



FINAL REPORT

Robotically Emplaced and Recovered Underwater Test Bed: Underwater Robotic Test Bed Construction & Remediation

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C-2 Innovations, Inc.

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ACRONYMS AND ABBREVIATIONS

ADCP	Acoustic Doppler Current Profiler
BMS	Battery Management System
CPT	Cone penetrometer Test
C	centigrade
DVL	Doppler Velocity Log
EOD	Explosive Ordnance Disposal
Ft	feet
GPS	Global Positioning System
Hr.	hour
In	inches
IMU	Inertial Measurement Unit
IVS	International Verification Strip
Kg	kilogram
Km	kilometer
Kt	knot
kW-hr	kilowatt-hours
Lb.	pound
M	meters
Mm	millimeter
NM	Newton Meters
RF	radio Frequency
RTK	Real Time Kinetic
TIP	turn in place
USACE	US Army Corp of Engineers
USBL	ultra-short baseline
UXO	unexploded Ordnance
V	volts
VPM	vibrations per minute

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ABSTRACT

INTRODUCTION AND OBJECTIVES

The goal of the Harvester program was to robotically place target sets in the surf zone and very shallow regions of the ocean. The intent was to place the targets with submeter accuracy, as well as bury targets at predetermined orientations and depth.

TECHNOLOGY DESCRIPTION

The main drive platform is based on the Sea Beast autonomous, amphibious, bottom crawler (now referred to as the B350-HD) with an 800-lb payload capacity. The fully loaded Harvester system has a low dry ground pressure of 6.0 kilopascals (0.88psi) or half that when submerged, enabling transit across weak soils.

Two dispenser designs were constructed and tested that allows the system to carry and release multiple targets. The simpler drop rack uses gravity feed to drop targets on the ocean floor. The system has a high sail area and is restricted to predictable shapes but could hold sixteen, 155mm artillery shells (or more smaller diameter rounds).

Control is based on either RF command, man-in-the-loop or autonomously based on prearranged positions. Placement precision is centimeter accuracy using a mast mounted RTK as a guide, or .5-m accuracy using IMU guidance only. Clusters of 5 targets could be placed in 3-m square body-centered pattern with an accuracy of 0.15-m.

Experiments were performed on excavating emplacement holes for placing buried targets at various angles and depths to 1 meter. Power curves and control systems were designed and tested.

IMPLEMENTATION ISSUES

The economic impact of the pandemic and the need to redesign the vehicle to accommodate the heavier loads curtailed completion of the program. Component costs doubled, beach access restrictions prevented testing and delivery delays all lead to elimination of the final refinements and demonstration. The technology was demonstrated at a subsystem level to be a success, meeting capacity and placement accuracy goals in sea state 3 surf conditions. The dispensing of targets on the surface or in shallow partially buried, is achievable. Deeper 1-m burial is possible but with greater development cost and a much greater reliability risk.

EXECUTIVE SUMMARY

INTRODUCTION

The purpose of the Harvester test-target planting system is to place unexploded ordnance (UXO) surrogates (or targets) at various burial depths and orientations in waters ranging from the beachline through the surf into water depths of up to 30 meters. A key feature was the ability to precisely deposit the targets in a re-acquirable and verifiable location. The concept referred to as the 'Harvester' was based on using proven technologies such as pumps, caissons, gravity feeds, and plows.

A design challenge was to fit all the components on a delivery platform, including power. The delivery platform was based on the C-2 Innovations developed bottom crawlers, specifically the so-called Sea Beast class (now referred to as the B350). The Sea Best is an autonomous, amphibious bottom crawler that has a 16-km underwater range and is capable of carrying 400kg payloads to a depth of 100m. The stability and low profile enable the system to operate in sea State 3 surf conditions.

The Harvester payload consisted of the navigation and communications package, the munition dispenser and the excavation and burial system. The program required the sub-systems to work in a closely integrated fashion. The interdependency required the good definition of the subsystem space claims, dry and wet weights, power and control requirements, sequencing, and potential failure modes. Designs were tested at a prototype level, and the system characterized.

Testing focused on

- Excavation
- Orientation
- Dispenser
- Back filling
- Navigation (precision of target placement) in a GPS allowed and GPS denied environment
- Power
- Size of the delivery platform.

Subsystem development occurred in parallel.

OBJECTIVES

There are several purposes for the creation of a standardized test bed adjacent to any remediation site.

Every site is unique due to water clarity, depth, soil composition, hydrodynamics, salinity, and turbidity among other parameters. Instrumentation and procedures must adapt to the local conditions for optimum performance.

Standardized testbeds containing known precisely located targets in the natural environment would be used to evaluate, calibrate, and validate detection and mitigation instrumentation, skills and processes that in turn would instill confidence that the optimum approach is being followed.

The concept of creating a test bed is simple, but the reality is many test sites do not lend themselves to low cost, precise or safe development.

The surf zone and near shore littoral and estuarine environment is highly dynamic, with high currents, complex patterns, poor visibility, crashing waves and difficult to control soil conditions. Placing target sets in such hazardous conditions where individual munitions can weigh nearly 100-lbs is highly cumbersome, uncertain, and often dangerous.

The cost of divers, boat support, dependence on weather and sea state conditions, adds to the overall project cost. The result is that between high cost and low confidence of 100% detection and recovery success, maritime UXO sites receive a lower priority in the funding scheme.

A means that can minimize or even eliminate divers and the need for support craft while constructing a test field would be greatly beneficial to the UXO remediation effort. A system that could place targets at actual sites would have huge benefits.

The challenge is that UXO remediation sites represent a wide range of bottom and hydrographic condition. The placement system needs to be versatile, and mobile to be cost effective.

The cost, reliability, and precision of placing munitions at various depths and orientations for the purposes of validating underwater UXO detection methodologies is highly cumbersome, involved, and often dangerous. Munitions can be heavy, the waters murky, combined with currents and wave actions culminating in dangerous situations. The result can be imprecise placement in terms of location, orientation, and depth.

The program technical objectives were to:

- Design and develop a means of carrying munition-targets to the site
- Establish placement accuracy in GPS or nav aided and unaided conditions
- Design and develop a means of burying the targets
- Design and develop a dispenser that could carry and place multiple rounds
- Determine the power requirements and power plant for the system
- Design and develop a delivery platform.
- Test in operational environments

TECHNOLOGY DESCRIPTION

The originally proposed Harvester concept uses the Sea Ox tracked underwater mobility platform to carry and position a system that can `plant` or bury targets to various depths and vertical orientations.

The initial Harvester System concept consisted of:

- Caisson or trench box with dual eccentric rotating vibrating head and ratcheting thrust mechanism for driving the caisson into the soil
- Leading edge fluidizer jets to aid penetration in difficult soils
- Reverse thrust controls to remove caisson from the seabed in preparation for next burial site.
- Vacuum system with length and depth motion that can selectively remove soil to create flat or inclined bottoms
- Spoils dump and plow to backfill the hole
- Exchangeable carousels for munition stowage and deployment, shown in Figure 1:
 - (3) 155mm HE rounds,
 - (4) 105 mm HE rounds
 - (5) 81 mm Mortar rounds
 - (6) 60 mm Mortar rounds

The self-contained system uses a trench box or caisson driven in the seafloor (1' wide x 3' long x'3 deep) to provide structural soil support. The interior of the box is excavated using a pump to whatever geometry is needed, and a target is rolled-in from an on-board carousel. The caisson is extracted, the hole is filled, and the vehicle moves to the next location (figure 2).

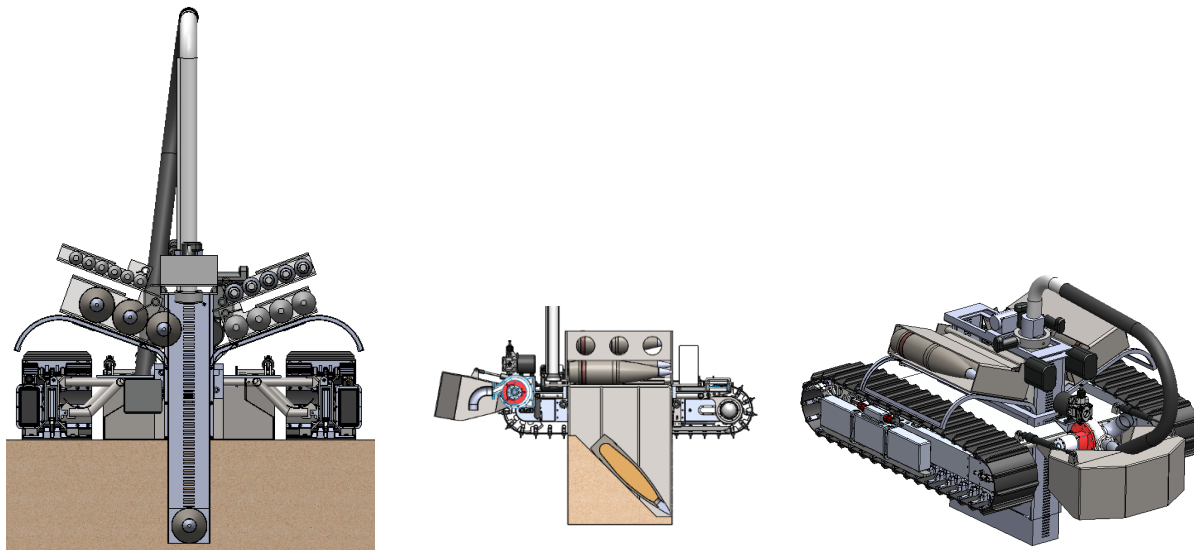


Figure 1. The initially Proposed “Harvester” Payload on “Sea Ox” Mobility Platform.

A) cross sectional amidship view of the dispenser, and caisson deployed B) fore-aft cross-sectional view. Backfill scraper is shown. Tilt of the munition can be achieved by controlled partial excavation C) oblique view

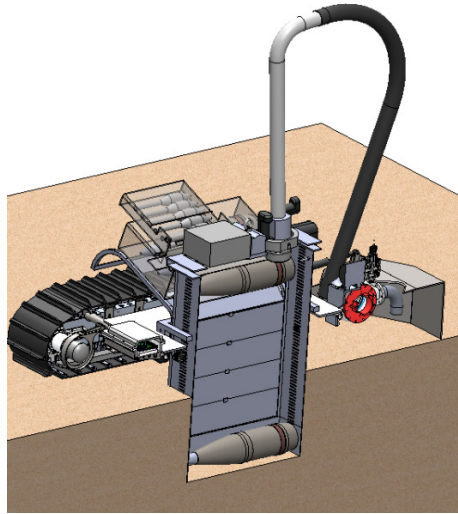


Figure 2. A) Cross Section of Operation B) Initial ¼ Scale Tests in Glacial Overburden.

The notional operational sequence for Harvester is:

- Harvester’s grid/bury plans can be preprogrammed within Harvester prior to deployment, inputs include distance, heading, plant location from initial position, plant type, plant depth, and orientation. The number of plant sites per lane is limited by the magazine loading capacity.
- Magazines are loaded onto Harvester, based on the row distribution plans.
- Harvester is launched from shore. Unaided navigation position estimate is good to 0.5% distance traveled. Down track error tends to be within 0.1 % distance traveled. Aided navigation (e.g., USBL or RTK GPS improves location farther
- If optionally equipped with a trailing RF buoy the Harvester autonomy can be interrupted and tele-operated

PERFORMANCE ASSESSMENT

The desire to optionally bury the targets was overly ambitious. The process was power intensive, highly soil dependent and imparted a high risk of catastrophic failure. Alternate approaches were conceived but not tested, but none offered a risk-free solution. In particular if the system failed mid-way during the excavation or insert process the vehicle would be anchored in place recruiting manual dismantling. Ultimately the decision was made to focus on surface laid targets.

Surface laid targets were straight forward, and the technology was successful.

The Sea beast was upgraded to carry 400kg in payload. A design improvement has been created that would permit 800 kg payloads (untested).

The Sea beast was designed, built and tested. Testing showed that it can operate in Sea State 3. Using UN38.8 certified Lithium Iron Phosphate batteries the Sea beast showed a range of 8km. It could operate on 45-deg slopes, and transit 0.6-m step heights unaided. Ground pressures were 3 kilopascals (0.45 psi), dry without payload or 1.5 kilopascals wet.

Navigation could be aided via RTK, GPS, or USBL or autonomous (dead reckoning). The Sea Beast can support a 5-m mast operating in 4-m water depths. Mounting a RTK on the mast allows centimeter positioning accuracy. Autonomous operation using an IMU and precision encoders resulted in positioning accuracies of 0.5-m at ranges of 0.5 km. A five-point 3-m cluster, that required multiple turns resulted in placement accuracies of 0.15m relative to each other.

The preprogrammed placement pattern was integrated into the Greensea System EOD Workspace software package. Dispensing operations could be performed on command or autonomously using the objective at waypoint function.

COST ASSESSMENT

A successful Harvester system would result in many DoD benefits including:

- Harvester-enabled on-site calibration fields:
 - Certification and periodic re-certification
 - Site-specific instrumentation and process validation
 - Increases confidence in site remediation effectiveness
- Removing the need for divers and surface craft would:
 - Significantly reduce operational cost
 - Open the weather window and improve scheduling ease
 - Greatly improves safety
 - Broaden operational envelop (e.g., surf zone)
- Represents a major technology step to recovery of live underwater UXO.

IMPLEMENTATION ISSUES

During the pandemic costs and delivery increased significantly. The cause of the cost growth include:

- Design: The need for more powerful motors and subsequently the redesign of the suspension, motor drivers, track guidance, track tensioners was needed to accommodate the higher motor output torque. Part of the additional load was self-imposed. Lighter loads or fewer targets per sortie would allow the lighter, lower torque motors to be used, however positional accuracy, mission times and reliability would suffer.
- Externally: Machine shop costs have increased significantly (essentially doubled)
- Externally: Software costs and support have more than doubled, almost tripling
- Efficiency and output slowdown from vendors and loss of work force, chip design delays of as much as 8 months that effects everything.

