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Methods for Mechanical Removal of Surface Oil in Ice Infested Waters

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ALION
SCIENCE AND TECHNOLOGY

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1. Introduction

Under contract with the United States Department of the Interior (DOI), Bureau of Safety and Environmental Enforcement (BSEE), Alion Science and Technology (Alion) is developing an oil recovery system with the capability to skim oil from ice-infested waters (see Figure 1). In 2013, Alion developed a submersible system called SEAHORSE for the United States Coast Guard (USCG) to recover heavy oil from the sea floor [1]. The SEAHORSE system used several remotely operated vehicles (ROVs) to position the oil recovery system under water. Based upon the SEAHORSE concept, Alion has designed an oil recovery system called ICEHORSE that submerges an oil skimmer in ice-infested waters, travels under the ice pack, and then surfaces in the open areas to collect oil.

Figure 1: Example ice-infested waters.

The ICEHORSE is designed to be deployed by three people using a davit, small crane, or rope sling from medium (~30 feet) to large vessels. Within ice-congested waters where oil has been detected, the system will have the ability to stay on the surface or dive below the ice congestion. The system will maneuver the oil collection hose, oil skimmer and pneumatic supply hoses for the skimmer and buoyancy system under the ice congestion to the oil patches on the surface. Because only the oil skimmer head and ice cage are on the surface, there is minimal contact with ice obstacles; most of the system remains underwater, clear of obstructions. Oil will be skimmed at the location and pumped from the skimmer sump by a pump located on the host vessel to the holding tank where a decanting system can further polish the oil/water solution. The system is designed to maximize maneuverability so that the ICEHORSE is able to clear oil in the area and then quickly move on to the next location.

The main components of the ICEHORSE proof-of-concept system are:

1) the assembly frame,
2) Elastec MiniMax drum skimmer,
3) three JW Fishers SeaLion-2 ROVs,
4) buoyancy compensation system, and
5) collection hose, air supply hoses, and control cables.

The shipboard pump, holding tank, and decanter system are not considered part of the ICEHORSE system.

This report gives an overview of the system design, results from field-testing of the system at the Oil and Hazardous Materials Simulated Environmental Test Tank (Ohmsett), the National Oil Spill Response Test Facility, located in Leonardo, NJ, and recommendations for future improvements.

2. System Design

Various aspects of the ICEHORSE system design are addressed in the following subsections. A picture of the completed system is shown in Figure 2. A schematic drawing of the unit is attached as Appendix A.

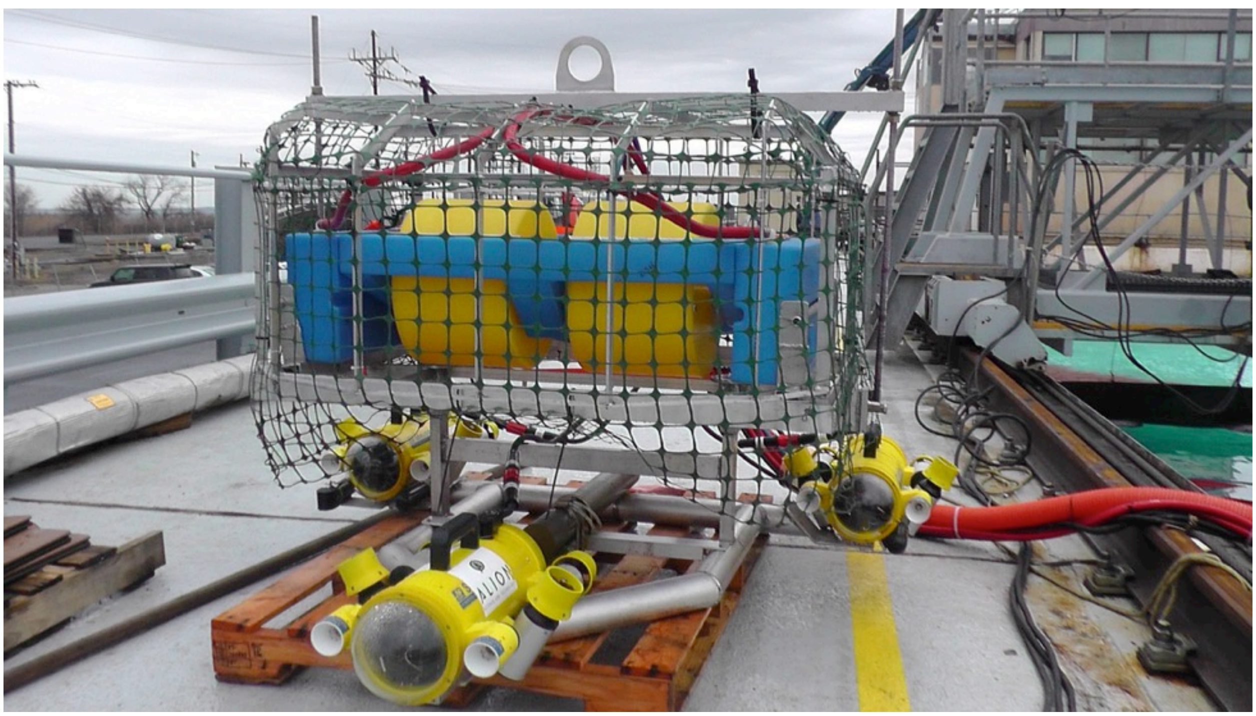


Figure 2: Complete ICEHORSE system on pallet at Ohmsett.

2.1. Skimmer Selection

The Alion team conducted a review of the various small skimmer options; assessing their ability to function in ice-infested water and their ability to be mated with the ROV-powered sled. Based upon the results of the ice testing conducted in Ohmsett in 2013 [2], the team focused on drum and disc type skimmers. The skimmer that seemed to best meet the criteria was the Elastec MiniMax drum skimmer (see Figure 3 from http://img.nauticexpo.com). The standard model of this skimmer with pneumatic drive was purchased for this project.

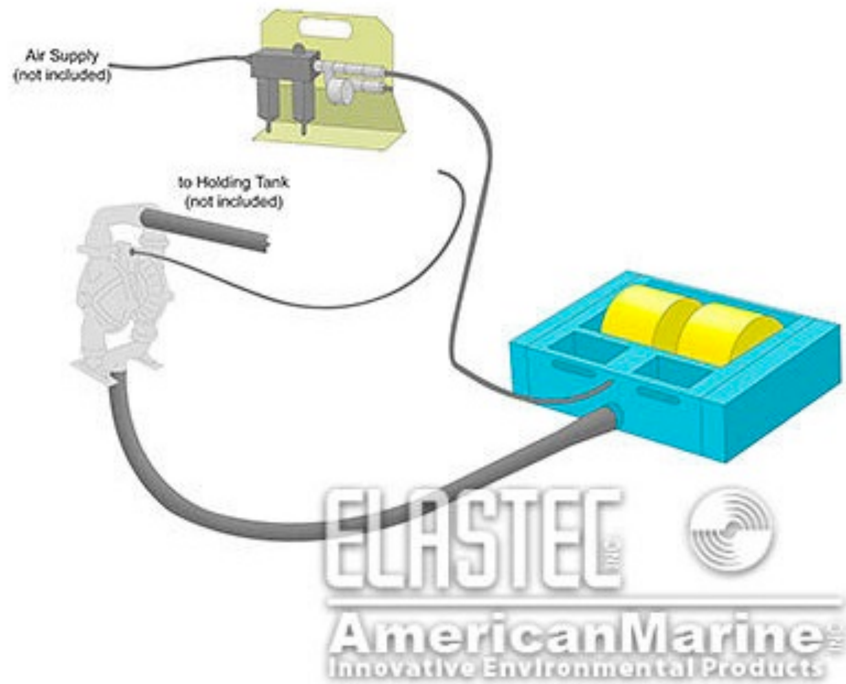


Figure 3 - Elastec MiniMax drum skimmer.

2.2. Buoyancy Compensation System

In order to submerge and surface the ICEHORSE, a buoyancy compensation system needed to be developed and Alion's Naval Architecture expertise was leveraged to design a system. The basic concept was to convert the air tanks on either side of the skimmer into ballast tanks that could be filled with water to dive. To do this, a hole was cut in the bottom of each tank and an air hose connected to the top. To submerge, the air valve is opened to allow the air to vent out the top of the tank as water floods in from the bottom. To surface, air is pumped into the tank through the hose at the top which forces water out through the bottom hole. In addition, a pneumatic valve was added to the bottom of the sump for more control of water entering or leaving the tank. To submerge, this is opened, so water can flood into the sump from the bottom; to surface this valve is closed.

This system was modified to the final configuration shown in Figure 4 through Figure 6 based upon the results of the initial system testing conducted at Alion's New London office. The primary change was to add an additional air line to allow each ballast tank to be flooded or filled independently. This feature was needed to ensure the ICEHORSE was able to surface and submerge in a level state. The skimmer drums are operated by a pneumatic motor so air is also supplied to the drum skimmer through a water remover and oiler with an integrated valve to control drum rate (see Figure 7). Air is supplied at all times to the motor to ensure that water does not back-feed into the motor through the exhaust, which could cause corrosion issues and potentially score the pneumatic cylinder due to the tight tolerances.

The ballast system is operated by an air control panel consisting of an air pressure regulator, one 3-position 3-way valve for each ballast tank, and a 2-position 3-way valve for the sump drain pneumatic valve. The air regulator is set at 60 psi to limit the pressure supplied to the ballast tanks to avoid scavenging air from the skimmer pneumatic motor to ensure its operation. The ballast tank three-way valves can be placed in the off position (for surfaced operation), or vent or supply air to the tanks at any desired rate, allowing precise control of the rate of descent or ascent. The sump drain three-way valve is essentially on or off. One position of the valve supplies air to the pneumatic cylinder, opening the sump gate valve. Flipping the lever to the second position vents the air in the line, which allows the spring of the air cylinder to force the gate valve closed.

