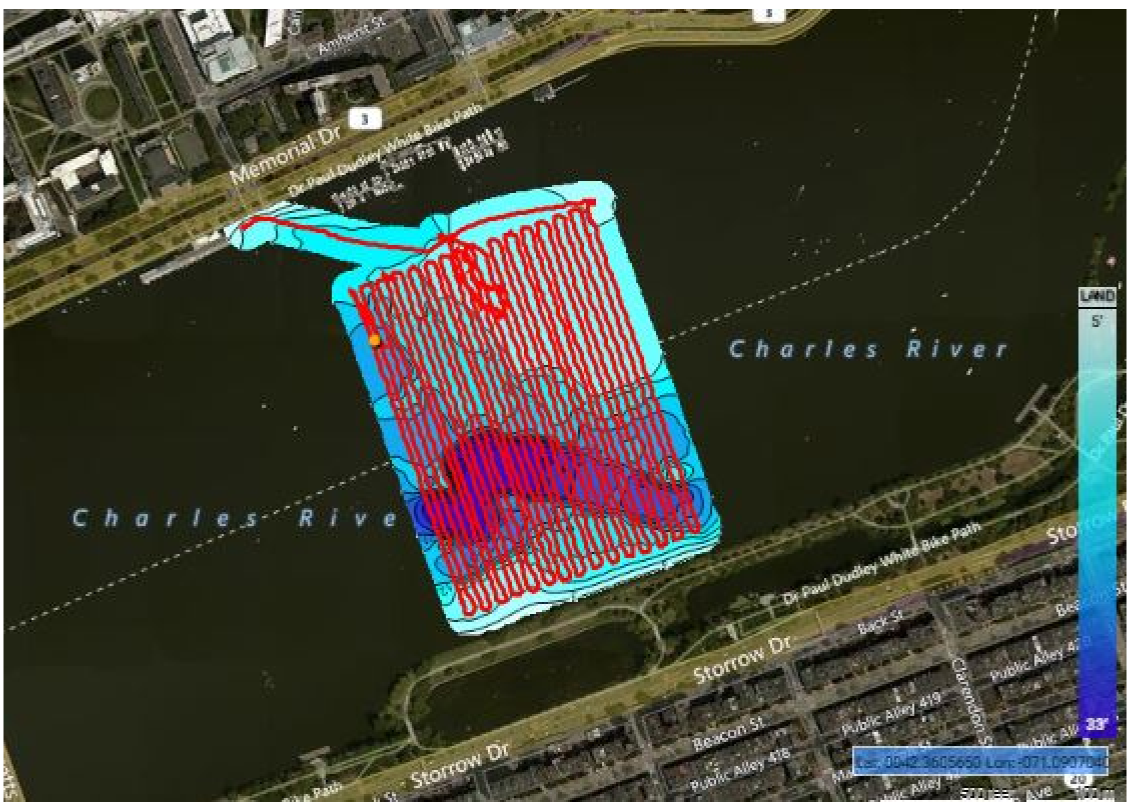

Figure 22: Insight Genesis – survey track lines. (Map courtesy of © Insight Genesis, 2015)