During the pandemic beaches were closed which inhibited testing progress. Many vendors and parts suppliers were either shut down or operating at reduced capacity so long lead items became longer in many cases greater than a full year.

1.0 INTRODUCTION

1.1 BACKGROUND

The purpose of the Harvester test-target planting system is to place unexploded ordnance (UXO) surrogates (or targets) at various burial depths and orientations in waters ranging from the beachline through the surf into water depths of up to 30 meters. A key feature was the ability to precisely deposit the targets in a re-acquirable and verifiable location. The concept referred to as the 'Harvester' was based on using proven technologies such as pumps, caissons, gravity feeds, and plows.

A design challenge was to fit all the components on a delivery platform, including power. The delivery platform was based on the C-2 Innovations developed bottom crawlers, specifically the so-called Sea Beast class (now referred to as the B350). The Sea Best is an autonomous, amphibious bottom crawler that has a 16-km underwater range and can carry 400kg payloads to a depth of 100m. The stability and low profile enable the system to operate in sea State 3 surf conditions.

The Harvester payload consisted of the navigation and communications package, the munition dispenser and the excavation and burial system. The program required the sub-systems to work in a closely integrated fashion. The interdependency required the good definition of the subsystem space claims, dry and wet weights, power and control requirements, sequencing, and potential failure modes. Designs were tested at a prototype level, and the system characterized.

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- Broaden operational envelop (e.g., surf zone)
- Represents a major technology step to recovery of live underwater UXO.

1.2 OBJECTIVE OF THE DEMONSTRATION

The objective of the demonstration was to show that a multiple of a variety of target shapes and sizes could be placed in the shore- through the surf-zone (0-20 ft) to very shallow 20-100-ft) depth with precision. Secondary objectives were to bury the target munitions at predetermined orientations and depths.

Penetration and excavation techniques were tested as a function of power, and speed. The limits of scaled down systems were tested. The precision of digging and the stability of the system and ease of backfilling were assessed, often qualitatively as the limits of penetration or digging were quickly realized.

1.3 REGULATORY DRIVERS AND EXPECTED DOD BENEFITS

Every remediation site is unique where the natural environment can affect instrumentation performance and remediation processes. A test and verification field will augment the international verification strip technique of calibrating and verifying detection and recovery procedures, personnel and equipment. The ability of the Harvester to plant targets in an active surf is unique, extending the calibration and verification process into environments that previously were impractical to implement.

2.0 TECHNICAL APPROACH

2.1 NOTIONAL CONCEPT

The originally proposed Harvester concept uses the Sea Ox tracked underwater mobility platform to carry and position a system that can 'plant' or bury targets to various depths and vertical orientations.

The initial "Harvester" System concept consists of:

- Caisson or trench box with dual eccentric rotating vibrating head and ratcheting thrust mechanism for driving the caisson into the soil
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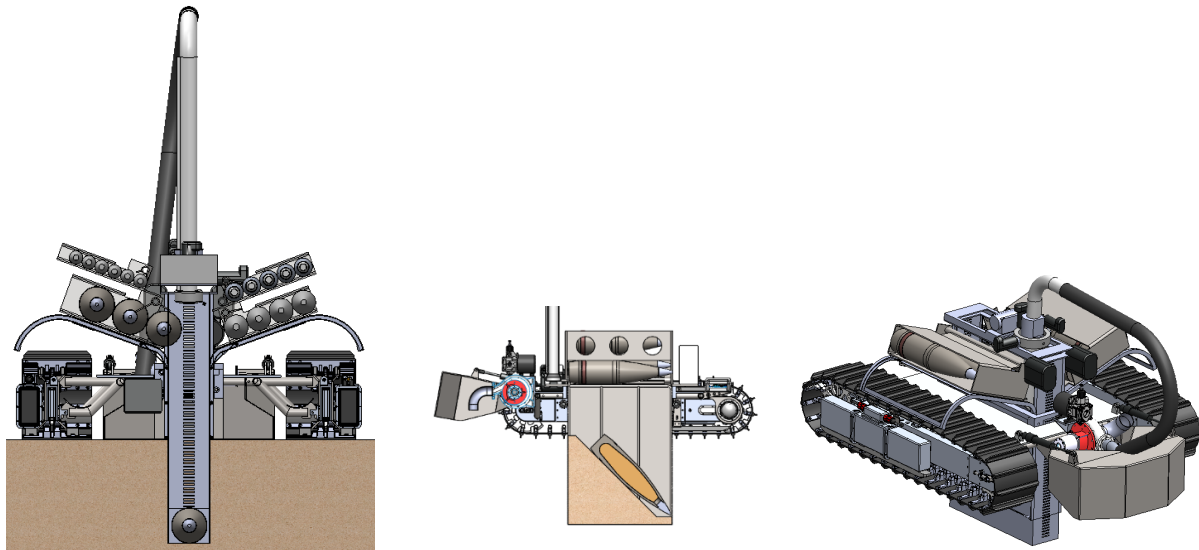


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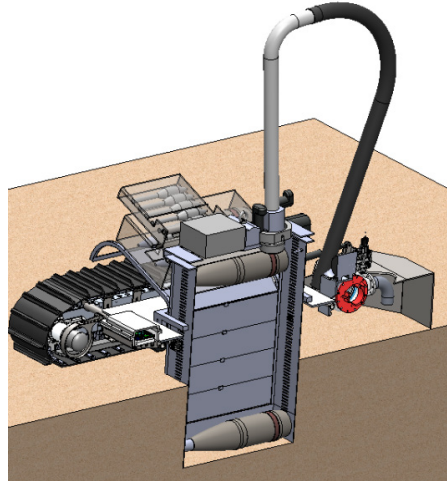


Figure 2. A) Cross Section of Operation B) Initial ¼ Scale Tests in Glacial Overburden.

The notional operational sequence for Harvester is:

- Harvester’s grid/bury plans can be preprogrammed within Harvester prior to deployment, inputs include distance, heading, plant location from initial position, plant type, plant depth, and orientation. The number of plant sites per lane is limited by the magazine loading capacity.
- Magazines are loaded onto Harvester, based on the row distribution plans.
- Harvester is launched from shore. Unaided navigation position estimate is good to 0.5% distance traveled. Down track error tends to be within 0.1 % distance traveled. Aided navigation (e.g., USBL or RTK GPS improves location farther
- If optionally equipped with a trailing RF buoy the Harvester autonomy can be interrupted and tele-operated

Figure 3 shows a 2-row pattern off First Encounter Beach, MA.



Figure 3. Harvester Planting Pattern.

Shown are 18 target sites off of First Encounter Beach

Process of planting Targets (along each row):

- The Trench Box lowers and contacts the sea floor via ratcheting system and electric motor drive.
- The Trench Box is driven into the ground with the aid of a vibrating head driven from the top (like vibro-corers) and fluidized jets located at the leading edge of the Trench Box. Thrust is supplied by reaction weight of the drive platform.
- As the Trench Box is driven into the ground the slurry pump removes the soil from the center of the box and discharges it between the aft end of the Sea Ox and Rear Plow.
- The vacuum nozzle can be controlled in pitch, roll and depth wand, allowing for sloped surfaces to be produced for angled munition deployment.
- Once the desired depth is achieved, the vacuum hose is extracted allowing for munition deployment.
- The indexer releases a munition from either the left or right Magazine allowing it to roll and fall into the hole. Indexer and Magazine shown are configured to allow for 60mm, 81mm, 105mm, and 155mm rounds. It can carry 6 x 155mm artillery rounds.
- After the munition has been deployed, the Trench Box is retracted, and the Sea Ox moves forward pulling the Rear Plow and filling the hole.

The greatest system complexity is the task of creating a hole, stabilizing it, and dropping the munition in the hole. It consumed the most parts, sensor feedback and control needs, it consumed more power than actual driving. A stuck caisson would represent a catastrophic failure mode.

Ease of digging was very soil type dependent as was driving the caisson. Rocks, pebbles, or shells could essentially stall the system due to the effectively increased penetration profile.

Since sail area or drag surface represents a considerable stability threat when operating in or transiting an active surf zone or river, every effort was made to minimize the exposed hydrodynamic profile. Designing and implementing a caisson that maintained a low profile while on deck yet was strong enough to stabilize the excavation sides was a real challenge. Removing the burial component greatly simplifies the overall design and reliability.

2.2 TECHNICAL RISK WITH NOTIONAL CONCEPT

All the major `actions` or subsystems are essentially proven. Vibratory insertion of cores, trench boxes and caissons are common techniques in the construction industry. Vacuuming soil in the form of dredging and cleaning sumps is common as a soft excavation technique. The Sea Ox that includes the vehicle, drive train and payload capacity as well as the navigation and controls was a work in process at the beginning of the program.

The challenges and risk were to properly scale the components to the small platform while still maintaining the ability to do useful work in a wide range of real-world environments.

The approach was iterative. Each of the major subsystems were characterized, sized, the control and power required determined, and integrated into the whole.

The performance scalability of the initial design was overly optimistic. Under ideal conditions each component could work well, but once the soil conditions exceeded the optimum conditions, brute force, power, and size were needed.

The program is structured in a stepwise manner increasing in complexity and exposing itself to more challenging environments as confidence increases. The technical issues were categorized as:

- Navigation and precision placement
- Control
- Excavation, hole stability (Caisson), backfill
- Dispenser Design
- Power requirements
- Vehicle design

The program addressed all subsystem in parallel.

2.3 SUBSYSTEM DESIGN RESULTS

2.3.1 Navigation

Precise placement is a key requirement. The operating environment will dictate the navigation means.

In waters less than 5-m deep a mast with RTK, optical prism or GPS can be mounted on the vehicle and standard survey techniques can be utilized providing sub meter, precision. Figure 4 shows a 5m mast on the Sea Beast. The same system has operated in 6-ft plunging surf.



Figure 4. 5-m Mast Mounted on Sea Beast with RTK Receiver.

In deeper waters and where the infrastructure is available, external aiding by acoustic baseline systems can also provide centimeter level location accuracies.

On board instrumentation includes a 3-axis KVH tactical grade Fiber Optic Gyro (FOG), dual submillimeter shaft encoders, and an attitude heading reference system (AHRS) (or optional Doppler Velocity Log (DVL)). The navigation solutions are provided by the Greensea Opensea EOD Workspace architecture. EOD Workspace offers integrated inertial navigation, vehicle control, automated tasks (called objective at way point such as stopping to dispense munitions), payload integration and target-relative positioning. Multimode vehicle control allows the operator to pass as much or as little responsibility onto the vehicle as the operation requires. If a mast or RF buoy is available, the system can operate with manual control at ranges of up to a mile. Figure 5 is a screen shot of the graphical user interface that the operator sees.



Figure 5. Screen Shot of Greensea Systems EOD Workspace Graphical User Interface.

SafeC2™ provides over-the-horizon control of any ocean robotic platform built on OPENSEA. Operators can be located anywhere onshore while controlling a vehicle off shore. Using SafeC2, the operator no longer needs to be on the deployment vessel, reducing risk while freeing up valuable crew space.

The long-range control of the Sea beast is made practical by SafeC2's handling of the data stream between operator and vehicle. SafeC2 manages the data stream by transmitting the least amount of data necessary and synchronizing data so that even with slight delays, the sonar and video will remain in sync when the operator sees them.

The Harvester can be preprogrammed to drive set patterns autonomously. The OpenSea program fuses vehicle control, navigation, payload sensors, diagnostics, and data management into a single laptop screen. The centralized data framework allows visualization, logging, archival, and playback of all vehicle and payload data, including sonar and video.

Coverage test (Crow Island): A test was performed at Crow Island in Stow MA to demonstrate the coverage patterns using the Sea Ox Crawler. Ballast weights were added to match the added dry weight payload.

An autonomous mission was pre-programmed using a Modified Gapped pattern of waypoints. A Gap pattern is essentially a squared-off circle that increments diagonally with each pass. The advantage is that the turn radius could be large (10m) minimizing the motor torque and power draw while maintaining tight tracking. In addition, there are predictable points of cross over redundancy that provides good cross check of navigational and detection precision. The disadvantage is that the pattern runs over the same terrain multiple times resulting in production inefficiencies. The pattern was based on a 2-m wide sled and 100% coverage (no overlap).

Result of the ground-based demonstration at Crow Island was as follows:

- Coverage Area: 3011 meters squared (0.74 Acres)
- 100% coverage was achieved
- Time to perform mission: 1 hour 20 minutes
- Achieved Coverage Rate: 0.56 Acres/Hour

The pattern programming process is not fully automated (yet) therefore pre-planning and programming was time intensive (~2 hours to set up for simple geometries) but the results proved favorable for the crawler-sled combination.

GPS denied navigation test, (Duck NC): A lawn mower search pattern was performed at Duck NC at the USACE Field Research Facility. The lines were 350-m long and separated by 2m. GPS was disabled and the system tracked by the traces in the sand. After 1.6km the tracks remained in the same pattern as the previous runs (240mm offset) (figure 6). The drift error increased after 1.8km with an offset of 3.9m after 2.4km traveled (0.2% error over the distance traveled). The track was observable in the sand, and the beginning of the error could be traced to a specific turn location at the 1.7km mark. Most of the error could be attributed to down track error which is associated with a calibration error in the assumed wheel diameter.



Figure 6. Sea Ox Operating in GPS Denied Conditions, on the Same Track after 1.6km and 12 Turns Transit.

Tight Cluster test (First Encounter Beach): Patterns that are straight lines are relatively simple to implement, and testing has indicated that the placement precision would be high. But often munitions or false targets are in clusters and the separation spacing is crucial to assessing the ability of sensors to distinguish between clusters and a single large signature.

A series of tests were developed to test the ability of the Sea Beast to stop at a waypoint and then place several targets in a controlled pattern near each other. A 5-point body centered pattern was used (placement in 5 corners of a box and one in the center).