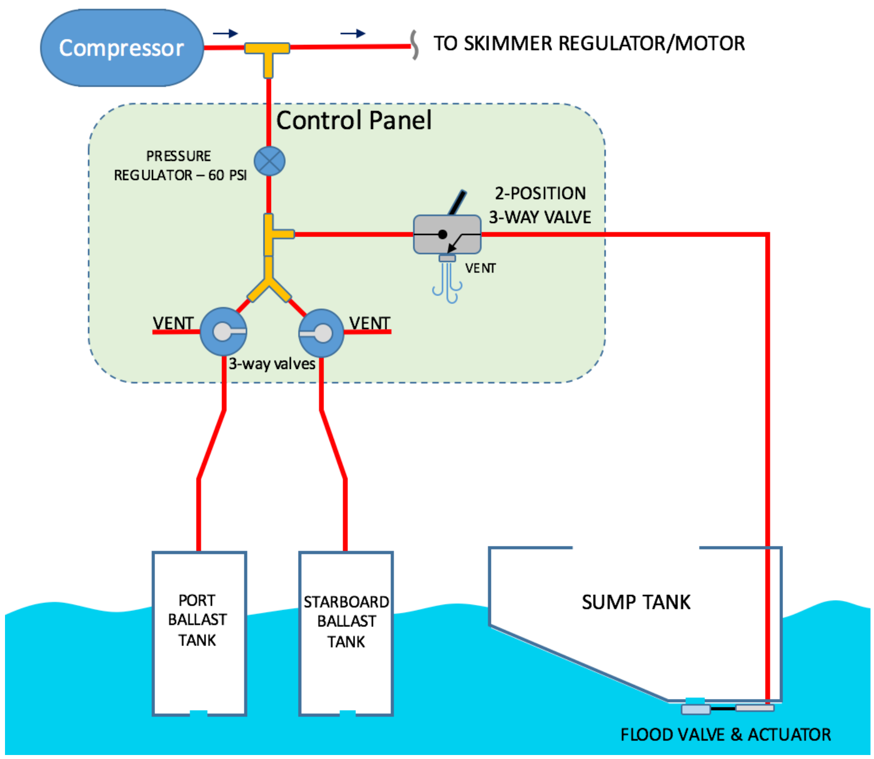


Figure 4: Final air system – surfaced.

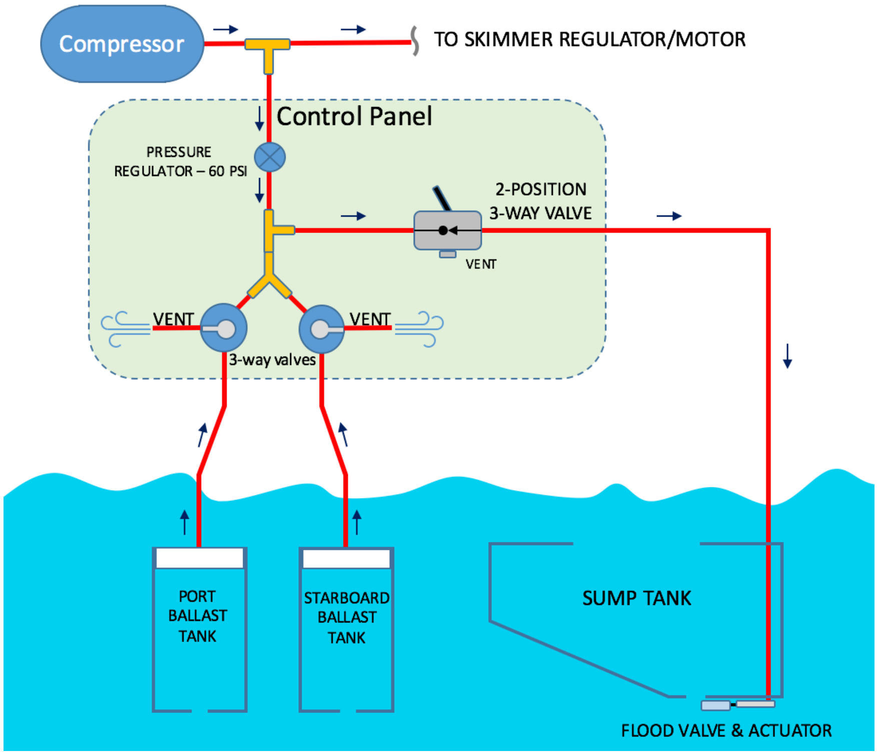


Figure 5: Final air system – submerging.

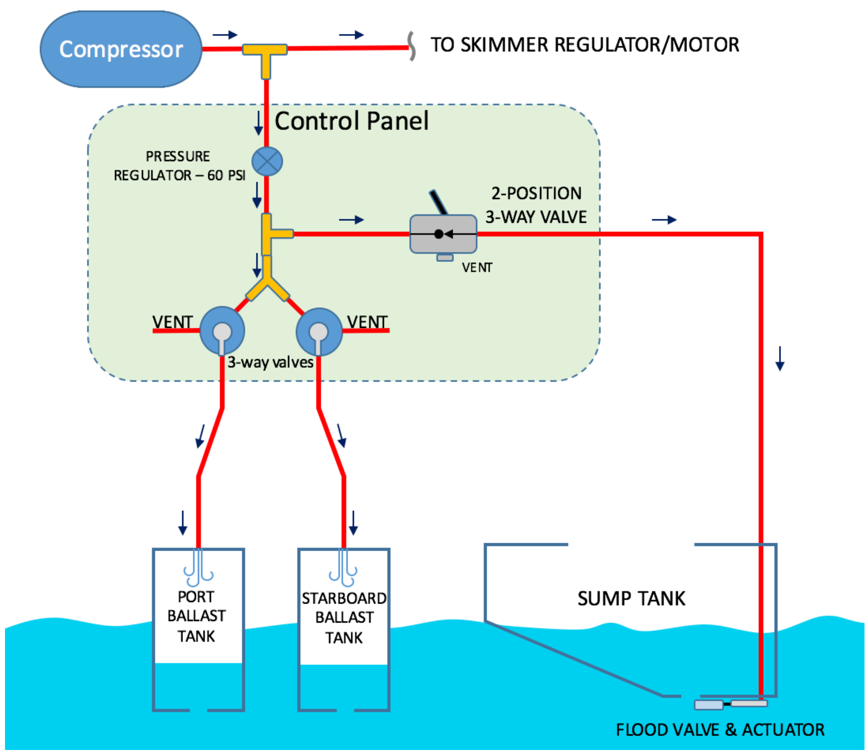


Figure 6: Final air system – surfacing.

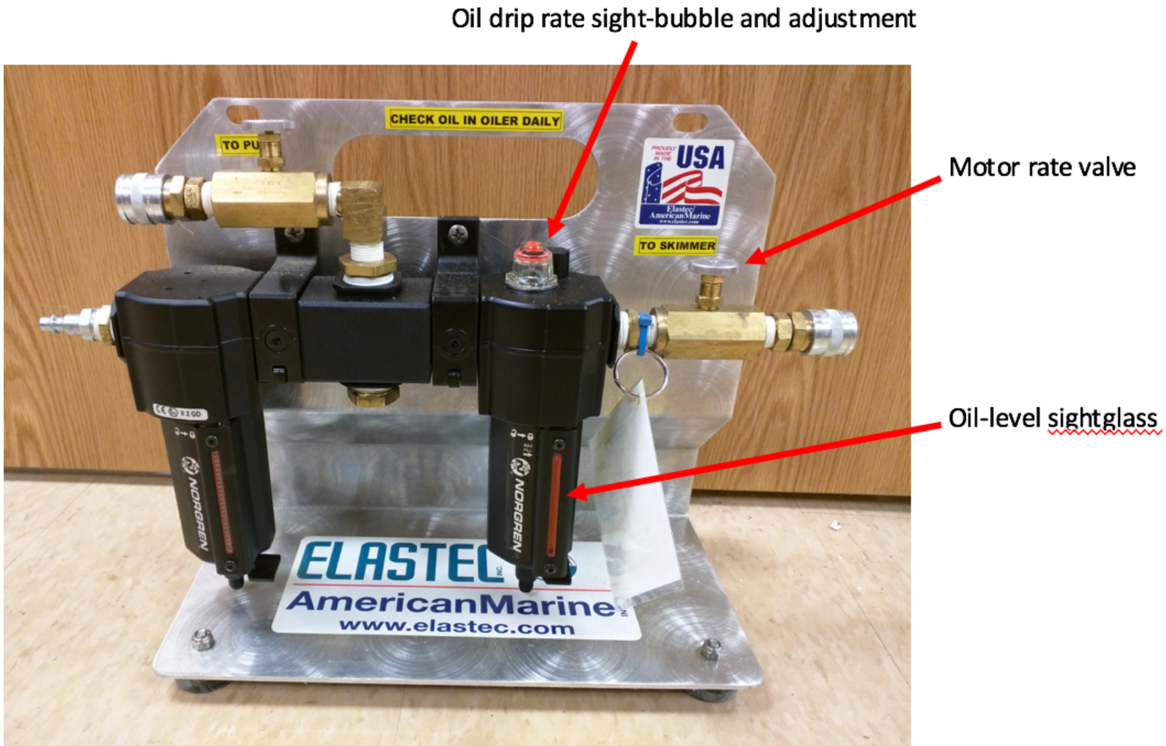


Figure 7: Skimmer pneumatic motor air control.

The sump valve did not prove to be very useful during the operational testing at Ohmsett. During submerging operations the sump quickly fills by increasing the rate of the drums (already necessary for diving operations), while the oil pump easily handles removing water. The air cylinder and valve in future ICEHORSEs would prove to just be another maintenance item and/or source of failure.

2.3. Control System

The control system consists of a joystick and thrust controller, three laptops and SeaLion-2 control boxes, a network switch, and custom control software to tie the distributed network of controllers together and map operator inputs to ROV thrusters. The skimmer operator can control the skimmer motion by using the joystick controller or optionally by using the numbers pad on the keyboard. For monitoring purposes the sensor information from the three ROVs is shown by the SeaLion-2 Control Software and the video data is displayed on the three SeaLion-2 Controller monitors.