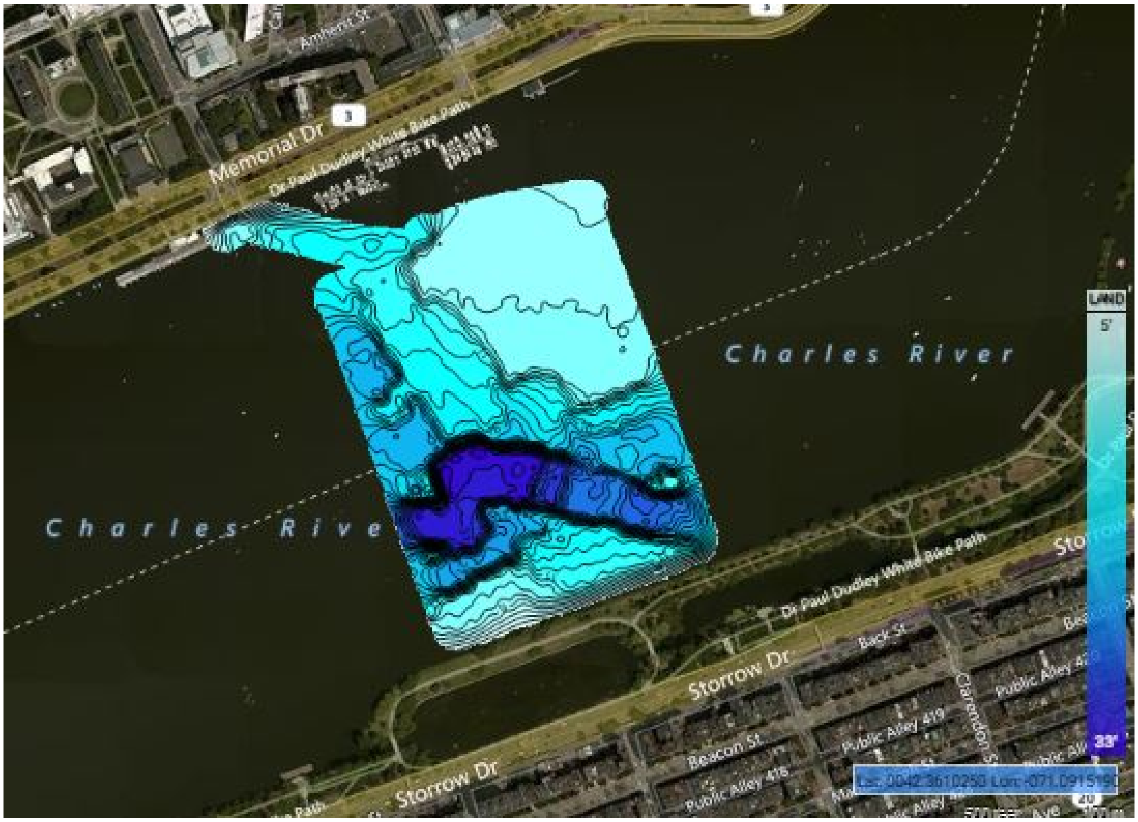

Figure 23: Insight Genesis – bathymetry (Map courtesy of © Insight Genesis, 2015)