Testing was performed at First Encounter Beach) Eastham MA). The vehicle (in this case the Sea Ox) was programmed with a 650-m in-and-out pattern and at either end the 5-point excursion was commanded. The box was 3m on a side and a drop rod marked the precise location as opposed to the munition.

Figure 7 shows the graphical interface depiction of the pathway and the drop points. The system worked on INS only (GPS denied). The box corners were within 15 cm of the mark.



Figure 7. GPS Denied, 5-point Cluster.
3-m on a side

2.3.2 Controls

The vehicle level controls, and navigation are native to the base vehicle, the C2i Sea Ox. The main vehicle controller communicates with the various peripherals via a combination of CAN, RS232, RS485 and Ethernet buses to provide appropriate bandwidth for each function. The centrally mounted vehicle controller communicates with each traction drive pod via a CAN bus using the CANOpen protocol. The pods are self-sufficient drive units, each drive pod consists of the structural framework, sprockets, track, motor, gearbox, motor controller and battery pack. The central controller sends velocity and position commands to the pods via the CAN bus and receives back sensor readings such as encoder position, battery health and other status and warning signals.

An Ethernet switch supports multiple video cameras as well as an optional tether for use during testing or if surface conditions and visibility allow remote control via a buoy and radio link. User interaction and downloads are performed using a combination of RS232 and discrete IO ports.

The pan was to use a vacuum pump and wand are used to remove material from the caisson structure while it is being inserted. The wand is controlled in three degrees of freedom relative to the vehicle, pitch, roll and Z height. This combination allows the wand to cover the entire area of the caisson box at depths down to 1 meter below the ground surface. The sequencing and wand pattern can be controlled to produce either a level bottom or a sloped bottom to provide a variety of UXO orientations.

The process of burying a target is involved though not overly complicated. The depths are shallow enough and the tolerances appear to be wide enough that the system should still function even when impacted with disturbing forces (such as wave impact). However, all the potential failure modes will only become evident after considerable field experience in different operating conditions. The challenge will be to accommodate the unforeseen and unknown failure modes autonomously.

Both the caisson penetration and pump/jet parameters will be instrumented for feedback and autonomous control loop design. On/off, displacement over time (rate), power consumption and resistance will be collected with independent sensors and assigned limits to prevent failure modes (e.g., refusal, stuck position, jamming, etc.). A library of behaviors would be created to reflect excavation profiles and tied to the dispenser system. The payload parameter swill resides in a Payload Interface Module (PIM) that is connected to but separate from the main control box.

Figure 8 shows a schematic of the control architecture.

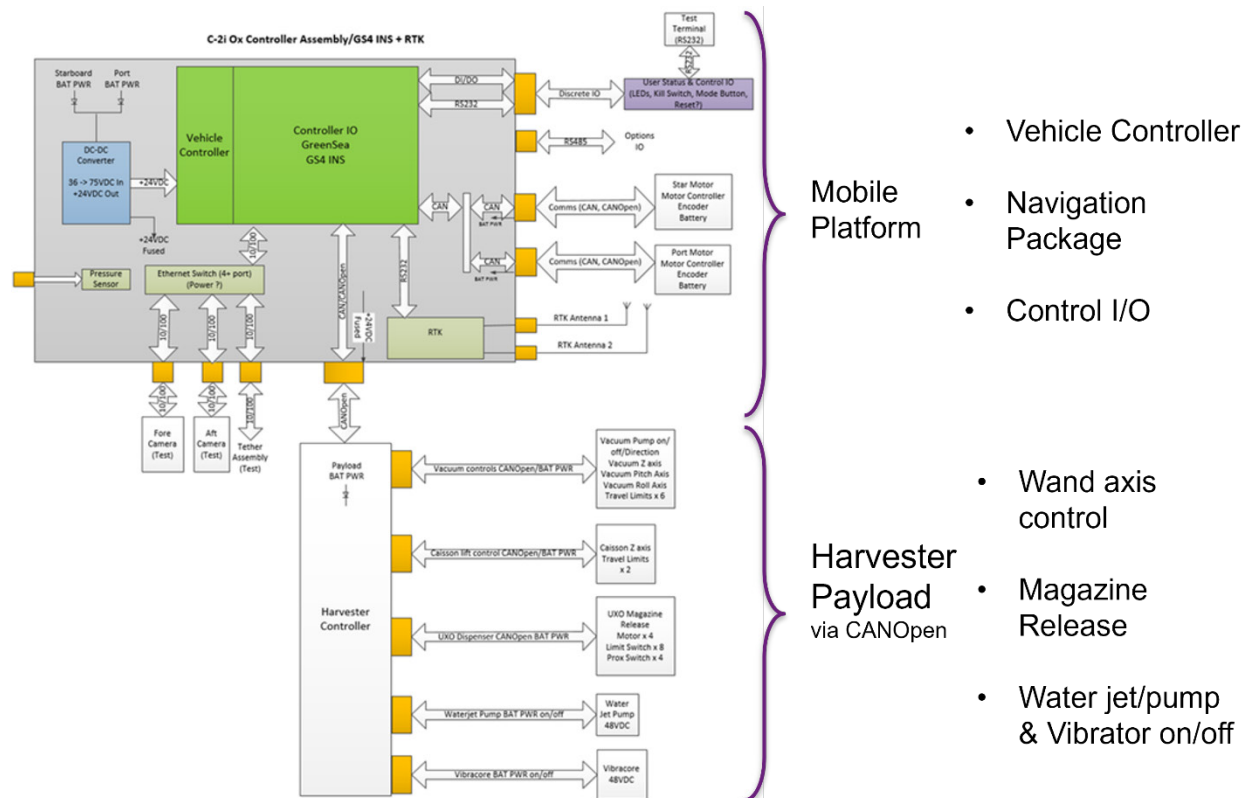


Figure 8. Sea Ox Controls Diagram Shown with Interface with Harvester Payload.

Overall software control is accomplished via the commercially available Opensea Workspace published by GreenSea Systems, Inc. Opensea Workspace provides the graphical interface, motor controls, navigational solutions and can command actions at the designated waypoints (called objective at waypoint).

2.3.3 Caisson, Excavation and Backfill

The most challenging requirement to fulfill was the need to bury munitions to specific depths and tilt angles. Burial consists of several steps including:

- Excavation
- Hole stabilization during excavation
- Shaping the floor of the excavation
- Dispensing the munition into the excavation
- Extraction of the excavator and the hole stabilization caisson
- Backfill

The burial requirements presented several significant challenges:

In the surf and where significant fine-grained sediment was present, the bubble curtain and turbidity would eliminate any visual feedback so that the system would need to be fully automatic.

The wide range in possible soil compositions and densities precluded tailored optimization and generalized solutions were examined.

In an unconstrained environment the steps are solvable using conventional techniques, but with all components mounted on a single vehicle, a conflict of space exists. In particular, the maximum hole depth is 1-meter. If a conventional rigid caisson was used to stabilize the hole, the caisson would stand up as a 1-meter-high sail during transit or when depositing surface laid targets.

The problem is more problematic when the target burial is shallower. The munition needs to be fed in from the top of the caisson. The elevated structure will make the system unbalanced but also would represent a very large sail area.

The system must be robust. A stuck caisson would anchor the vehicle in place and extraction could be very complex.

Caisson design

The problem was split into the subsystems,

Using a caisson for keeping an excavation open in unstable soils is a standard technique in civil works programs, though typically at a much larger scale. Caissons are driven in by impact or in cohesionless soils, by a combination of weight and vibration to overcome the bearing load resistance, and skin friction. The vibrocore can be aided by fluidization of the virgin soil using water jets located along the bottom edge of the caisson.

Field tests were performed to optimize the frequency and amplitude. Power draws and estimated time to complete were determined to estimate mission life.

A series of vibratory tests were performed at the different test sites. Testing included:

1. Power in (result of Electrical draw times duration of test)
2. Amplitude (force per cycle)
3. Frequency (measured in cycles per minute)
4. Time (measured in minutes)
5. Leading Edge width, hardness
6. Stiffness of caisson wall structure (material and design features)
7. Surface area of caisson wall structure
8. Self-weight
9. Addition of driving force (ballast, wet weight of vehicle)
10. Use of fluidization and power/advancement benefit.

Figure 9 and 10 shows some of the caisson designs that were tested.



Figure 9. Caisson Designs Tested Include Full Rigid Box, $\frac{1}{4}$ and $\frac{1}{2}$ Scale, Screen and Frame.



Figure 10. Vibrator Mounted onto the Caisson Boxes.

Over 20 tests were performed with a full-scale caisson (a sheet metal box) and vibrator bolted to a weldment located in the center of the top end. The concept provided usable feasibility data, and initial timing. Using an SCR motor, the vibrating rotational frequency can be varied, and the weights of the cams increased or decreased.

Vibrator performance was proven using the electrically driven Vibco SCR-200 yet positioning the vibrator on the payload assembly will require more consideration in systems design. The favored location is on the centerline of the caisson, positioned over the center of gravity eliminating unnecessary power loss due to uneven loading/bending.

Discussions with Vibco application engineers about a dual vibrator approach evenly spaced and away from the caisson opening did not identify any design ‘red flags’ however there will be additional work to tune it correctly. While adding complexity, coordinating the dual system was reported to be common practice, lowering technical risk in what is assumed to be a necessary step to free the caisson opening for insertion of the munition plant. Figure 11 shows power advantages of the SCR 1000.

Model	SCR-300	SCR-400	SCR-500	SCR-1000
Vibration per Minute (VPM)	950-4000 adjustable	950-4000 adjustable	950-4000 adjustable	950-4000 adjustable
Power (W)	186.5	186.5	248.4	373.0
Amplitude Force (lbs)	300	400	500	1000
Weight (lbs)	16	18	45	65

Figure 11. Model Sizes for Vibco SCR Vibrators.

An interesting point during payload investigations was hydraulic driven pumps and motors offer attractive power benefits over electric motor vibration systems by a factor of two. The details of these tradeoffs should be further investigated to fully understand the potential power density benefits.

The pull-out loads were determined with a load cell attached to an independent manual jack. Figure 12 shows the test setup.

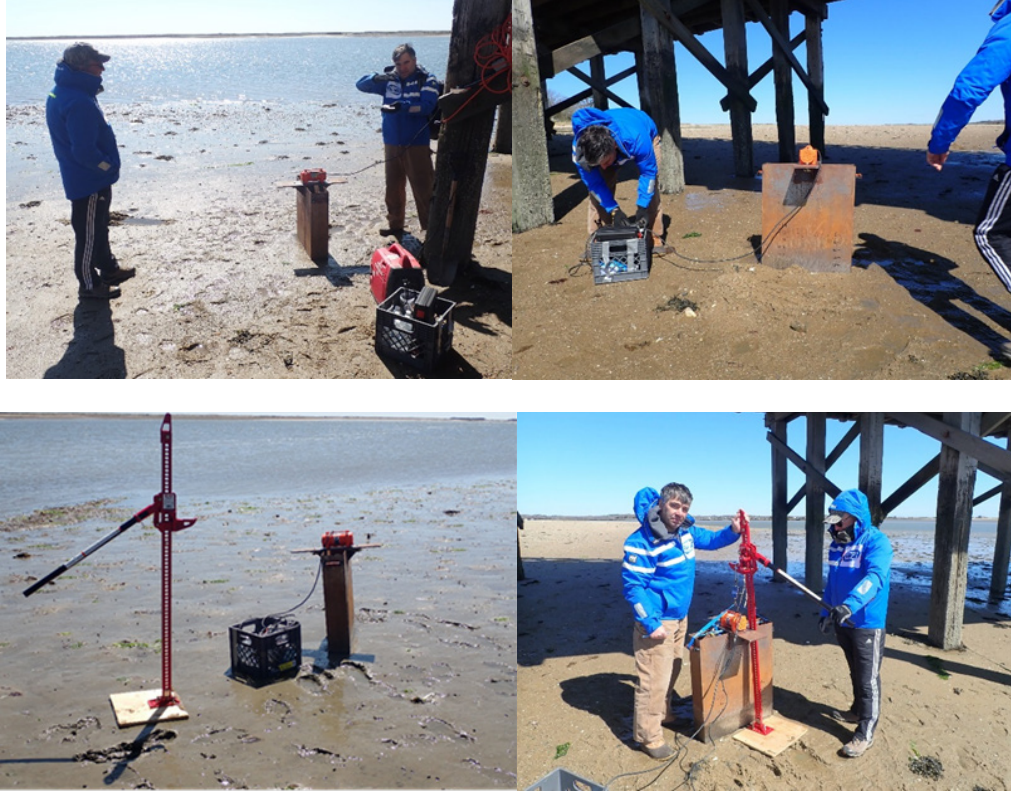


Figure 12. Caisson Penetration Tests.

Power draw rate of penetration and pull-out forces were measured.

Figures 13a and 13b show typical penetration rates. The dead weight of the caisson would often penetrate the first few inches without any vibration. Refusal was reached at 12 inches using the SCR 200 vibracore. Deeper depths are achievable with the larger vibrating head and with simultaneous extraction of the interior.

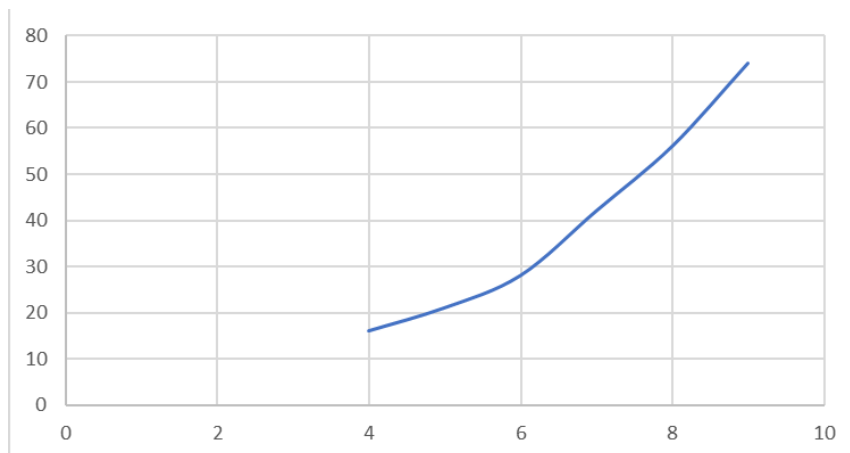


Figure 13a. Time in Seconds (Y axis) vs Depth of Penetration (x axis) Full Scale, Sand.