The control system hardware consists of the following items:

- Joystick/throttle controller,
- Ethernet switch,
- three laptops,
- three SeaLion-2 Computer Interfaces,
- three SeaLion-2 controllers/monitors, and
- Associated cabling.

The control system software consists of one instance of Joystick Controller Software that in turn controls three instances of SeaLion Control Software (one instance per SeaLion). This is shown in Figure 8. The ICEHORSE control system components, including ROV control boxes/monitors, laptops for computer control, and joystick, are shown in Figure 9.

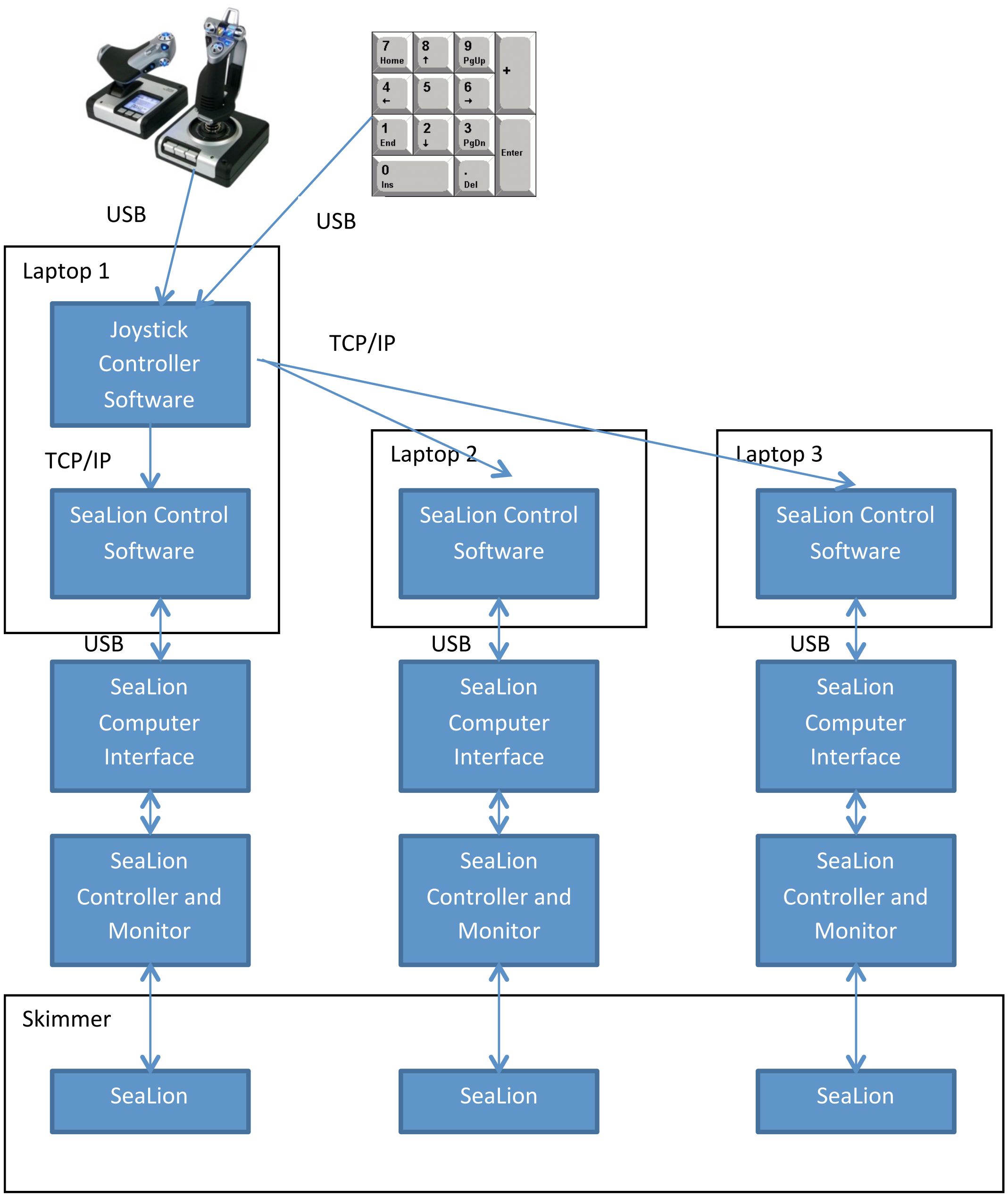


Figure 8: Control system diagram.

Figure 9: Shore side equipment for ICEHORSE.

2.3.1. SeaLion-2 Components

Two components of the Control System provided by JW Fishers are the SeaLion-2 Controller Box and the SeaLion-2 PC Interface.

2.3.1.1. SeaLion-2 Controller Box

The SeaLion-2 ROVs normally use the SeaLion controller box to control the ROV. The SeaLion-2 controller boxes (see Figure 10) have video monitors that show the live video feed from ROV cameras. A joy stick and other controls in the box are intended for manual operation of a single SeaLion ROV. The controls on the box are not used but are replaced by the SeaLion PC Interface.

Figure 10: SeaLion 2 controller/monitor.

2.3.1.2. SeaLion-2 PC Interface

JW Fishers provides a SeaLion-2 PC interface and the corresponding Software Development Kit (SDK) that allows custom personal computer (PC) software to operate the SeaLion-2 ROV. The SeaLion-2 PC interface plugs into the SeaLion-2 Controller box in place of the joystick control. This interface allows for control of all ROV functions normally controlled by joystick interface as well as overrides controls located in the base of the SeaLion-2 ROV Controller box. One laptop (or PC) can only control one SeaLion-2 ROV due to limitations in JW Fishers' SeaLion-2 PC interface; thus three laptops were used to allow simultaneous control of three ROVs from a single operator input device.

2.3.2. SeaLion-2 Control Software

The SeaLion-2 Control Software was developed by Alion to allow control of a Sea Lion through a network, thus several networked PCs can be arranged to control several ROVs from a single master controller. The SeaLion-2 Control software runs an internal TCP/IP server and accepts Comma Separated Values (CSV) command sentences. CSV command sentences are decoded and used to set and continuously update various SeaLion controls. The software also provides a Graphical User Interface (GUI) (see Figure 11) to allow monitoring of control settings, diagnostics of the network interface, monitoring of SeaLion-2 sensor readings, and setting manual override of controls as needed. Alion developed a custom algorithm to optimize the Universal Serial Bus (USB) and TCP/IP communication and ensure high-response rate of the system.

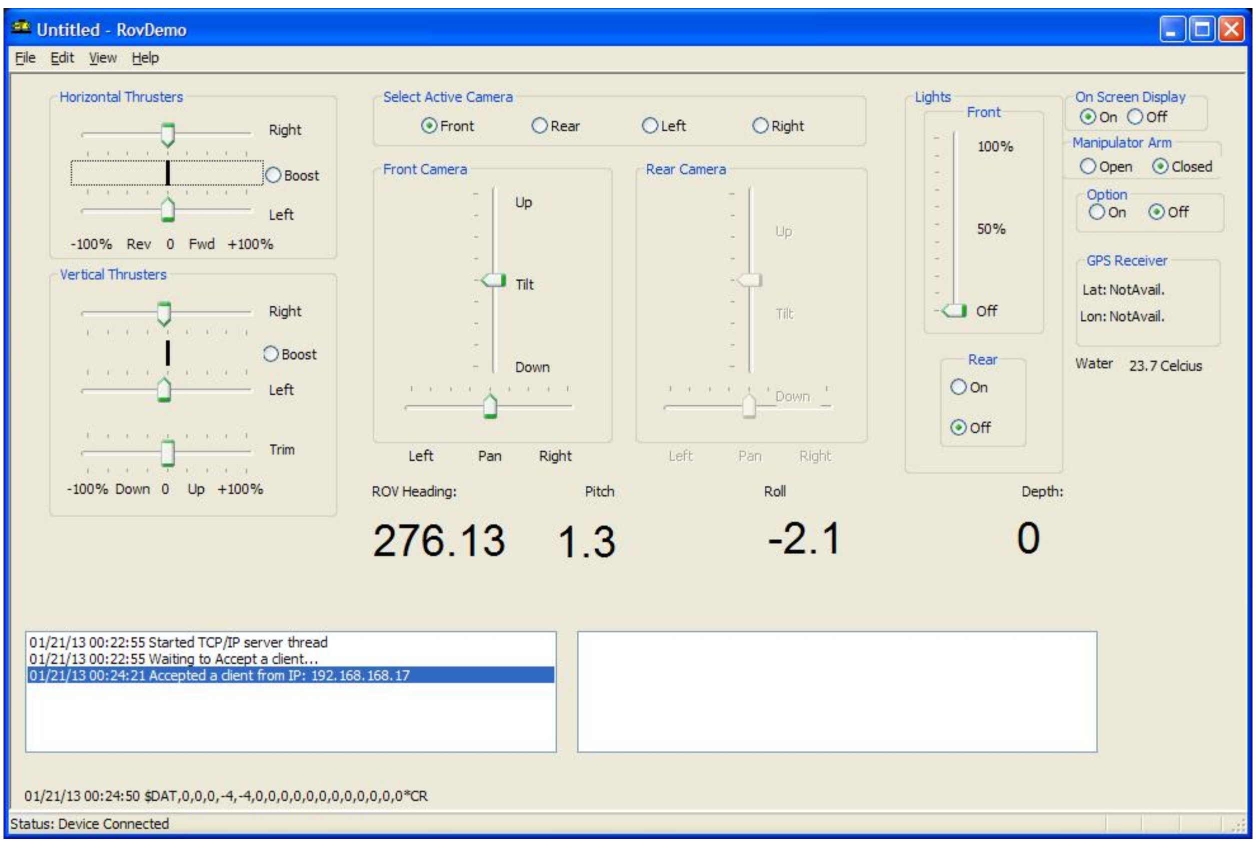


Figure 11: Screen shot of SeaLion-2 control software.

The SeaLion-2 Control software supports display of data from an optional Sea-Lion2 on-board Honeywell HMR3000 compass/pitch/roll sensor. This is a sensor that was added to one of the ROVs by Alion. The HMR3000 is setup to output only pitch and roll data; the ROV heading comes from the SeaLion-2 built-in sensor.