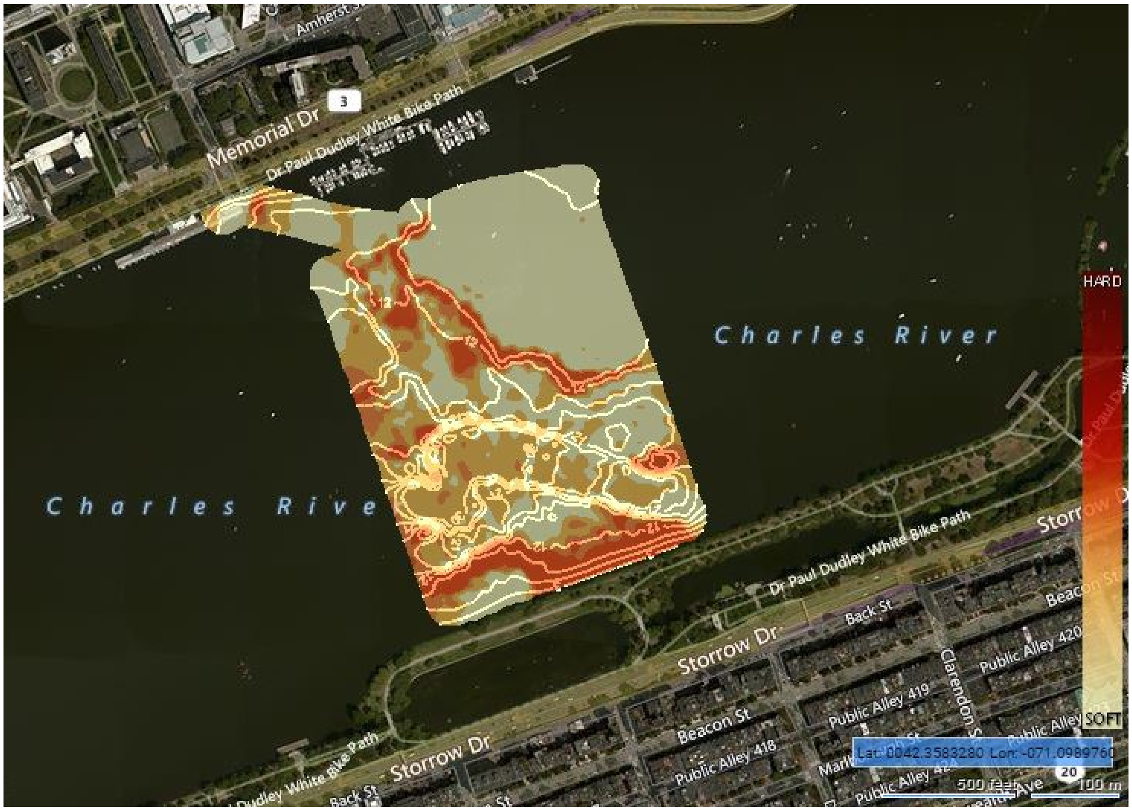

Figure 24: Insight Genesis – composition (Map courtesy of © Insight Genesis, 2015)

Insight Genesis provides a very straightforward way to create charts, and is oriented towards the recreational fishing community. Some features of this cloud-based service are:

- No cost to upload and create custom contour, hardness, and vegetation charts
- Integrated sonar viewer
- Automatic access to a database of “zero lines”, the outlines of mapped water bodies.
- Access to the Insight Genesis Social Map, an online presentation of community-sourced inland and coastal data
- Ability to offset depth for lake level or tide correction
- Ability to merge data from multiple trips into one chart

The charts produced by Insight Genesis are visually very appealing. The background composite aerial/street map image and symbology are clean and attractive.

ciBioBase is a related, fee-based, online service oriented more towards the scientific community, such as those performing surveys of subaquatic vegetation. While the contour, hardness, and vegetation charts produced are similar to those of Insight Genesis, ciBioBase has expanded abilities to access, edit, and export merged data. This service also provides quality control review of all files submitted.

The Lab also investigated using ReefMaster software to produce charts. Figure 25 shows bathymetry from the single-beam sonar files. Some features of this traditional, Windows-based application are:

- Accepts sonar files in Lowrance, Humminbird, Garmin, and other formats
- Integrated sonar viewer
- Ability to offset depths by lake level, tide correction, or custom time-series
- Ability to merge data from multiple trips into one chart
- Ability to export chart data into Google Earth, chartplotter, and GIS shape-file formats
- One-time cost model