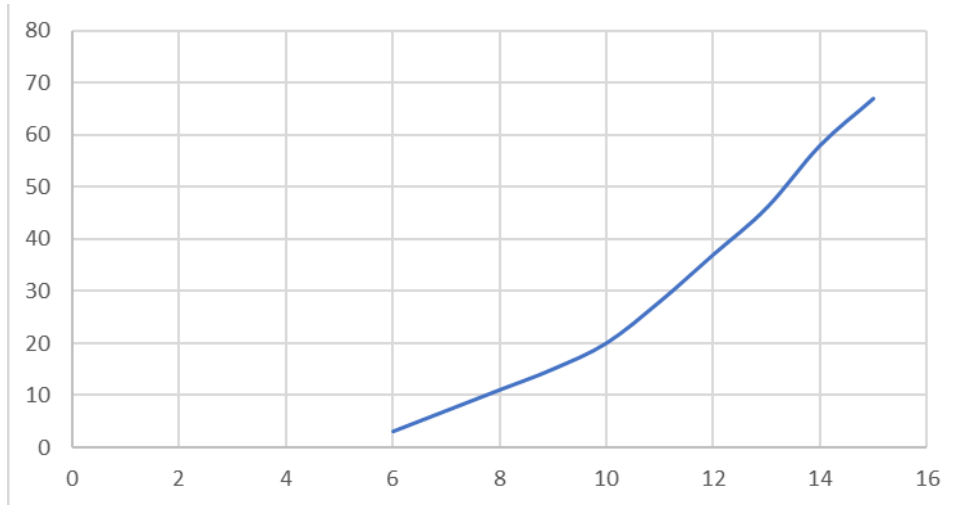


Figure 13b. Time in Seconds (Y axis) vs Depth of Penetration (x axis) Full Scale, Silty Sand.

Figure 14 shows the test results for driving the caisson in course and fine-grained soils by Duxbury Beach, MA. Penetration was limited to 6 and 10-in respectively. A dense clay that contained a lot of pebbles and oyster shells was encountered at 10-in and became impenetrable. Adding thrust or sitting increasing the endurance of the system did not aid in penetration.

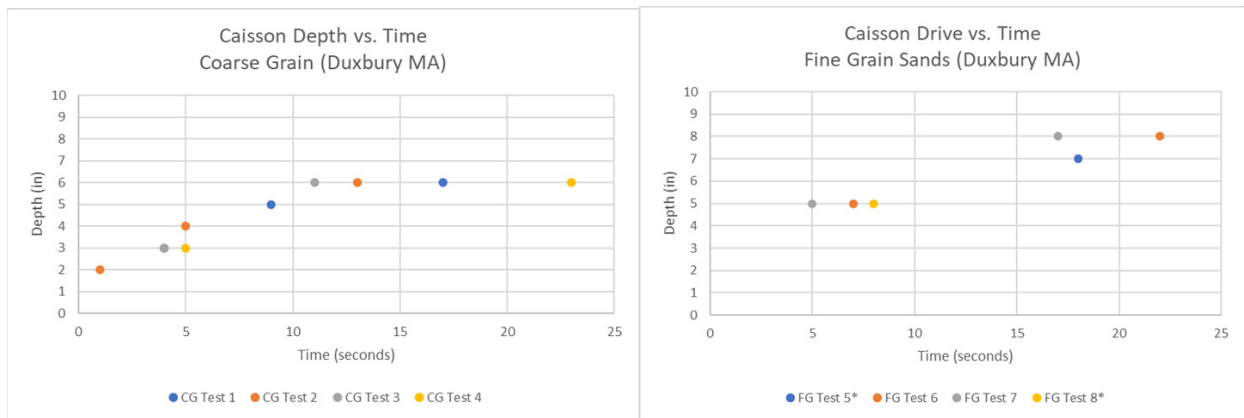


Figure 14. Caisson Penetration Limits in Duxbury Well Graded Course Sands and Poorly Graded Fine Sands.

Tests in well graded sand were more promising (figure 15). 24-in penetration with a full scale caisson could be achieved in less than 45-seconds. Hand pressure was needed to balance the caisson, indicating a guide frame would be necessary. The optimal penetration rates were achieved with 3820 vibrations per minumte (VPM), and represented approximately 2.5 W-hrs or .03% of the standard battery pack capacity.



Figure 15. Caisson Testing in Well Graded Sands, AT4 (84-mm) Round Inserted for Scale.

Pull forces were less than 50-lbs (caisson weight with drive was 35-lbs) and reduced to self weight (35-lbs) after the skin friction was overcome.

Identified issues include:

- Large sail area in the stowed position
- A need to drive the caisson to full depth even when a shallow burial is needed
- The center location of the vibrator impedes the pumping action

A heavier SCR-1000 vibratory would provide 3.3 times the amplitude force yet only consumes twice the power, thereby providing a more efficient solution that would also address a broader range of soil types.

Informal testing with water jetting with jets located at the leading edge of the caisson would further reduce loads, and simultaneous excavation of the interior would halve the skin friction. Neither excavation or water jets would solve the shell or pebble issue.

Objects (shells/rocks/ debris) would interfere with bury progress where one of three possibilities were available.

1. Stop work and accept the depth achieved.
2. Continue work/effort with little or no gain
3. Implement another tool (i.e., water jet) with the goal of disrupting the object to continue the bury depth

Designs were generated as alternatives that included a:

- Frame and louvered design
- Frame, screen, and scrim
- Frame and batten design

A folding caisson concept was developed to minimize the vertical profile and sail area (figure 16). The plates were segmented and rode in a rail of supporting corner posts. Vibration and drive were initiated through the support frame, whereas the wall of segments went along for the ride.

After excavation of the interior soils the target munitions could be rolled in from the sides in between the corner supports.

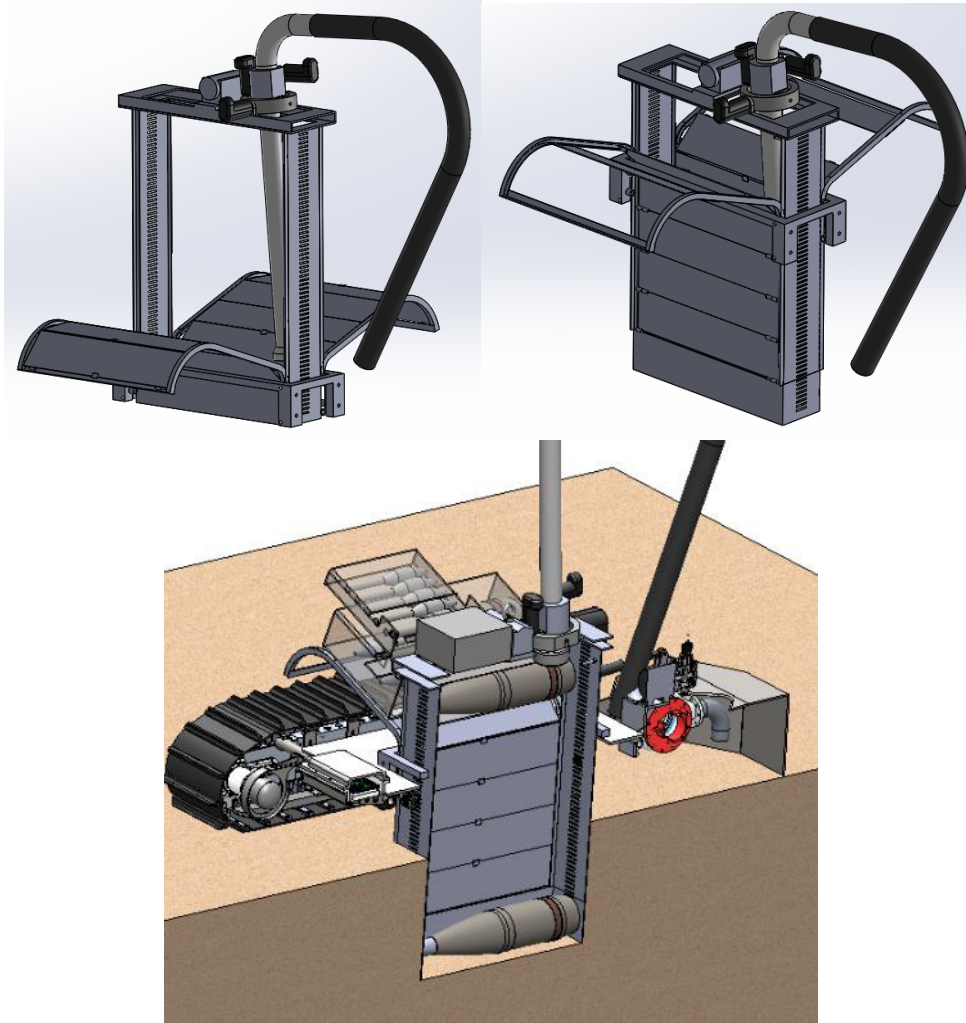


Figure 16. Caisson Advancement, Left Showing Stowed Right Showing Deployed, Bottom Deployed.

Driving the frame would not be as efficient as a single piece box and the probability of sand jamming the segment guides is high. The solution was viewed as an `engineering `solution but not necessarily a viable one.

Another alternative was to use a screen that would roll down eliminating the concern of sand jamming the segments. Since the excavation was only temporary it was hoped that the mesh would be enough to hold back the surrounding soil until the munition was emplaced.

Initial tests showed that the screen did work but in fluid soils or in strong currents the side walls tended to bulge inwards. A solution was to add intermediate supports but that negated the advantages of the entire system. The bulging not only prevented emplacement of the larger targets, but it made extraction far more difficult.

While a solution can likely be designed, the complexity and sensitivity to soil conditions and propensity to jamming results in excavation stability representing a high-risk task.

Excavation

The excavation scheme was based on a pump or vacuum system. By placing the pump on deck and extending a vacuum hose or pipe down the caisson, different cross sectional excavation profiles could be accommodated that would enable depositing the target munitions at any tilt angle. The hose is supported at the top of the caisson frame and can pivot, the length of the top caisson frame. The drives resulted in a single degree of freedom pivot. The fore and aft direction was controlled by a liner actuator, and the depth is driven by a motor and pinion gear driving a rack on the side of the vacuum tube or wand. Figure 17 illustrates the process.

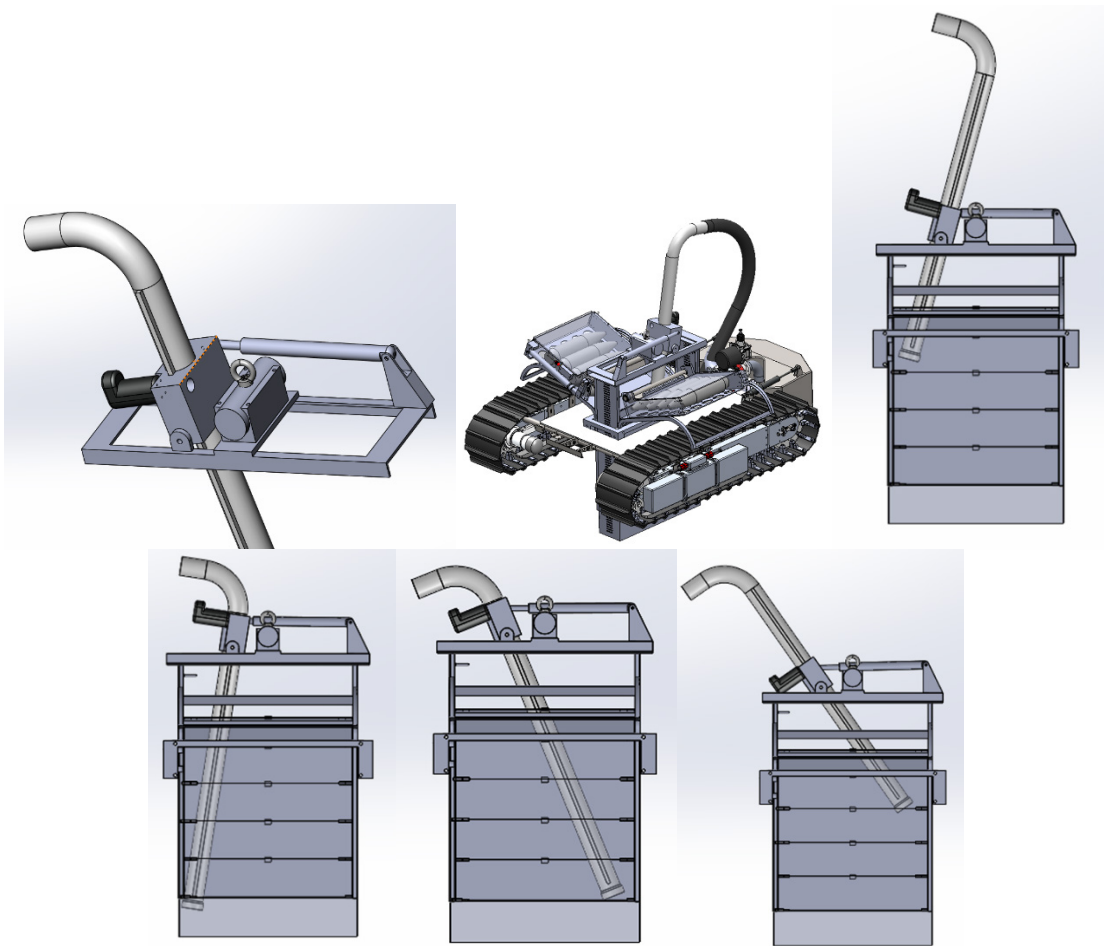


Figure 17. Excavation with a Pivoting, Extending Vacuum Wand.