The Control Software normally receives commands from a joystick. The Control Software can optionally use the numbers pad on the keyboard to operate the skimmer. On start-up the software checks for the joystick control, and if it is not detected, it displays an information message and uses the keyboard control instead. Up and down motion is controlled by the “8” and “2” keys, left/right by the “4” and “6”, and increase/decrease speed by the “7” and “1”.

2.3.3. Joystick Control Software

The Joystick Control Software uses a Saitek X52Pro Flight Controller (see Figure 12).

Controller assignments are as follows:

- Joystick X-axis – steering and turning (motion left/right)
- Joystick Y-axis – speed (motion forward/backward)
- Throttle (Z-axis) – vertical motion (up/down)
- Joystick left trim-tabs (at the bottom) – vertical motion (up/down) trim
- Throttle top wheel – roll (left/right)
- Throttle side wheel – pitch (forward/backward)
- Joystick middle trim-tabs (at the bottom) - lights
- Button A - vertical thrust boosters
- Button B - horizontal thrust boosters
- Safe Button – disable all motors and lights

Figure 12: Saitek X52Pro flight controller.

3. Ohmsett Test

Alion worked with BSEE and Ohmsett on a plan for the testing that was conducted at Ohmsett on1 through 5 February 2016. The goals of the testing and the type of assessment for each goal are listed in Table 1. A diagram of the test set-up that was designed for the Ohmsett tank is shown in Figure 13.

Table 1: Test Goals and Assessments.

Test Goal	Assessment	Data Record	Test Number
Assess Maneuverability	Perform a series of maneuvers Pull against force sensor – forward and reverse Straight line speed trial – forward and vertical	Time maneuvers and measure distance Measure thrust force developed Time to complete a set distance. Time to surface (passive and thruster assisted). Time to submerge (passive and thruster assisted). Record roll/pitch during all maneuvers and tests.	1
Assess ICEHORSE Concept	Observe ability to go under the ice and pop up in the clear (oiled) area during tests	Video, photo, notes on observations. Answer questions: Can the ICEHORSE maneuver in the ice field to get to the oil? Record percentage of oil able to be recovered.	2
Assess Ice Cage Performance	Observe skimmer operation in ice field – try with both plastic and metal mesh	Video, photo, notes on observations. Answer questions: Does ice get through the mesh? If so does it impact operations? Is the metal mesh better/worse than the plastic?	2
Assess amount of oil lost as system submerges	Observer skimmer operation as it leaves the ice field	Video, photos notes on observations. Answer questions: Does the check valve prevent oil from escaping the discharge line? How well can the sump be flushed by running the drums fast to get water in the sump and then pumping it out.	2
Assess impact of ICEHORSE on the oil patch	Observe skimmer operation as it enters the oil patch	Video, photos notes on observations. Answer questions: Does the skimmer/thrusters push oil out of the way/away from the skimmer as it surfaces?	2

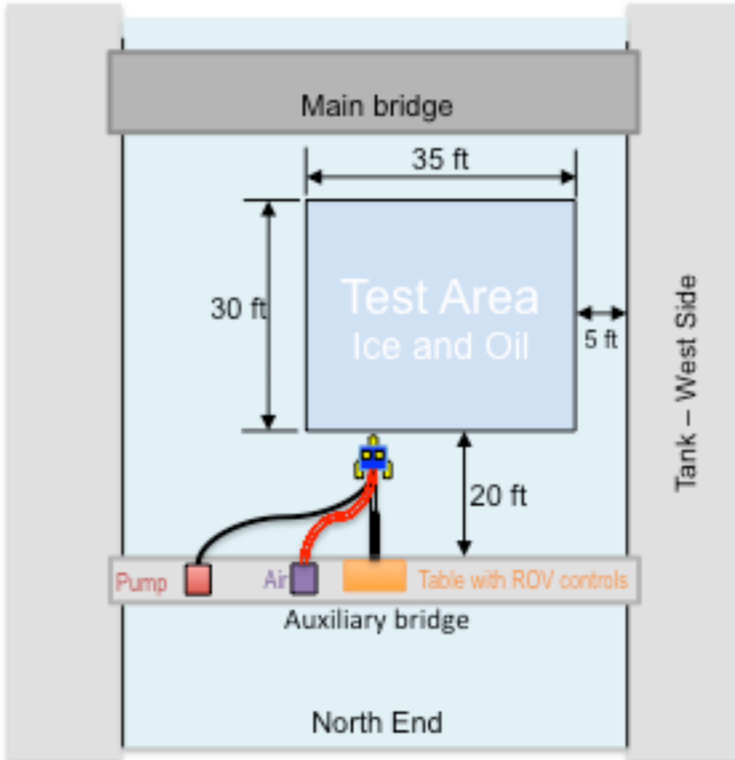


Figure 13: Test diagram for Ohmsett tank.

3.1. Test 1 – System Assessment

The first test was designed to assess the system performance including maneuverability. All tests were conducted with the full ICEHORSE system, in a clear area of the tank (no ice or oil). Prior to starting the tests, the weight/flotation on the discharge line was adjusted. For these tests the Auxiliary bridge and Main bridge were moved slightly farther apart to provide some additional clear area.

3.1.1. Test 1a – Timed Maneuver Test

- Start with the ICEHORSE on the surface in a clear area of the tank with sufficient slack in the hoses so that they are not an encumbrance.
- Start moving forward and then turn to the right until the course is reversed (180° turn); time how long it takes to turn and measure the turn radius using the laser distance measurement device at the beginning and end of the turn to measure the cross-track distance.
- Repeat but turn to the left.

3.1.2. Test 1b – Thrust test

- Connect the ICEHORSE to the thrust measurement system using a Y-bridle; thrust attachment needs to be approximately 2 feet below the water line.
- Pull forward against the thrust measurement system for 30 seconds at full speed; record the amount of thrust developed.
- Reconnect the thrust measurement system to the opposite end of the ICEHORSE and repeat the test in reverse.

3.1.3. Test 1c – Straight Line Time Trial

- Start with the ICEHORSE on the surface in a clear area of the tank with sufficient slack in the hoses so that they are not an encumbrance.
- Engage the horizontal thrusters and start the timer when a mark on the side of the tank is reached and stop the time when the second mark is reached (17 feet). The goal is to have the system at speed before the first mark is reached. Calculate the average speed.
- Repeat the test while submerged.

3.1.4. Test 1d – Diving Test

- Start with the ICEHORSE on the surface at rest.
- Flood the tanks and time how long it takes for the system to submerge to the bottom (or reach equilibrium).
- With the ICEHORSE sitting on the bottom fill the tanks with air and time how long it takes the system to rise to the surface (or reach equilibrium).
- Flood the tanks and engage the vertical thrusters and time how long it takes for the system to submerge to the bottom.
- Fill the tanks with air and engage the vertical thrusters and time how long it takes the system to rise to the surface.

3.2. Test 2 and 3 Operational Tests

This series of tests was to assess the overall concept and performance of the system in the operational environment. For each of these tests the boomed off recovery area was used. There were 2 different ice concentrations (30% and 70%) and testing was done with no oil and then with oil (repeated) for a total of six tests. The tests with 30% ice are labeled Test 2 (a, b, c) and the tests with 70% ice are labeled Test 3 (a, b, c).

For each test, the ICEHORSE started on the surface near the bridge. It was submerged then maneuvered underwater to the middle of the square where it surfaced and commenced skimming oil. The ICEHORSE was maneuvered on the surface within the square as needed to skim the oil. Oil was skimmed until the layer was reduced from 1inch to 2/3 inch (based upon gallons recovered). This process was timed. The oil was then re-filled to 1inch and then the test repeated and timed. The remaining oil was then recovered and timed.

Once done, the ICEHORSE was submerged and maneuvered back to near the Auxiliary bridge and surfaced. Prior to submerging the drums were run at high speed while still pumping to introduce water into the sump to purge the sump. The pumping continued as the system submerged and then secured.

All of the tests are summarized in Table 2. A fourth option test, to assess skimmer performance, was not run.

Table 2: Test Matrix.

Test Number	Test	Ice Concentration	Oil	Data Collection
1a	Timed Maneuver	None	None	Adjust hose floats – weights Video and notes on maneuverability - 180 turn –time to complete and turn radius - both sides - start from amidships
1b	Thrust	None	None	Measure thrust force – both directions
1c	Time trial	None	None	time speed forward (use boom for distance and stopwatch on side of tank) - do both on surface and underwater
1d	Diving	None	None	Time to submerge - from surface to bottom. Time to surface - from bottom of tank to surface.
2a	ICEHORSE Concept	30%	None	Test surfacing and maneuvering in ice with NO OIL first.
2b	ICEHORSE Concept	30%	~1in thick	Time to reduce to 2/3in oil. Observations of oil slick as ICEHORSE submerges and leaves area.
2c	ICEHORSE Concept	30%	~1in thick	Repeat of 2b. Time to reduce to 2/3in oil Time to clean area (or max possible) Observations of oil slick as ICEHORSE submerges and leaves area.
3a	ICEHORSE Concept	70%	None	Test surfacing and maneuvering in ice with NO OIL first.
3b	ICEHORSE Concept	70%	~1in thick	Time to reduce to 2/3in oil. Observations of oil slick as ICEHORSE submerges and leaves area.
3c	ICEHORSE Concept	70%	~1in thick	Repeat of 3b. Time to reduce to 2/3in oil. Time to clean area. Observations of oil slick as ICEHORSE submerges and leaves area.
4	Skimmer test	None	~1in thick	Baseline oil collection – if time – use a smaller area for collection

4. Test Results

The tank was configured according to the test plan. Figure 14 shows the test area as set up with 70% ice concentration. In the figure, the Auxiliary bridge is to the right and the Main bridge to the left. Figure 15 shows the installation of the double diaphragm air pump (yellow) and air manifold board (above yellow pump with red air lines) located on the Auxiliary bridge. The ROV controls were originally located on the upper level of the Auxiliary bridge, according to the plan (see Figure 16). However, due to the wind and the rain, the cables were re-routed to the Main bridge, so the controls could be indoors out of the rain (see Figure 17).