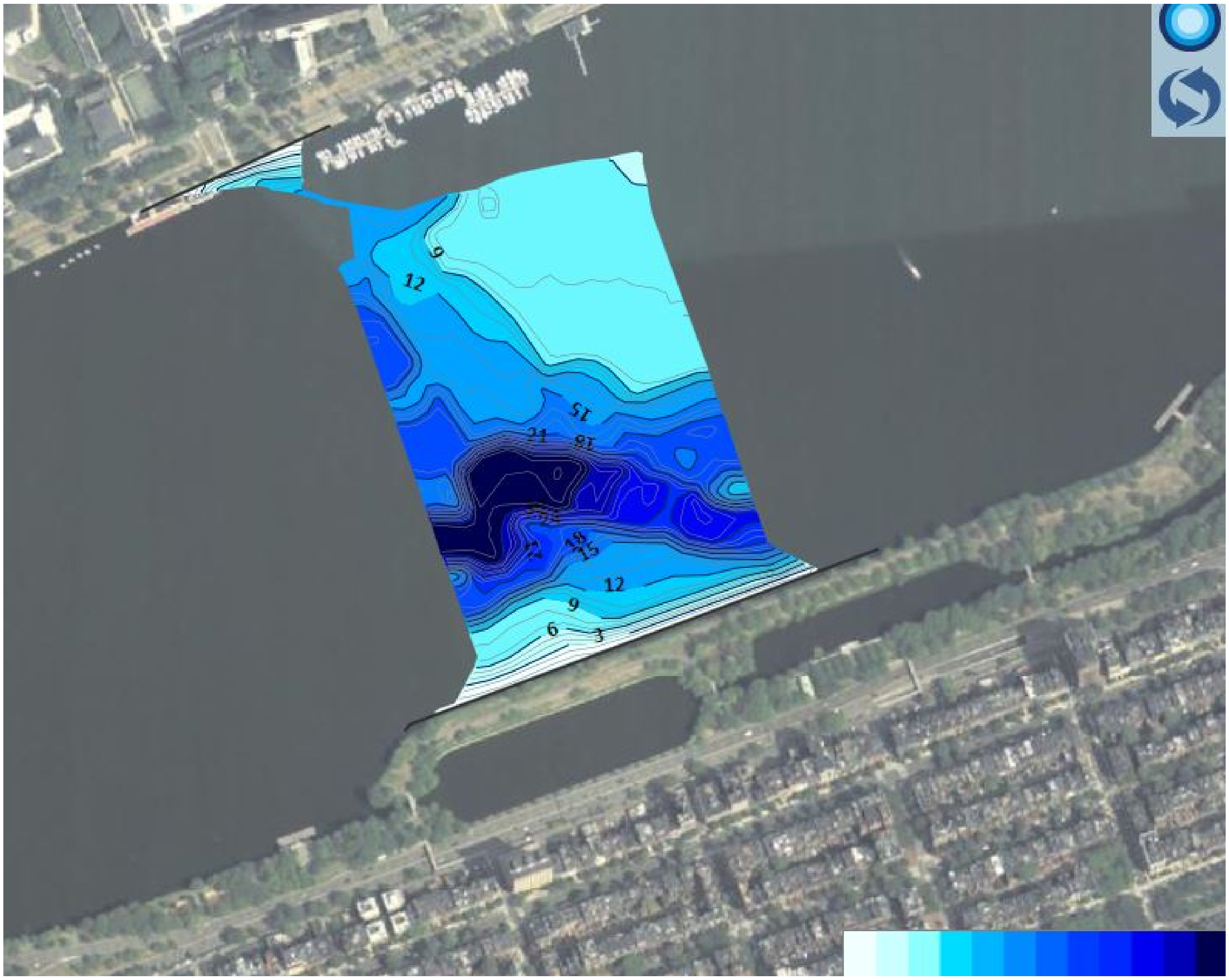

Figure 25: ReefMaster - bathymetry

Contour charts from the products are the result of different processing. At the time of this document, ciBioBase used geostatistical kriging to interpolate between points, while ReefMaster used TIN (Triangulated Irregular Network) and Gaussian smoothing.

Figure 26: REx 4 performing a "lawnmower" search pattern on the Charles River

2.6. Origin of the CRAB-MIT Chart Project

At the same time that the Lab was investigating fish finder sonar and charting methods, it was approached by the Charles River Alliance of Boaters [16], which was looking for a cost-effective way to chart the lower Charles River. The CRAB-MIT Chart Project [17] resulted from this meeting, "a survey of the lower Charles River by and for the boating community." The sonar data for the chart will be collected from volunteers trained in fish finder use and is expected to get underway in summer of 2016.

3. Lessons learned (and relearned)

The REx 4 project met the majority of its objectives for 2015, extending the Lab's expertise in inexpensive sonar, sensor deployment by winch, and field operations. Here are a few of the "lessons learned" from the experience:

- **Identify critical resources and make sure that they are available -** Lack of a chase boat sometimes impacted our ability to run trials, for example. Between weather, tide cycle, equipment, and staff, useful field time can be severely limited.
- **Be vigilant about fixing intermittent problems** – An intermittent problem in a critical system cable can jeopardize an otherwise successful trial. Chase down and resolve such problems early.
- **Be alert to anomalies in navigation and pay attention to detail** – Whether autonomous or not, good navigating practices are an important part of situational awareness. There are excellent training materials available [18] - take advantage of them.

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