The pump design was more challenging than initially anticipated. The nozzle needed a slight standoff to be able water to enter the suction hose and mix with the suspended soils. The amount of stand off was relatively sensitive to the sediment load and could quickly clog the system or inefficiently just pump water. Small stand off skirts were constructed that doubled as filters.

In nearly all the sediment types that were tested, pebbles, shells or organics clogged the nozzle within seconds of operation.

A surprising issue was the deposition of the soil sediment. It was assumed the discharge would deposit the soil in a pile that could then be plowed in for backfilling the target hole. The discharge flow was sufficient that it tended to create its own hole, and the sediment dispersed to the point where no pile was created. Dispersion tanks, or a vortex separator would solve the problem but the system was adding more components that made it heavier and more complex.

Water jetting was tested for excavation. In the consolidated silts of Duxbury beach area, suction was ineffective. The flows were reversed and the soil jetted out (figure 18). The approach created a lot of turbidity but was simpler and clog free compared to the vacuum approach.



Figure 18. Jetting Results.

Hoel shape was much less controlled but not prone to clogging.

An estimate was made of the power required to operate the pump. Assuming a Piranha, model PS-75 slurry pump, $\frac{3}{4}$ horse power, 115V single phase, 7.5a system that pumped 30 gallons per minute at the most efficient point in the operating curve. The Harvester hole is 7-in wide, 36-in wide and 36-in deep, or 5.25 cubic feet (39.4 gallons). At 30 gallons per minute and a 50% soil extraction efficiency, 2.6 minutes to excavate resulting in 37.4 W-hrs of power. Assuming a factor of safety of 2, the pump would consume 70 w-hrs per hole (for reference the Ox has 6.5 KW-hrs battery capacity).

Backfilling

Initially it was assumed that there would be a need to backfill the target-munition excavations. Plows and drag bars were tested with good success, however it was found that after a single tidal cycle (often in the matter of minutes) the natural processes would fill the holes, with the rate of natural backfilling a function of the local water velocity.

Alternate methods

As the complexity of a caisson/pump scheme became evident, alternate methods were explored. Direct thrust and vibration of a munition was tested but the frontal area of the munitions was too large to effectively penetrate even a few inches.

Water jetting was more effective but requires some development.

Creating a trench using a plow appears to be effective for shallow burial of several inches but not for deeper holes.

2.3.4 Dispenser

The dispenser is a relatively simple component of the entire system. It was designed to accommodate as many rounds as possible, accommodate different sizes ranging from 60mm to 120mm, and ideally accommodate odd, shaped targets that would represent false targets. The dispenser had to not upset the balance and minimally add additional drag. The system would operate autonomously and dispense on command at pre planned waypoints.

Roll-in-place

The simplest design was a drop in place, that used gravity to roll the munition down the storage bin, like a soda can dispenser system. The disadvantage is it needs a high angle to take advantage of gravity thereby creating a large sail area, and it could only accommodate a limited size and shape of false targets.

Figure 19 shows a dispenser for 105mm rounds. The storage unit could be stored flat to minimize drag until the objective was reached, when the unit would be raised (shown on Sea Beast).

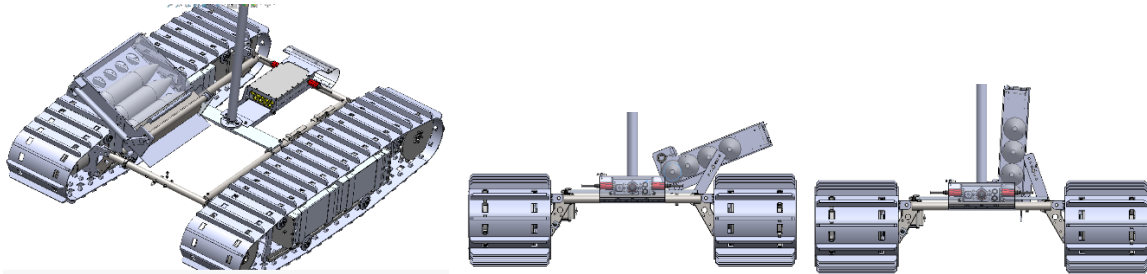


Figure 19. Roll-in-place Dispenser with Elevating Magazine.

The release sequence is a simple latch mechanism controlled with a linear actuator. Figure 20 shows the sequence, from top to bottom:

- Start position
- Release first shell, holds rest of shells in place
- Rotate back to catch next shells
- Shells drop about 15mm when released

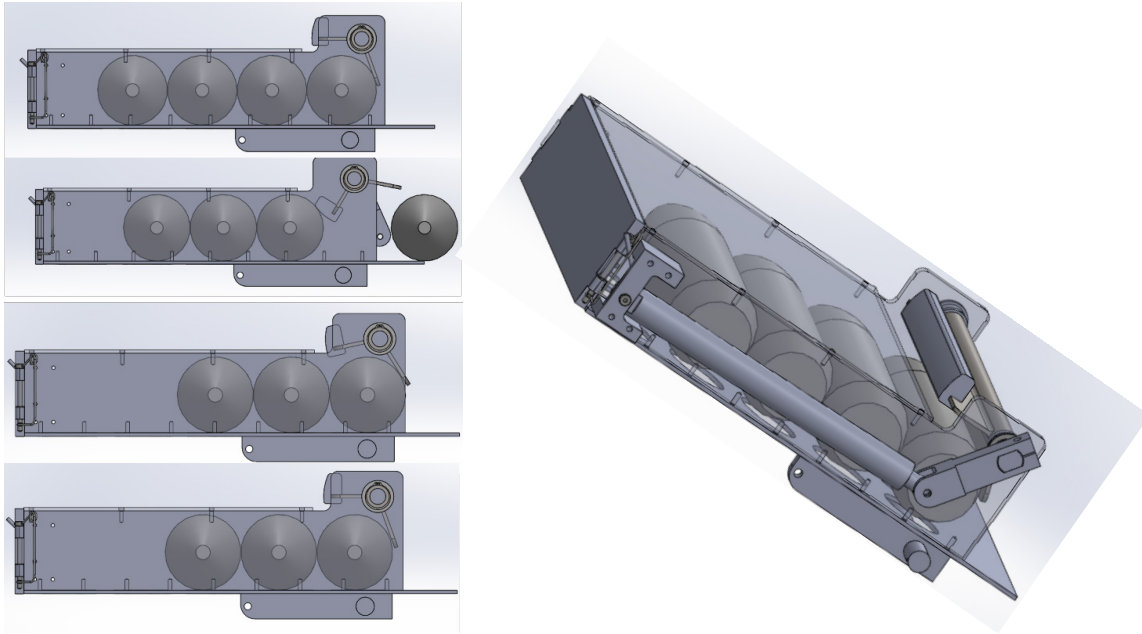


Figure 20. Roll-in-place Dispensing Latching Mechanism.

Control is simple where the stainless flipper and rod were momentary toggle switches for open and closed condition and limit switches at both ends of travel to prevent stalling. Figure 21 shows the dispenser mounted on the Sea Beast. Two to four could be mounted fore and aft and on the starboard and port sides. The systems could also be stacked.



Figure 21. Roll-in-place Dispenser Mounted on Sea Beast.

Conveyor

To reduce sail area and accommodate odd shaped non-rolling targets a conveyor system could be built on deck. The conveyor (not built) could stretch or contract in width and length and number and width of slots (105 shell shown) (figure 22). By lowering the control box, 12 to 12 105mm shells could be accommodated. By mounting fenders over the track 3 conveyors could be carried for a load of 36 x 105mm rounds. The conveyor can be built with 3-in rollers, and commercial belting.

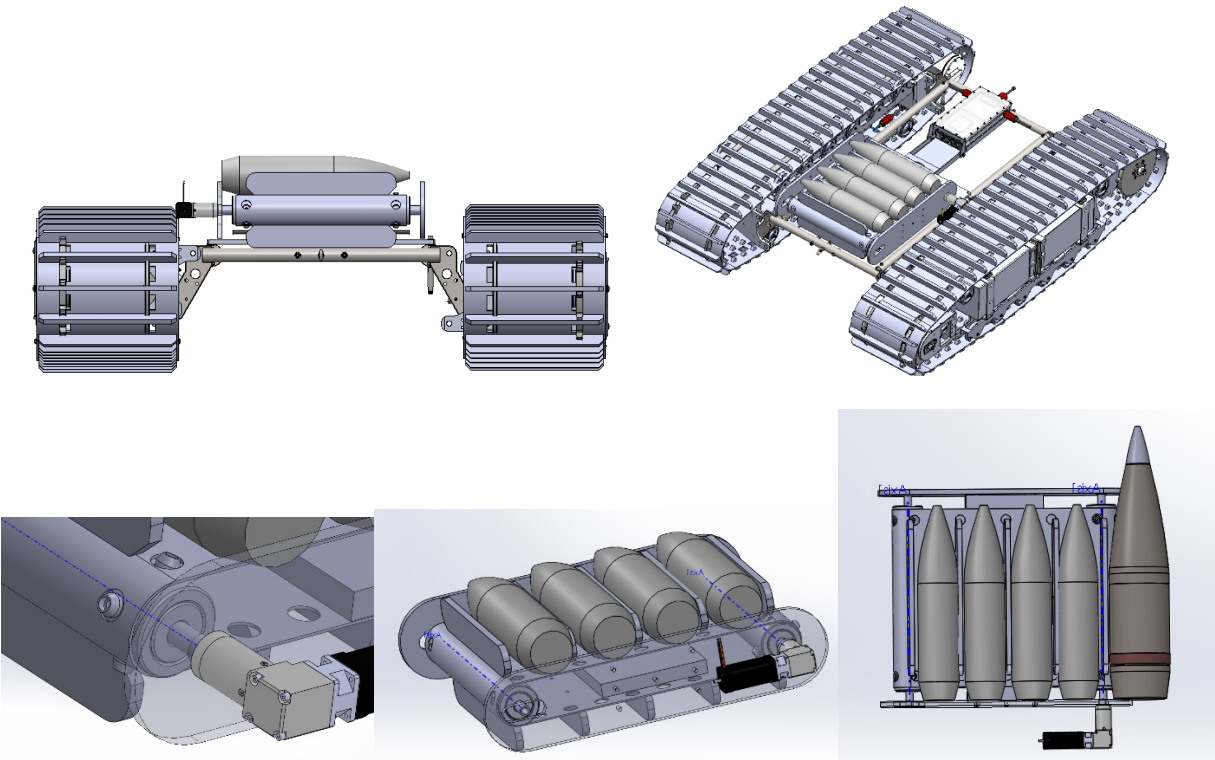


Figure 22. Conveyor Design.

By mounting fenders over the track, two additional conveyors could be added (figure 23).

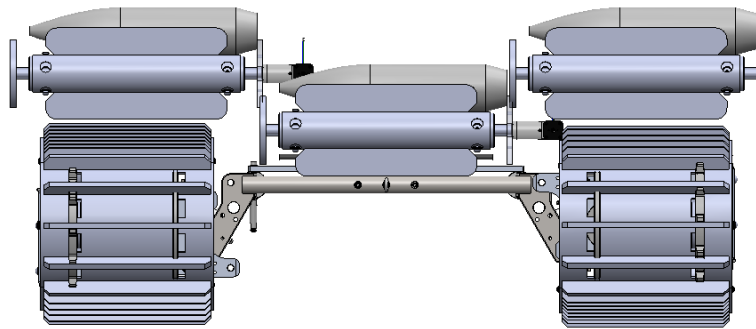


Figure 23. 3-conveyor System with 105-mm Rounds.

2.3.5 Power

The Harvester payload will consist of a caisson, a pump/reservoir for soil removal, gantry for support, a latching or dispenser system for the round-insertion, payload retraction mechanism, controls logic, and potentially dedicated power source. The volume of a single burial site will have a direct proportional impact on power draw, overall size/weight, and control.

In addition, the operational environment for an amphibious crawler payload will contend with known scalable effects to include high friction due to dry sands/soils, high drag due to surf/tide currents, and broad thermal differences ranging between 120 degrees F on hot sands to 40 degrees F underwater in the same mission. All these factors that will draw on the amphibious crawler's power capacity.

The amphibious crawler vehicle offers mobility, navigation, communications, and its own power plant that may (not) be shared with the Harvester payload.

Battery power is packaged on the crawlers in easy to handle multiple 1 KWh battery cells readily connected in parallel. The power cells are located both on the vehicle for mission range and can be positioned to dedicate the battery cells to the payload demands. The battery packs are designed to be field swappable on land and during a mission to keep the job moving along. With rechargeable reserve batteries on site the mission can continue indefinitely.

Based on the experiments, figure 24 is a summary of the predicted power budget. It should be cautioned that under stressed conditions such as stall the current draws can spike and rapidly consume large amounts of energy.

	Soil Types	Tools	Metric	Time (hrs)	Power Required (Watts)	Total Power Used (WHrs)	# of Bury Sites	%Used (8,208 Watt-Hrs Total)
Hotel Load (measured)				2	50	100		1.2%
Mobility load, Straight (measured)		Larger motor sets	2.5 KM	1.4	825	1145.8		14.0%
Mobility load, turns (measured)		Larger motor sets	20 turns	0.2	1720	286.7		3.49%
Dwell load, motor draw when payload working			18 bury sites	2.0	8	16.0		0.19%
Advance Caisson (shallow measured, 10")	Sands/ fine grain & course grain	Single vibrator	6.2 Gallons	0.33	187	62.3		0.76%
Excavate (Estimated)	Sands/ fine grain & course grain		2.5 HP 4 minutes/site	1.2		120	18	26.3%
Retrieve Caisson	Sands/ fine grain & course grain		18 bury sites			3.5	18	0.77%
Refill Bury Target						0	0	0.00%
TOTAL								46.71%

Figure 24. Summary of Power Requirements for Notional Mission Based on Predicted and Measured Power Levels.