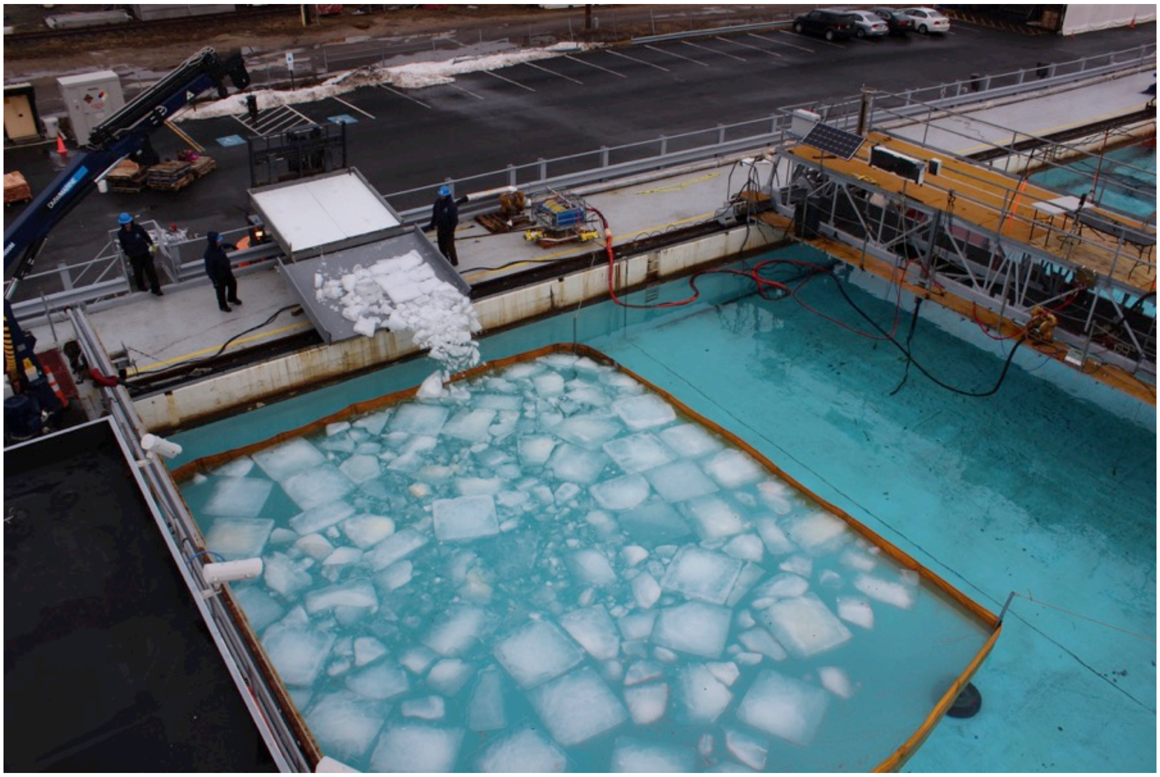


Figure 14: Test Area as set up at Ohmsett; Auxiliary bridge is to the right, Main bridge to the left, yellow boomed area is the test area. Shown here with ice being loaded for the 70% ice concentration.

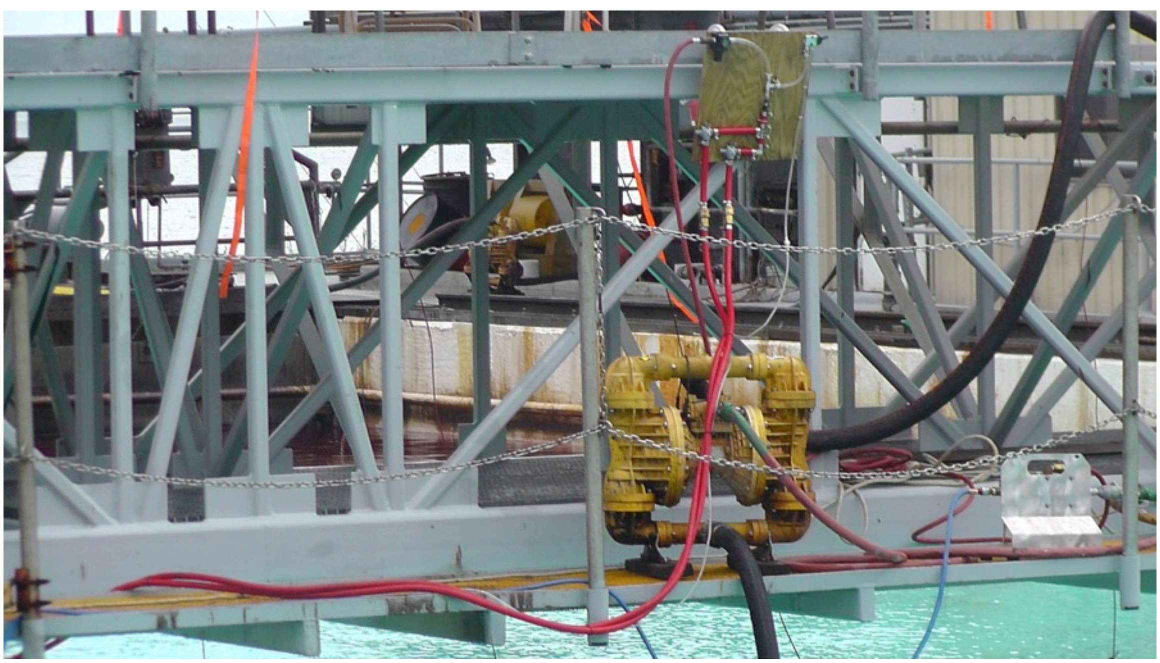


Figure 15: Location of double diaphragm air pump (yellow) and air manifold board (above yellow pump with red air lines) on the Auxiliary bridge.

Figure 16: Initial location of ROV controllers on upper level of Auxiliary bridge.

Figure 17: ROV controllers located on table in the Main bridge.

4.1. System Assessment

The tests were run at Ohmsett in a slightly different order; the thrust test was run first and then the timed maneuver test run last. A summary of the four system assessment tests is in Table 3. At the start of the testing it was noticed that the starboard thruster on the forward ROV was not functioning. This did not appear to limit the maneuverability at all but probably reduced the thrust and speed slightly (by approximately 15%).

4.1.1. Timed Maneuver Test

This test was conducted in the space between the Auxiliary bridge and the test area. ICEHORSE was able to execute 180-degree turns in both directions in 15-20 seconds with virtually no turning radius; the limitation on the turn radius was the flexibility of the hose and whether the system was becoming tangled up in the hose turning. Figure 18 shows the ICEHORSE turning to the left. The turn shows little turn radius.

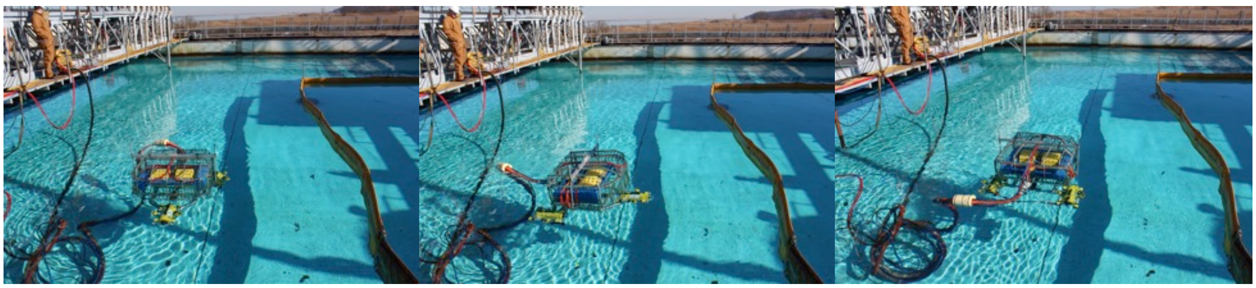


Figure 18: ICEHORSE turning to left; note that there is virtually no horizontal displacement.

4.1.2. Thrust Test

For this test a load cell was attached to the ICEHORSE using a bridle and straps; the other side of the load cell was secured to the Auxiliary bridge with another strap. ICEHORSE then pulled against this on the surface. The test was conducted in reverse first and then re-rigged for the forward thrust test. In both cases the test was run at low and high power on the thrusters. The thrust test showed only 12 lbs thrust in the forward direction and about 2 lbs thrust in reverse (using high power). These results seemed low compared to the manufacturer’s specification sheet, but were conducted at the lower range of the load cell meter, which measures up to 2,000 lbs so there may have been some error in the measurements. The load cell was fairly heavy and sank toward the bottom of the tank (see Figure 19) so the thrust axis was not exactly in line with the load cell; this may have introduced some error as well. The system in operational use did not appear to be thrust-limited despite these low measurements.

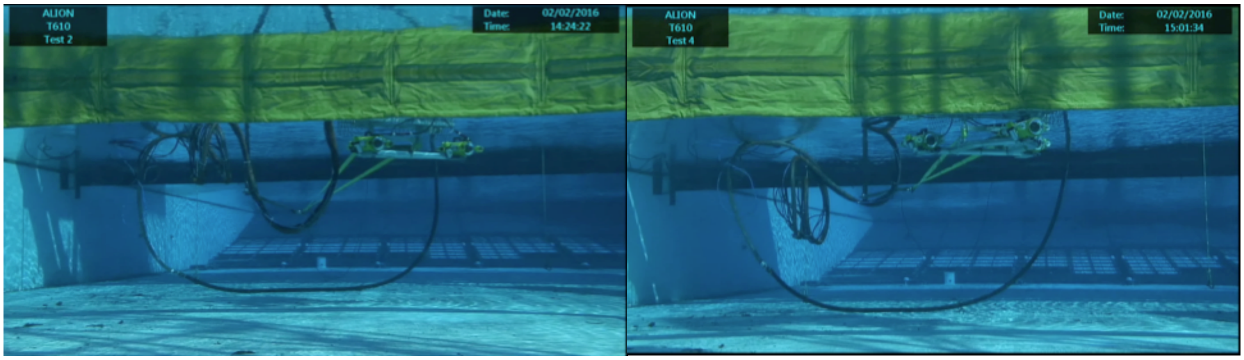


Figure 19: Underwater photo of thrust test in reverse (on left) and forward (on right). Note the catenary in the straps caused by the weight of the load cell (center).