A review of power densities of batteries confirms that of the currently available battery chemistries, lithium-ion have the best volumetric and density per unit energy density (figure 25). Another often overlooked factor is the peak power draw of `C` rating that a battery can support. Many of the fuel cell or more exotic battery chemistries cannot provide the high amperage currents that the tractive motors demand.

Though Lithium-Ion batteries have been used in both the smaller Sea Otter and mid-sized Sea Ox with very good results, the perceived hazards often preclude their use. Though lithium-ion batteries can receive safety certifications, the cost of achieving such a rating is prohibitively expensive. Lithium Iron Phosphates have been certified for domestic shipping (UN38.8) and are readily available and were selected as the `standard` battery.

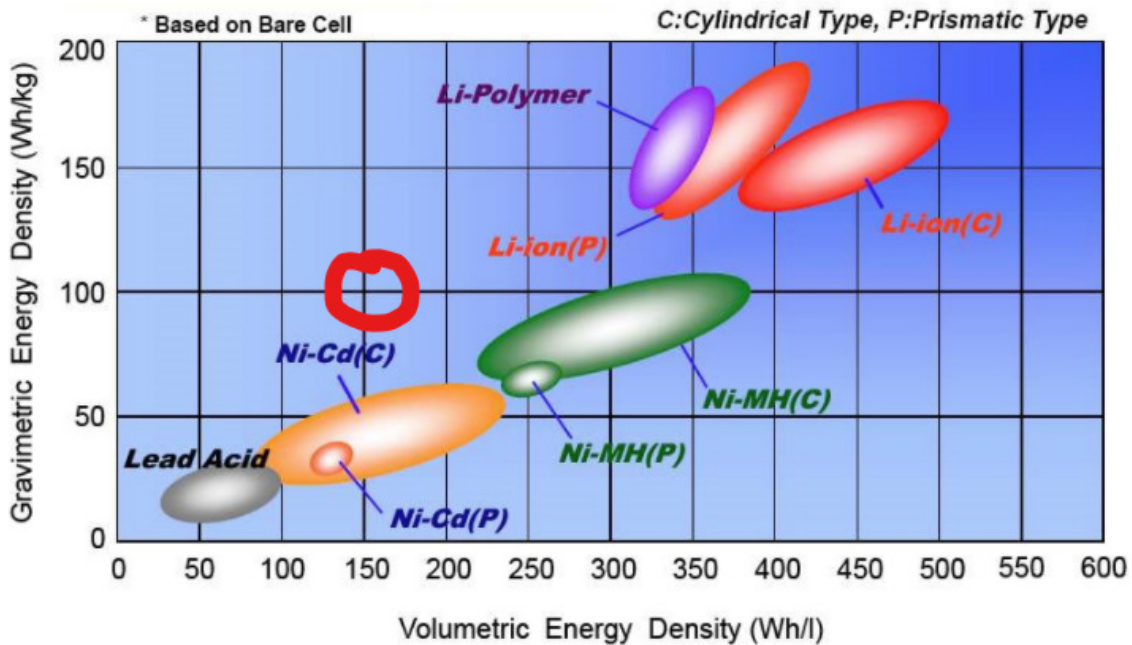


Figure 25. Power Densities for Common Battery Systems.

Red circle is Lithium Iron Phosphate, used during the program.

As a point of comparison:

- By Volume: where Lithium Iron is nominal, whereas Lithium Ion is 2x and lead acids are 0.5x
- By weight: where Lithium iron is nominal, Lithium ion is 0.5x and lead acid batteries are 4x.

Figure 26 shows the difference in size for the same capacity between the lithium ion (foreground) and the lithium iron phosphate.



Figure 26. 42 amp-hr Battery Packs Lithium-Ion (Foreground) vs Lithium Iron Phosphate.

A 5x6 ft Sea Beast (Bv350) can carry 4 sets of 42 amp-hour, 48V batteries within the pontoons (8,000-Watt hours) which is ample to meet the assumed mission profile. More can be carried on deck if necessary. The double packs shown in figure 27 need a modified battery management system (BMS) and charging system to ensure safe and balanced charge capacities. The battery capacity is manageable. The vehicle requires 48V@80 amp-hours (Li-iron = 3840 W-hrs) and the payload 52V @84 amp-hours (Li-iron = 4368 W-hrs)

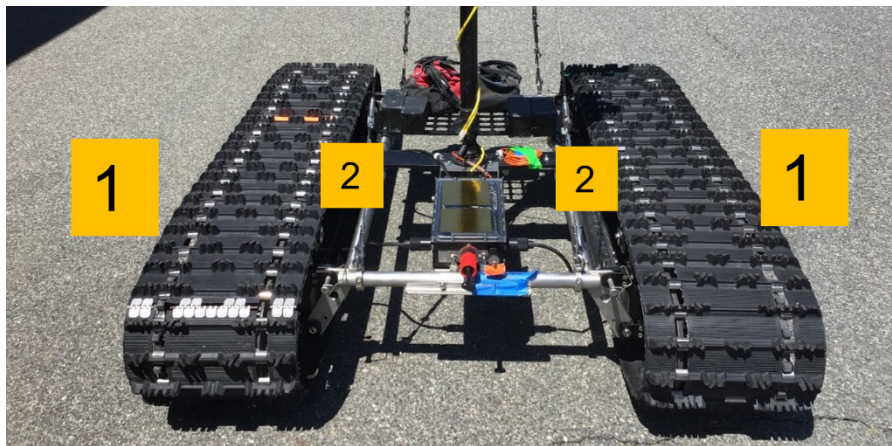


Figure 27. Battery Placement within the Track Pontoons.

2.3.6 Mobility Platform Vehicle

At the time of this writing, the C-2 Innovations line of crawler robots has been acquired by Bayonet Ocean Vehicles, Inc. located in 10 Cordage circle, Plymouth, MA. Bayonet Ocean Vehicles is closely affiliated with Greensea Systems the providers of the control and navigation software. Bayonet has renamed the vehicles; the Sea Otter is the B150, Sea Ox is the B250, and the Sea Beast is the B350. For the purposes of this report the original nomenclature has been preserved.

C-2i's approach was to leverage the Sea Ox mobility platform being developed for ESTCP under MR-201712. The Sea Ox precisely maneuvers a UXO sensor sled developed by White River Technologies. The system can operate to depths of 300ft with an autonomous range of 10mi. It is amphibious and can operate in soft cohesive and cohesion-less soils, and in high current wave surge environments.

The Sea Ox was an ideal platform for assessing the individual components, but it became quickly obvious that more deck space would be required. The Sea Ox design has always included a mechanical architecture that is readily scalable in size/power, so the vehicle was rebuilt to a plan area of 5 x 6-ft. Due to expediency the same motors, controls and batteries were used as the Sea Ox. The Sea Ox used a 234 NM, motor/transmission at a nominal operating speed of 0.5 m/s.

In the unloaded condition the larger 5 x 6-ft platform (called the Sea Beast and now referred to as the B350) had good maneuverability and stability in the surf. But as the payload increased to an anticipated 1,200-lbs gross vehicle weight (vehicle plus payload), there was concern about the vehicle power draw.

Using the Sea Ox platform engineering data was gathered for the purposes of sizing necessary power and motors to handle the loads we anticipated. The Sea Ox was at first widened to accommodate expected payload footprint. Then power draw was recorded when driving across asphalt, sand, grass, and underwater using original Sea Ox power plant. The ballast was increased, and current draws monitored as a basis to size the motors and gears needed to meet Harvester mission goals. The mission assumptions (no bury) were 2.5 KM, 20 stops/starts, 40 turns, 10 'peak' events (example, stalling).

Figure 28 shows the asphalt track. The system was pre-programmed to navigate and stop autonomously to minimize human driver bias.

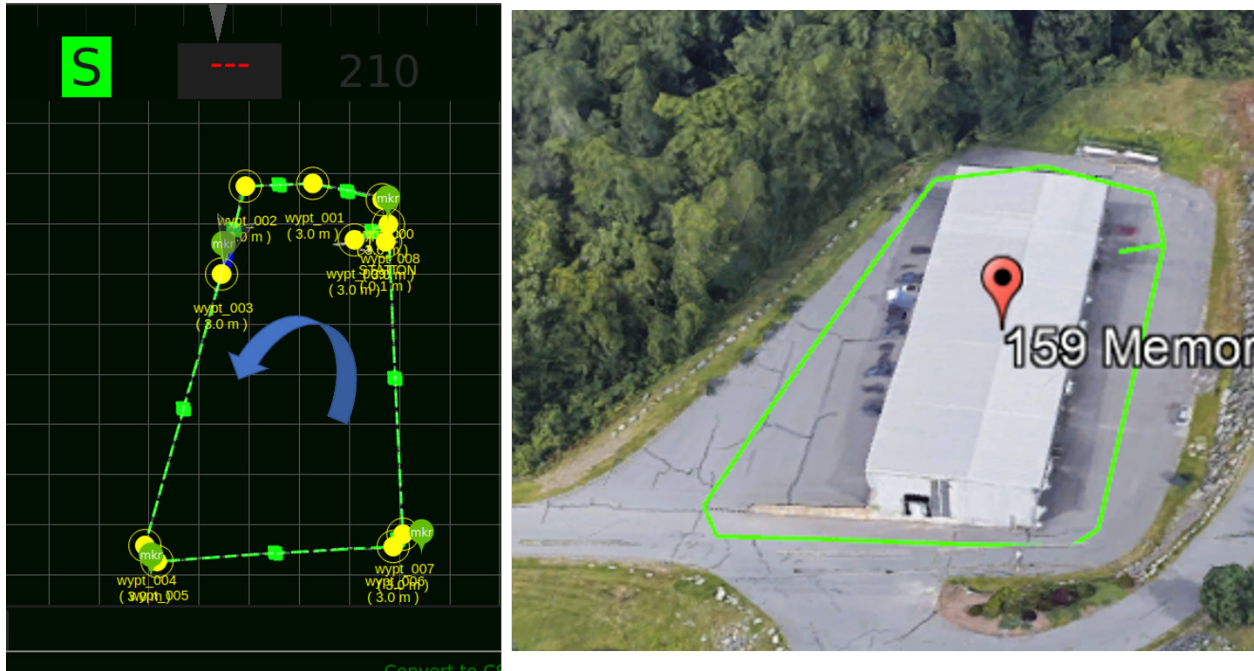
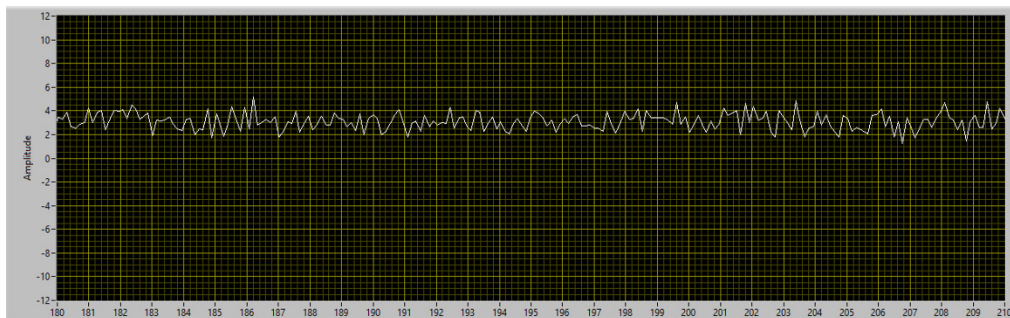
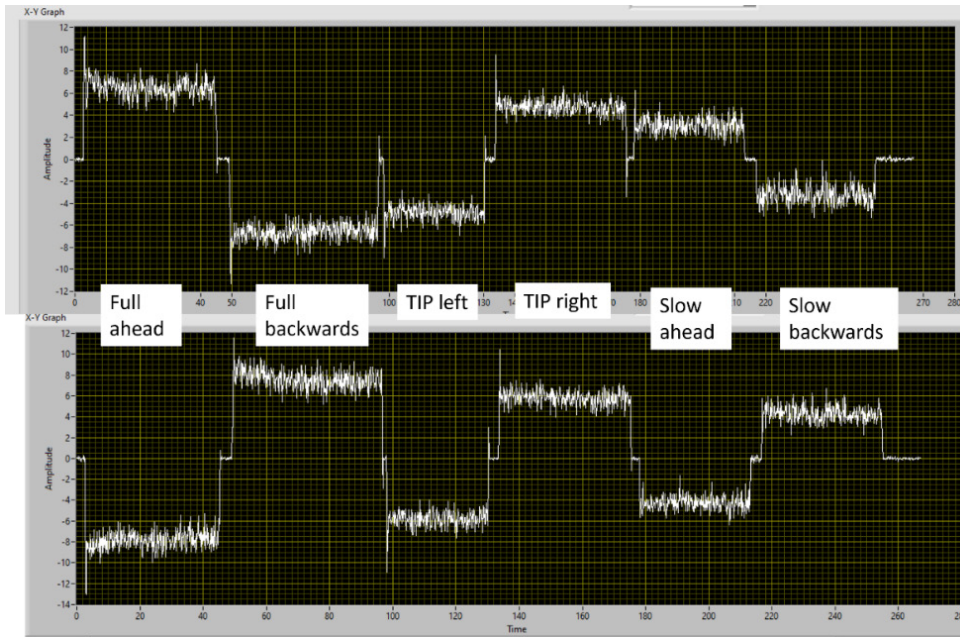


Figure 28. Power Testing on Asphalt.

In addition, forward and backward tests were performed. Figure 29 illustrates current draws for the port and starboard motors (TIP = turn in place or spin turn, representing a worst case load).