4.1.3. Straight Line Time Trial

The time trial was conducted across the tank in front of the Auxiliary bridge. A distance of about 17 ft was marked out with vertical lines hanging from the bridge. ICEHORSE was started next to the near wall and accelerated to maximum speed. The timer was started when the first line was crossed and stopped when the second was reached. The ICEHORSE speed was approximately 0.75 kts on the surface and approximately 0.4 kts when submerged. Moving forward induced a slight pitch up both on the surface (see Figure 20) and submerged (see Figure 21). In Figure 20 the start and stop markers (lines hanging down from Auxiliary bridge) are circled in orange.

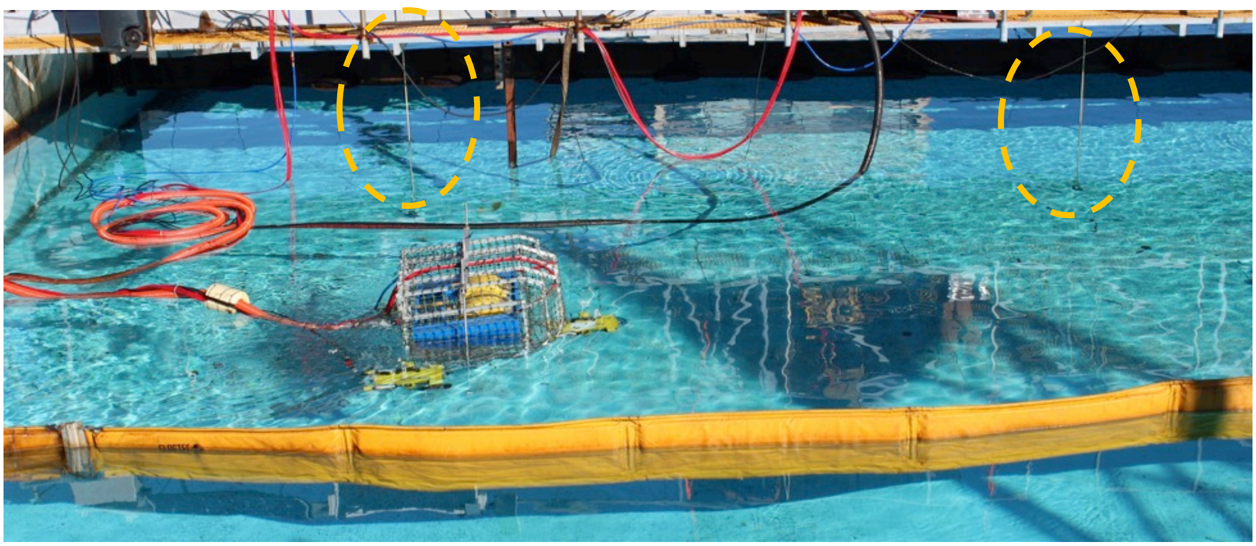


Figure 20: ICEHORSE time trial on surface; notice slight upward pitch when accelerating. The start and stop markers (lines hanging down from Auxiliary bridge) are circled in orange.

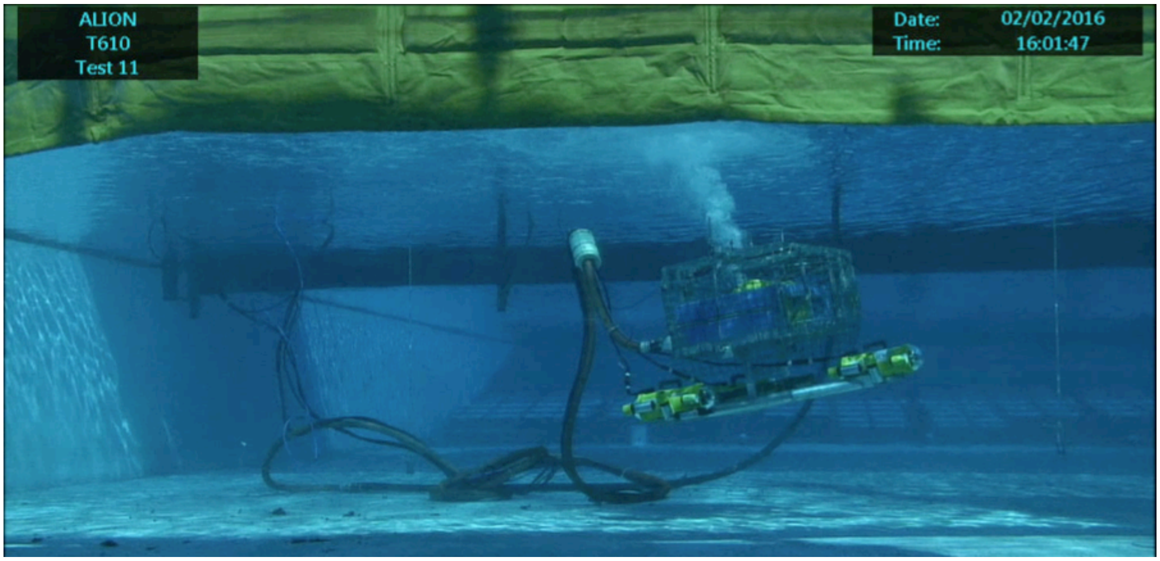


Figure 21: ICEHORSE time trial underwater; note upward pitch.

4.1.4. Diving Test

In a passive submerge mode (venting air from the tanks and allowing them to fill with water but not using thrusters) the system would submerge to about the point that the lift bar was even with the surface; the float on the discharge hose prevented it from sinking any further (see Figure 22). This took about 1 minute. To resurface using just air into the tanks (no thrusters) from this position took about 4 seconds. Using thrusters to assist with submerging, the time to submerge to the bottom (see Figure 23) was approximately 48 seconds and the time to resurface (from the bottom of the tank) using both air and thrusters was about 8 seconds. The buoyancy compensation worked but could be improved by adding a valve to directly vent the tanks rather than by venting back through the supply line (which is slow). Unfortunately the stress of the quick surfacing resulted in a crack in the frame, which was repaired using a nylon strap to allow the testing to continue.

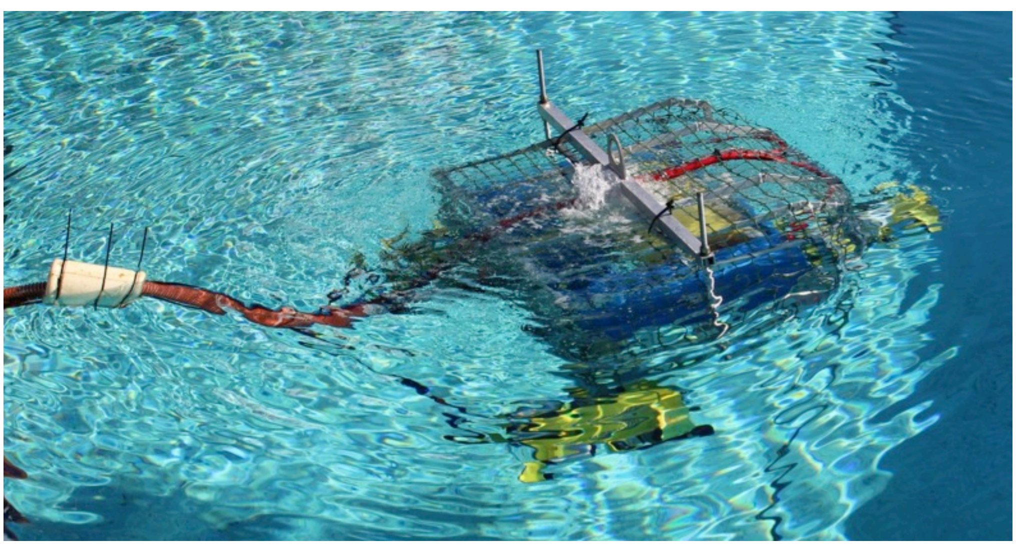


Figure 22: ICEHORSE passive submerging; note that equilibrium is reached with the lift bar about at the surface of the water.

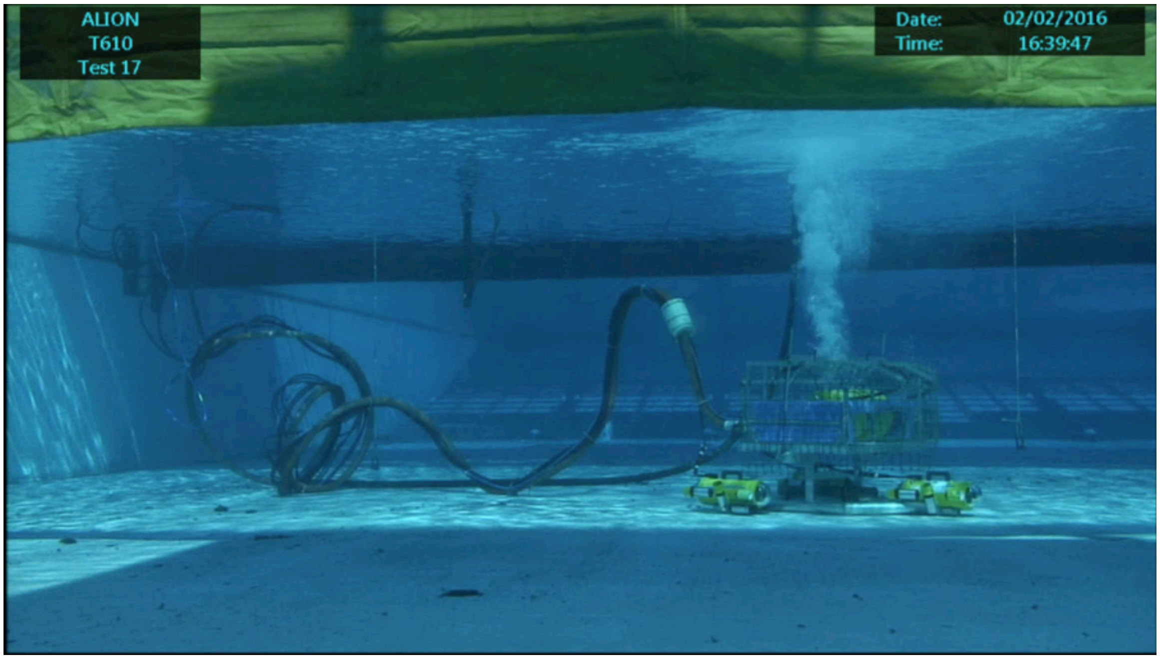


Figure 23: ICEHORSE powered submerging; ICEHORSE sitting on the tank bottom.