Slow Forward
17000 cts/sec

Port over Stbd

Port draws slightly
less load, port is
consistently below
4 amperes.

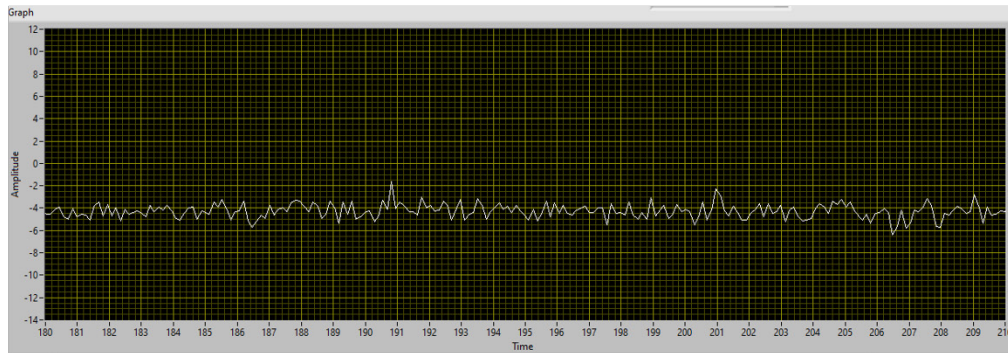


Figure 29. Current Draw Starboard and Port Side for TIP Turns and Straight Runs.

Testing showed that the Sea Ox motors were insufficient for the heavier loads. The power draws were excessive, and internal temperatures exceeded the 120-c Degree self-protection threshold. A higher torque motor transmission system rated to 450NM at 0.5 m/sec was procured and tested.

Even though the motor was larger and heavier, it was more efficient at the predicted loads.

Figure 30 illustrates the design impact for the anticipated operational ranges. The x axis is torque, the y axis speed, the design goal is to operate on the peak of the efficiency curve most of the time (shown in green), and when the motors are loaded the operating point moves closer to a position aligned with maximum output power (yellow).

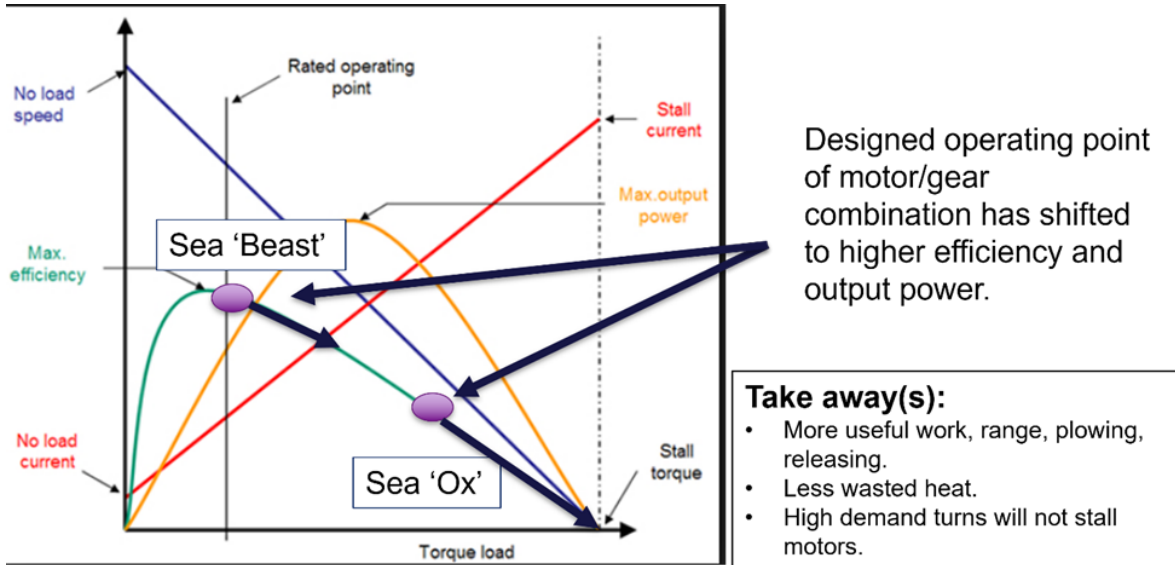


Figure 30. Power Efficiency Curves for 'Light' and High Torque Motors.

The analysis showed that a 20%+ battery capacity savings is possible with larger drive motors for Harvester, with a concurrent X2 the torque increase. In comparison, the Sea Ox would consume 41.79 A-hrs, while the Harvester motors would only consume 32.5 A-hrs. The crawler design point increased from 250 kg Gross Vehicle Weight (GVW) to 500 kg GVW.

Tests with the higher torque motors were performed with ballast loads of up to 550-lbs. The motor drivers were limited to 30 amps. While straight line runs were comfortable at 20 amps, turns in grass often triggered the 30-amp limit. New motor drivers were ordered but not received that could accommodate higher thresholds. Temperatures were well under the 120-deg C threshold even with full ballast (figures 31).

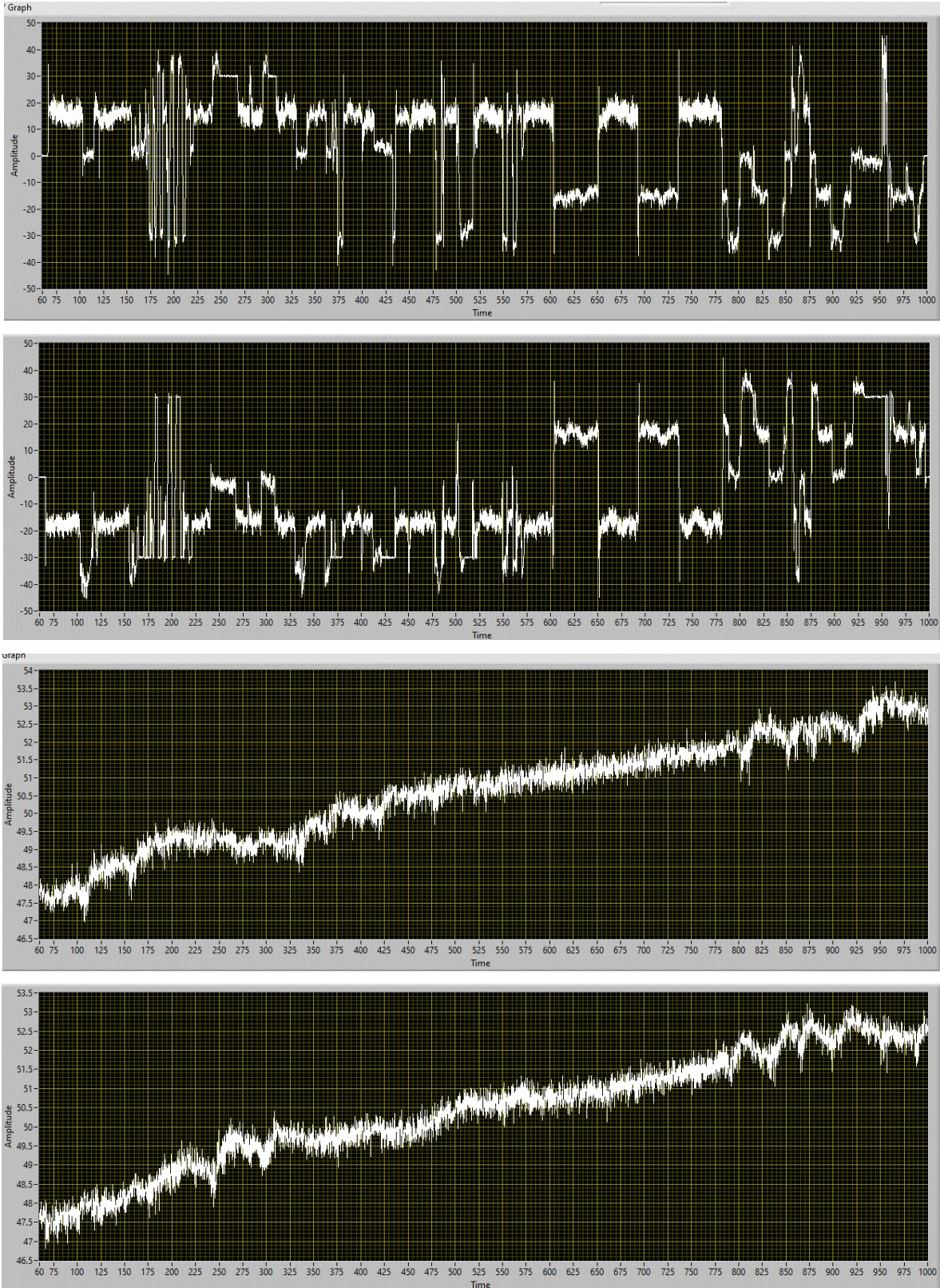


Figure 31. Current Draws and Motor Temperature Profiles of High Torque Motors Under Load.

In summary figure 32 shows that the higher torque motors are necessary.

Mission Event		Sea Ox Motor	Sea Beast Motors
Straight line distance (normal power)	2.5 miles (4km)	9.2E6 Joules (J)	6.6E6 Joules (J)
# of turns (max power)	20	1.05E6 J	1.03E6 J
# of 'peak' power events	10	1.76E6 J	2.14E6 J
Hotel load	Always on	4.35E5 J	4.35E5 J
OAW bury events	20	2.40E5 J	2.40E5 J
Total Energy (joules)		1.07E7 J	8.08E6 J
Total amp-hours		62	47
Motor Efficiency		54%	79%
Battery Capacity used		74%	56%

Figure 32. Comparing the Lighter but Lower Torque Motor/Transmissions with the Heavier High Torque Motors.

The new motors came with consequences as well. The motors and transmission are larger (4-6-in diameter; figure 33) and shafts had to be upgraded to accommodate the higher torque, and the support structure changed to withstand the heavier loads.

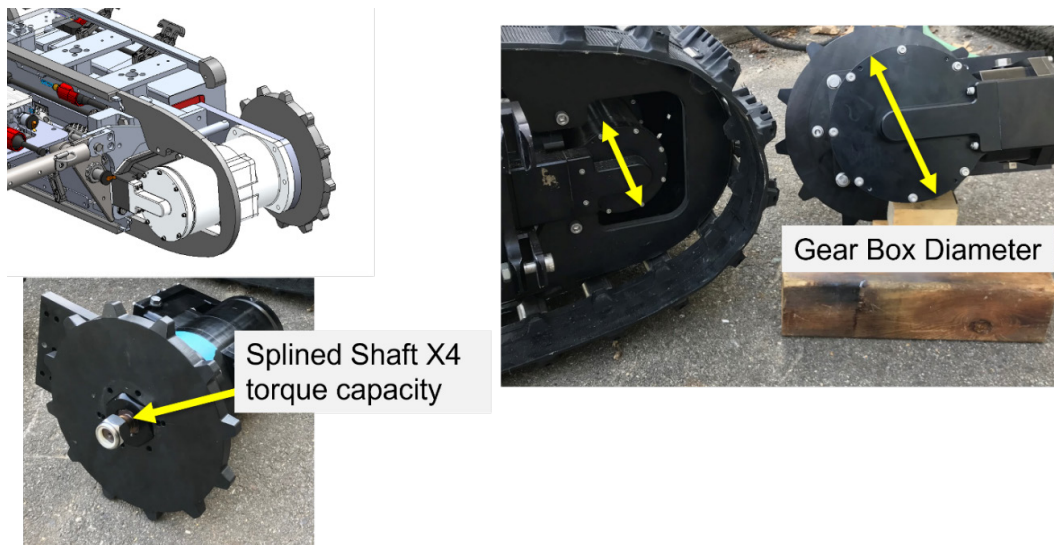


Figure 33. Heavier Torque Motors Were Larger, Required Support Sturcture Material Changes and More Efficient Shaft Designs.

The length in vehicle increased a couple of inches and the wheel diameter grew one inch, as such odometry navigation required updates. Wear, strength, and stiffness needed reinforcement throughout the entire crawler. In general, the vehicle will now operate continuously at 1 horsepower and can peak load at over 2 horsepower.

During Turn-In-Place (TIP) turns a very high side load is imparted on the track that often leads to de-tracking. The smaller lighter vehicles could resist the de-tracking loads with guides and runners that made maintenance simple. Increasing track tension is a common technique to combat de-tracking but it comes with the penalty of increased power consumption.

An assessment of track guiding methods was undertaken to look at track tensioning, skids vs bogies. Overtightening the track tension improved de-tracking but at a 18% higher power consumption penalty on maximum speed straight runs. Bogies are more expensive and harder to maintain, but effective. A 6-boggy design was constructed and tested with success.

TIP turns are a worst case. If the turns are designed to have a minimum radius, for examples 10 meters, the load on the track and motors is greatly reduced. Using a turn radius strategy allows both motors to participate in the work of pivoting the sled at nearly equal effort. Average motor loads during turns on grass and straight paths were within acceptable limits (10-12 amperes (threshold is 30A). In water (wet weight) the motor loading is reduced by an additional 20%.

On dry beaches where softer sands are encountered, steeper fore slopes, and where the full dry weight is experienced (that includes sand build up, increased friction, climbing the sand `bow wave`), the smaller 1.2Hp motor system capabilities are exceeded (figure 4).