Table 3: System Assessment Test Results.

Test Plan #	Ohmsett Test #	Test Description	Water Temp (°F)	Air Temp (°F)	Wind (mph)	Test Start Time	Result	Notes
1B	1	Thrust test - reverse	37.2	42.7	3.2 @ 296.4	9:16	~0	in reverse never even got the straps out straight
	2	Thrust test - reverse boost	37.2	43.1	3.9 @ 315.1	9:22	~2 lbs	
	3	Thrust test - forward	37.3	45.7	4.4 @ 338.7	9:56	~3-4 lbs	better in forward but still a catenary
	4	Thrust test - forward boost	37.3	46.1	5.0 @ 325.0	10:00	~10-12 lbs	
1C	5	Time trial - surface	37.3	47.7	4.2 @340.8	10:30	13-14 sec, 1.26 ft/sec or 0.75 kts	Started at wall. Started time at first rope, ended at second. Did 3 trials.
	6	Time trial - surface	37.4	47.8	4.4 @ 324.0	10:35		
	7	Time trial - surface	37.4	48.1	5.1 @ 320.1	10:39		
	8	Time trial - submerged	37.4	48.4	5.0 @ 314.9	10:44	24-25 sec, 0.68 ft/sec or 0.4 kts	Started at wall. Started time at first rope, ended at second. Did 4 trials
	9	Time trial - submerged	37.4	48.6	6.8 @ 319.4	10:53		
	10	Time trial - submerged	37.4	48.9	4.1 @ 325.0	10:57		
	11	Time trial - submerged	37.4	48.9	3.8 @ 345.9	11:00		
1D	12	Submerge (passive)	37.6	49.3	2.8 @ 309.8	11:19		stopped with water level at bar - hose float prevented from sinking totally
	13	Surface (passive)	37.5	49.9	3.7 @ 337.9	11:24		slight pitch up until sump is pumped
	14	Submerge (passive)	37.5	49.9	6.4 @ 342.4	11:27	58.8sec	
	15	Surface (passive)	37.5	49.9	3.3 @ 358.9	11:31	3.9 sec	from just below surface
	16	Submerge (with thrusters)	37.5	50.2	5.0 @ 349.2	11:34		power failed on first trial
	17	Submerge (with thrusters)	37.5	50.2	5.0 @346.8	11:38	48 sec	
	18	Surface (with thrusters)	37.5	50.2	4.8 @ 349.1	11:44	7.85 sec	from bottom of tank
1A	19	180 turn, left then right	38.1	50.8	1.0 @ 31.2	13:06	15 - 20 sec	turn rate is fast, virually zero radius until hose has to be dragged
	20	180 turn, left	38.1	52	3.5 @ 42.3	13:16	0 ft radius	
	21	180 turn, left then right	38.1	51.9	1.7 @44.6	13:22		

4.2. Operational Tests

The operational tests were very successful. There were two operational tests, one in 30% ice (see Figure 24) coverage and one in 70% ice coverage (see Figure 25). On the day of the 30% coverage test, the wind was blowing so that the ice was compacted, making it more like 60% coverage in the area that there was ice. In both cases, the ICEHORSE system performed well.

Figure 24 Test area with 30% ice coverage with oil; note that ice is all drifted into about half of the test area.

Figure 25 Test area with 70% ice coverage with no oil, note even distribution of ice and range of ice sizes.

4.2.1. Surfacing and Maneuvering in Ice

ICEHORSE was very successful in surfacing into the broken ice field. The air bubbling up from the skimmer was a major advantage in pushing the ice and oil out of the way as ICEHORSE surfaced. This was true in both 30% and 70% ice cover (see Figure 26).

Figure 26: ICEHORSE surfacing into oil and ice (70% ice coverage).

ICEHORSE maneuvered well in and around the ice. It was also able to push the ice around and out of the way, even though the large blocks were over 400 lbs. The only time it had an issue was when the ice piled up against the boom and had nowhere to go (see Figure 27). In this case however, it was easy enough to back up and rotate the system and go another direction. The ice cage also worked well at keeping the ice out of the skimmer (see Figure 28).

Figure 27: ICEHORSE with ice jammed against the boom.

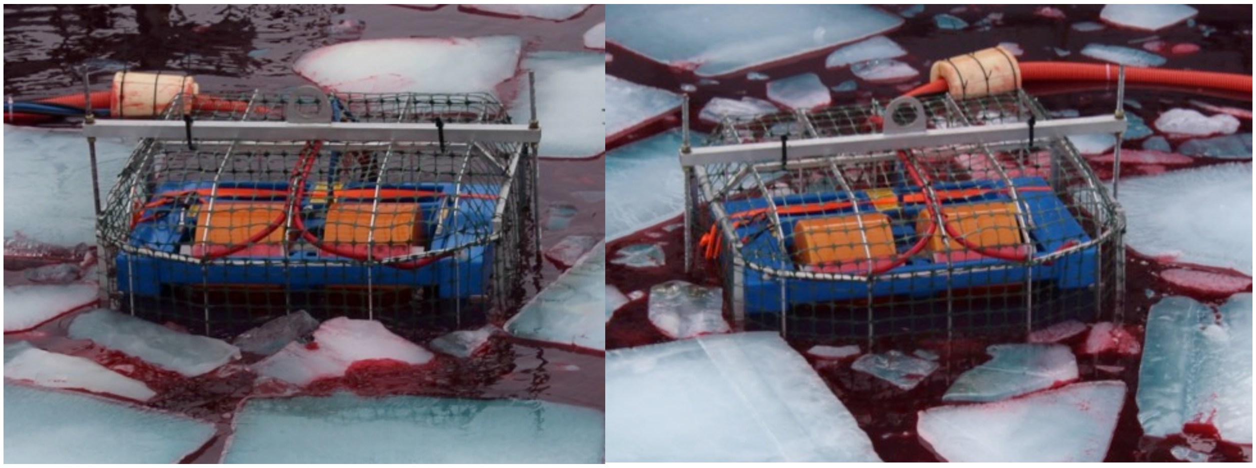


Figure 28: ICEHORSE ice cage and mesh were effective at keeping ice out.

4.2.2. Skimmer Performance

The times to skim to various levels are listed in Table 4 (30% ice coverage) and **Error! Reference source not found.**Table 5 (70% ice coverage). The time to skim was primarily a function of how well the skimmer was optimized. The drum speed impacted pickup performance (rate and efficiency), especially with the low viscosity of the diesel. For this viscosity of oil a different type of skimmer may have performed better. The efficiency was qualitatively determined visually and the drum speed adjusted as necessary to achieve the best efficiency. Figure 29 shows when the skimmer was operating at high efficiency while Figure 30 shows when the skimmer was operating at low efficiency. At times it appeared there was less oil on the drum due to the skimmer encountering slushy ice that made it through the ice cage, other times it was due to the drum speed being too high for the thickness (and viscosity) of the oil.

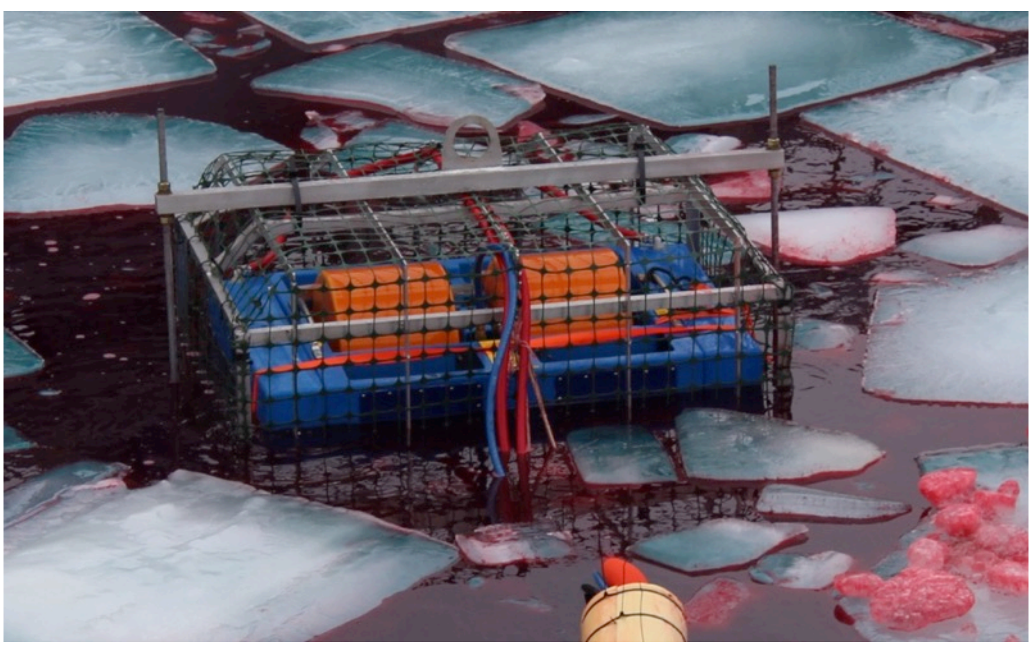


Figure 29: ICEHORSE in operation - drum fully coated with oil indicating that it is picking up oil well - the drum speed is good.

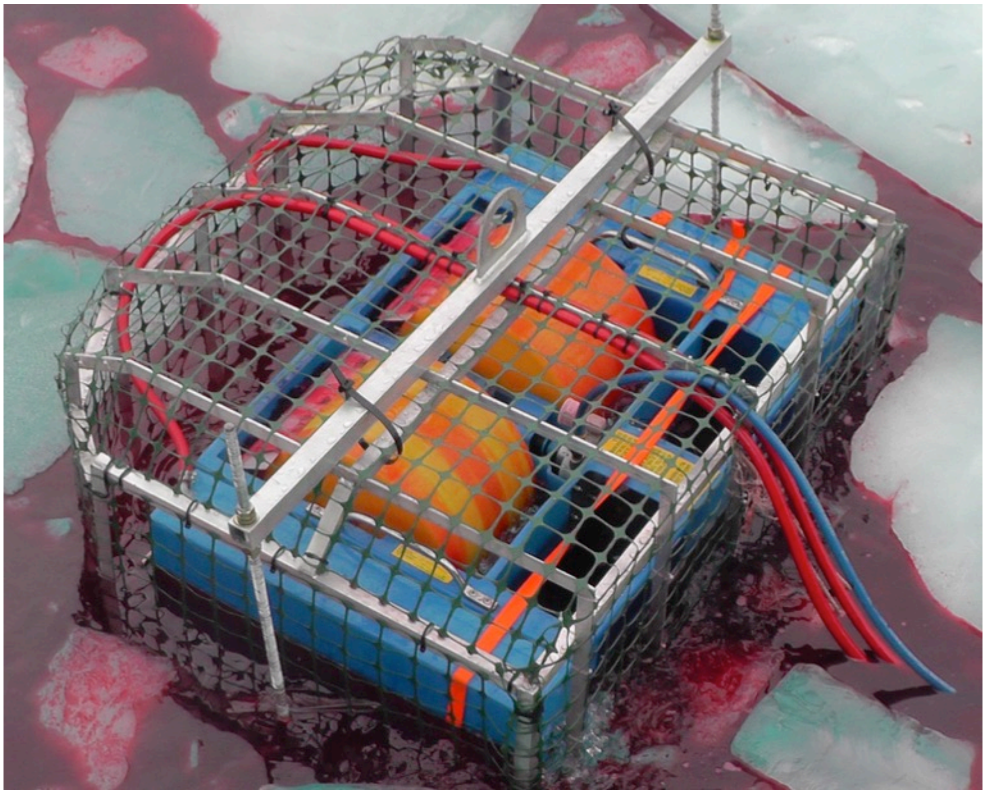


Figure 30: ICEHORSE in operation not effectively picking up oil - drum NOT fully coated, the drum speed is too fast.

Maneuvering did not impact the oil recovery as long as the system was not maneuvered too fast. Using the vertical thrusters did impact recovery as the wash from the propellers tended to push the oil away. Keeping the ICEHORSE in motion helped in the oil recovery by allowing the skimmer to stay in areas of thicker oil.

Table 4: 30% Ice Coverage Skimming Results.

Test Plan #	Ohmsett test #	Test Desc.	Water Temp (°F)	Air Temp (°F)	Wind (mph)	Test Start Time	Result	Notes
2a	22	Surface and maneuver - no ice	38.7	54.5	8.4 @ 185.9	10:26	N/A	ICEHORSE maneuvered in ice without difficulty. Air bubbles from drum cleared the area above as the unit surfaced. No problem pushing through ice and around big blocks(~400lbs ea!).
2b	23	Enter areea, surface, time to reduce from 1" to 2/3" oil, submerge, and leave	38.7	55.3	3.9 @ 315.1	10:54	21 min to get 152 gal (5gpm), 69% efficiency - drum at 72 rpm	Very little oil lost as unit submerged. Skimming rate limited by skimmer - ran drums as fast as possible without introducing water (RPM ~72). Pump could handle a lot more than skimmer produced into the sump; it introduced air into the discharge line when the sump got low - this caused the line to float. Was easy to maneuver the skimmer as needed.
2c	24	Enter areea, surface, time to reduce from 1" to 2/3" oil	39.2	57.6	13.8 @ 169.3 (gusts to 25)	12:40	~18 min to get to 150 gal (8.3gpm), 75% efficiency - drum at 60-78 rpm	Ran drum at 60rpm then increased to 78rpm. Have to be careful when moving ICEHORSE - if move too fast then start picking up water. Very little seepage on submerging; came up clean.
		Time to celan all oil, submerge, and leave					40 min for 310 gal (7.75 gpm),50.6% eff drum at 70 rpm	

Table 5: 70% Ice Coverage Skimming Results.

Test Plan #	Ohmsett test #	Test Desc.	Water Temp (°F)	Air Temp (°F)	Wind (mph)	Test Start Time	Result	Notes
3a	25	Surface and maneuver - no ice	41	49.7	13.6 @ 311.2	10:04	N/A	Maneuvered well, no problems with large ice. Mesh worked well on holding out smaller stuff.
3b	26	Enter areea, surface, time to reduce from 1" to 2/3" oil, submerge, and leave	40.9	50.3	9.1 @ 315.1	10:46	13 min to get 65gal (5 gpm), at 44.4% efficiency, drum at 75 rpm	Some slush and ice wiped oil from drum; difficulty finding optimum efficiency drum speed. Little to no oil lost as unit submeerged.
3c	27	Enter areea, surface, time to reduce from 1" to 2/3" oil	40.8	50.7	8.9 @ 312.3	11:41	23 min to get 65 ga (2.3 gpm), at 65% efficiency, drum at 23 rpm	ICEHORSE maneuvered well through ice field; no difficulties.
		Time to reduce from 2/3" to 1/3" oil, submerge, and leave					26 min to get 64 gal (2.03 gpm) at 82% eff, drum at 33rpm	Needed to keep system moving as oil started to get thin.

4.3. ICEHORSE Design Issues

4.3.1. Structural Performance

The size of the ICEHORSE system was based on the ROVs available and the size (depth primarily) of the Ohmsett tank. This led to a system design that was fairly small and used the smallest drum skimmer we could find.

The ice cage worked well to keep out large chunks and was not negatively affected by the pressure of pushing against the ice. The mesh kept out small pieces, but slush was able to get through.

The air motor used to run the skimmer drum is not really suited for underwater use. Its long-term reliability for this application may not be acceptable.

The system frame was not sturdy enough (both in design and in construction). During the high speed surfacing the frame cracked at one of the welds.

4.3.2. Other Considerations

During the tests, the pump used was over-powered for the skimmer; even at minimum pump speed it would sometimes pump the sump dry and introduce air into the hose (this caused the hose to float). A pump should be used that is sized for the skimmer.

The hose floated when air was in it and sank when filled with oil/water. This would be an issue in deep water and would need compensation to keep the hose neutral or slightly negative when filled so it wouldn’t pull the skimmer under water when filled with oil/water. The flexible PVC hose, designed for vacuum applications, which we used was more than sufficiently flexible to allow full motion of the ICEHORSE. The only time the hose became unwieldy was when it filled with air and floated to the surface.

One of the ROV thrusters failed (starboard forward horizontal). This reduced the forward power by about 15%, but did not noticeably impact performance.

5. Future Development

Further development is needed on the ICEHORSE proof-of-concept to improve the design to make it more useful in an operational environment. Specifically, it must have the ability to locate and guide the system from beyond visual sight of the tending vessel, as well as below the ice pack. Also, the system needs to be refined to make it easier to deploy and maintain. Other improvements to be implemented in an ICEHORSE II are:

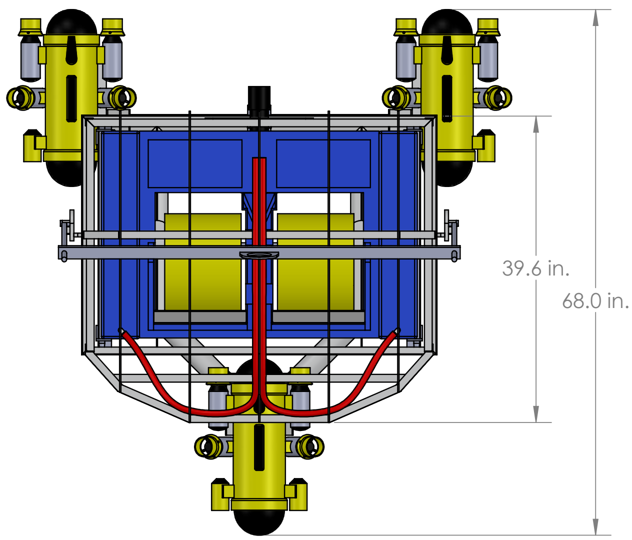
- Skimmer selection
- ROV changes
- Camera changes
- Buoyancy system changes
- Structural changes

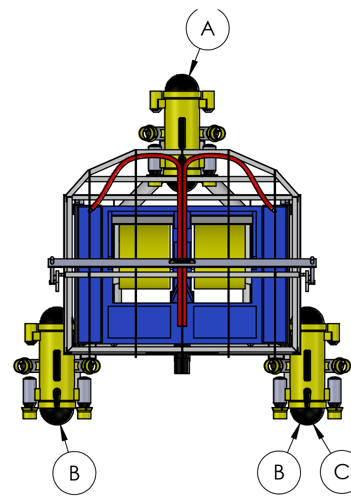
6. References

[1] G. W. Johnson, "Alion Sea Horse – Phase 3 Demonstration Report," Preapred for USCG Research and Development Center, New London, CT, Del 9 under Contract HSCG32-10-C-R0000231 January 2013.

[2] "Skimmer Tests in Drift Ice: Ice Month 2013 at Ohmsett," SL Ross Environmental Research Limited, Ottawa, ON, Report Prepared for Bureau of Safety and Environmental Enforcement, August 2013.

Appendix A. ICEHORSE Dimensioned Drawing





A - Pitch/Roll Sensor (HMR3000)
B - Compass, depth, and temperature sensor
C - Distance from bottom sensor