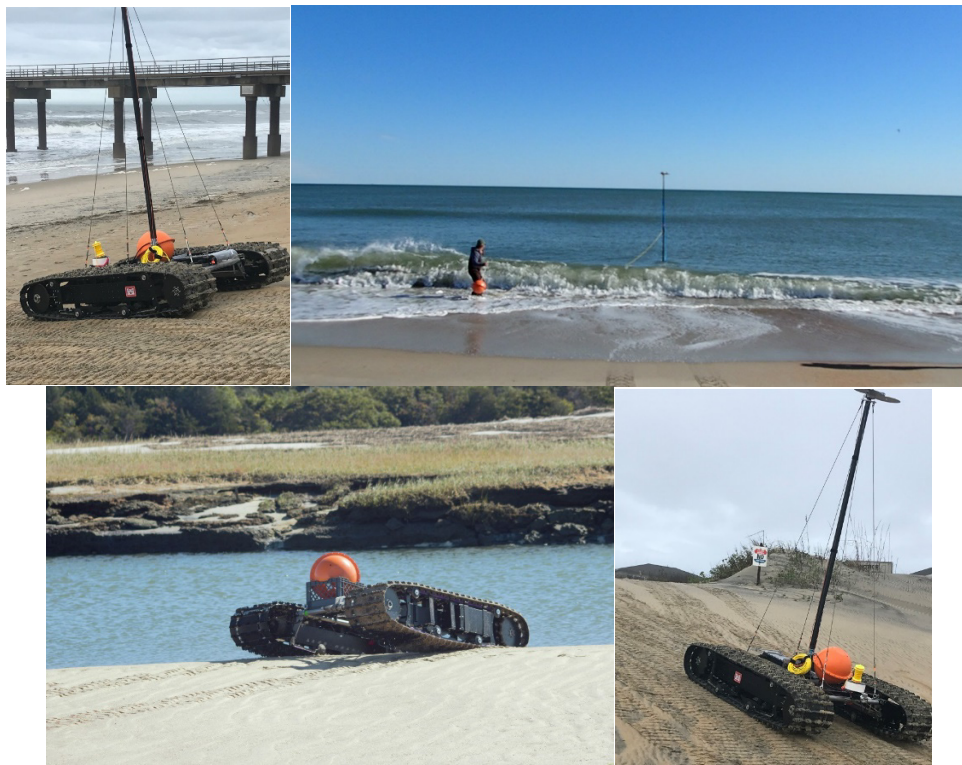


Figure 34. Power Draw Testing in Sand and In Surf.

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The Harvester has numerous advantages over conventional target deployment methods.

- Humans can be kept entirely out of the water which is a major safety consideration.
- No boat or diver assistance is necessary – a major cost and time savings. Boat access is not always practical.
- No weather restrictions opening scheduling windows and saving costs.
- Deployment from the beach results in low logistical cost.
- Can operate in the Surf Zone; an area that is practically denied due to harsh conditions and safety considerations.
- Can operate in soft soils in ground conditions that cannot support human traffic.
- Accuracy of placement.
- Speed of implementing. Multiple rounds can be carried and placed on a single sortie, day or night.

The disadvantages are more limited.

- While proven feasible the complexity and risk of the target-burial task is high.
- The system can be flummoxed by maneuverability barriers such as step heights greater than 1-m, very soft ground, and the danger of high-centering on obstacles such as rocks or debris.

3.0 PERFORMANCE OBJECTIVES

3.1 GENERAL

The cost, reliability, and precision of placing munitions at various depths and orientations for the purposes of validating underwater UXO detection methodologies is highly cumbersome, involved, and often dangerous. Munitions can be heavy, the waters murky, combined with currents and wave actions culminating in dangerous situations. The result can be imprecise placement in terms of location, orientation, and depth.

The program technical objectives were to:

- Design and develop a means of carrying munition-targets to the site
- Establish placement accuracy in GPS or nav aided and unaided conditions
- Design and develop a means of burying the targets
- Design and develop a dispenser that could carry and place multiple rounds
- Determine the power requirements and power plant for the system
- Design and develop a delivery platform.
- Test in operational environments

3.2 PROBLEM STATEMENT

There are several purposes for the creation of a standardized test bed adjacent to any remediation site.

Every site is unique due to water clarity, depth, soil composition, hydrodynamics, salinity, and turbidity among other parameters. Instrumentation and procedures must adapt to the local conditions for optimum performance.

Standardized testbeds containing known precisely located targets in the natural environment would be used to evaluate, calibrate, and validate detection and mitigation instrumentation, skills and processes that in turn would instill confidence that the optimum approach is being followed.

The concept of creating a test bed is simple, but the reality is many test sites do not lend themselves to low cost, precise or safe development.

The surf zone and near shore littoral and estuarine environment is highly dynamic, with high currents, complex patterns, poor visibility, crashing waves and difficult to control soil conditions. Placing target sets in such hazardous conditions where individual munitions can weigh nearly 100-lbs is highly cumbersome, uncertain, and often dangerous.

The cost of divers, boat support, dependence on weather and sea state conditions, adds to the overall project cost. The result is that between high cost and low confidence of 100% detection and recovery success, maritime UXO sites receive a lower priority in the funding scheme.

A means that can minimize or even eliminate divers and the need for support craft while constructing a test field would be greatly beneficial to the UXO remediation effort. A system that could place targets at actual sites would have huge benefits.

The challenge is that UXO remediation sites represent a wide range of bottom and hydrographic condition. The placement system needs to be versatile, and mobile to be cost effective.

Discussion with ESTCP senior leadership covered points to address demonstration goals. Key points included:

- Targets proud to surface in sandy environment ~25% cases.
- Targets buried in sandy environments ~50% cases.
- Targets in softer soil environments ~25% cases.
- A means to assess site trafficability of the Harvester would be desired to determine operational feasibility in softer soils.
- There are several shapes of interest for target clusters, as a starting point the most prolific would be in the 60mm mortar rounds, 80mm mortar rounds, 105mm artillery, and 155mm artillery, standard Instrumentation Verification Strip (IVS) objects, but should also include false positives such as shrapnel or trash. The false positive targets could be of irregular shape and size.
- Submeter placement accuracy

The ability to assess site trafficability was out of the scope of the program, however during a parallel development for UK DSTL, C-2i, designed, built and successfully tested a cone penetrometer (CPT) that was used directly to determine bearing capacity and trafficability as related to the NATO Reference Mobility Model.

3.3 TECHNOLOGY CHALLENGES

The process of placing targets in such varied and dynamic environments encompassed several technical challenges.

Target types: Target sets can include a wide variety of shapes and sizes. Target types included 60mm, 80mm, 105mm and 155mm as well as IVS. False targets such as shrapnel or junk, while undefined should also be placed. The shape and weight influence the dispenser mechanisms, and the carrying capacity of the platform.

Target placement accuracy: In order to measure instrument detection and location accuracy the target position must be known to sub meter, and ideally centimeter accuracy. Where the water is less than 3.5m, a mast can be mounted on the vehicle hosting either a survey prism or RTK system. Integrated over the entire height and including the wire stabilization stays the surface area of the mast can be as much as 0.2-meter square of drag area. In calmer waters it is less of an issue, but in high currents or waves, the drag force represents a significant overturning moment.

Acoustic location works well in waters as shallow as a couple of meters, but in active surf, the bubble curtain, dynamically shifting suspended sediments and the acoustic wedge geometry of the beach eliminate the ultrashort, or short baseline systems.

The result is that in many applications positioning needs to be autonomous with minimal external guidance.

Target placement logistics: Target fields can contain many nodes. The logistics of placing upwards of 40 to 60 targets dictates that as many targets should be deployed in a single sortie as possible. In addition to minimizing dead heading, fewer deployments improve individual placement confidence. Even if errors occur the error source will be more systematic and relative. Multiple single sortie placements add weight to the system and increases the need for close monitoring of power consumption.

Target orientation: Most target matrices are designed as linear rows, but the targets themselves can be placed in various orientation in both plan view and in cross section view. Also, clusters are desired. To accommodate plan-view orientation the vehicle itself can pivot or the dispenser needs to accommodate the variation. The cross-section view orientation requires a sophisticated burial method.

Target burial: Burial of a target requires a burial method, either mechanical, water jet or vacuum. Beyond the complexity or the mechanism, control and power consumption, the excavation hole must remain stable during the placement. Saturated loose sands in an active surf are particularly challenging to maintain trench wall integrity for more than a few seconds. The addition of temporary sheet piles to maintain stability during the excavation and placement process complicates the entire process from a physical sequencing and remote controls perspective to power and implementation. A stuck caissons can represent a catastrophic failure requiring complex and expensive recovery methods.

Backfill: If an excavation is created it needs to be backfilled to represent realistic conditions. Test have shown that this is a more minor issue.

Soil: UXO sites contain soils that range from rocky, sandy to soft muck. The ground pressure of the vehicle, ground clearance, tractive pull, and means of excavation are all directly affected by the soil characteristics. Tests during the program addressed all soil conditions.

Water Depth and Hydrodynamics, turbidity: Communications and power supply in the surf zone or in deeper water is extremely challenging. Entrained bubbles and suspended sediment can make the environment visually, acoustically and EM- opaque resulting in minimal to no status updates, or operator feedback and control. The system design was based on a fully autonomous operation.

3.4 PERFORMANCE OBJECTIVE

Performance Objective	Metric	Data Required	Success criteria	Results
Transit surf zone	Transit and deposit targets in an active surf	Visual	Sea State 3	Success demonstrated at 1st Encounter (SS2), White Beach (SS3)
System range	Distance travelled with Full payload	Full distance	8km	10km submerged
System depth	100m	Physical survival at a component level	100m	100m pressure vessel tested
Payload capacity	Ability to carry and maneuver	Ability to move, Straight and turn, power draw, motor temperature	400kg	400kg with high torque motors.
Burial depth	Munition depth of burial	Hole Depth	1m	0.3 due to caisson limitations
Burial angle	Pitch angle of munition	angle	45-degree	45 degree using manual vacuum
Production rate	Number of dispensable targets	Number of targets per dispenser	3 155mm	3 155mm
Target types	Ability to dispense multiple target types		60mm, 80mm, 105mm, 155mm	60mm, 80mm, 84mm, 105mm, 155mm
Maneuverability	Slope, step height	Obstacle negotiation	Beach slopes and escarpments	47-deg pitch angle up and down, 0.6m step height negotiated
High center	Ground clearance	Obstacle height	254 mm	254 mm
Modularity	Ease of use, beach assembly	Observation	Full assembly in 10-minutes	Full assembly in 4 minutes
Location accuracy	Precision of target placement	RTK confirmation	Sub-meter	RTK 5cm Dead reckoning: 0.5m Cluster: 150mm

4.0 SITE DESCRIPTION

4.1 SITE SELECTION

Initial testing was performed in Duxbury Massachusetts, Ogunquit Beach Maine and First Encounter Beach, Eastham, Massachusetts. Ultimate testing was tentatively scheduled for Sequim Bay Washington, but funding limitations curtailed the final demo task.

The test sites represented different beach topographies, soil conditions and hydrologic energy environments.

4.2 SITE HISTORY

All beaches are public beaches though are nearby formerly used military facilities including Wellfleet, and Cape Cod Bay

4.3 SITE GEOLOGY

Duxbury: Duxbury beaches were performed in Pilgrim Bay. Water depths ranged from water's edge to 30-ft with predictable tidal currents of 1kt (measured by a Acoustic Doppler Current Profiler). The soil stratigraphy was complex. The top level generally consisted of 70 to 100 centimeters of a loose sandy silt underlain with a dense silty clay layer. Pockets of well graded sand and poorly graded sand existed. The area is heavily populated with oysters that made penetration challenging.

Ogunquit Beach: Ogunquit Beach, Maine was a well graded sand to a bedrock outcrops or zones of cobbles. Surf was active. During testing the surf ranged from 0.5 to 1.5-meters.

First encounter Beach: First Encounter Beach is a well graded sand. At the Bees River, a 3-knot current created escarpments and strong ripples, up to 200 millimeters in amplitude. The advantage of First Encounter beach is the high tidal range of 3-meters that allowed submerged testing at high tide and submerged testing at low tide.

Duck USACE FRF: Navigation tests were performed at the USACE Duck Field Research Facility in conjunction with other, unrelated field tests. Well graded sand.

5.0 PERFORMANCE ASSESSMENT

5.1 WHAT WE HAVE ACCOMPLISHED

- Designed and built the vehicle (Sea Beast – light)
- Determined and cataloged power consumption for various missions and functions through buildup of prototypes and field experiments
- Tested navigation systems (RTK, IMU based) and determined precision of placement
- Wrote, tested, and verified a vehicle orientation algorithm to enable the vehicle to place a tight pattern of targets in various directions
- Wrote and preliminary tested placement control software (referred to as `Objective at Waypoint`)
- Redesigned and built a heavier duty motor and transmission system (Sea Beast - heavy)
- Redesigned, built and tested new suspension system (required due to the higher torque system)
- Tested drop-off of a limited number of munitions (4 x 105mm) using a `wing` dispenser design
- Designed, but did not build low profile, higher capacity conveyor design that could carry non cylindrical shapes
- Tested the power necessary to plow-in (bury) munitions

5.2 REMAINING TASKS

- Reliable Objective at Waypoint operation. The present solution is worked on an off-board computer but has not been successfully installed on board the vehicle
- Conveyor design (lower profile, more, and irregular targets deployed on a single sortie)
- Full plow dispenser design (partial burial, plow control software)
- Improved autonomous nav design (requires higher end IMU, USBL and integration to achieve accurate location at depth or range)
- Demo: On-site demos. (We can do a demo at our Eastham MA site and invite personnel or video the process, but not one that requires significant travel)

6.0 COST ASSESSMENT

The cost advantages and suitability of the Harvester are site dependent. Where surface laid targets are permitted, the logistical advantages over divers and support craft are significant. The Harvester can carry from 6 to 16 munitions, depending on size, and travels at 0.5m/second. Setup and programming waypoints is less than an hour leaving 6 hours for operations. Where dead heading is minimal a full 50+ field can be planted in a workday.

If burial is required the power consumption, battery change out and burial cycle time reduces the production rate by roughly a half.

7.0 IMPLEMENTATION ISSUES

Costs and delivery have increased significantly. The cause of the cost growth include:

- Internally: The need for more powerful motors and subsequently the redesign of the suspension, motor drivers, track guidance, track tensioners was needed to accommodate the higher motor output torque
- Externally: Machine shop costs have increased significantly (essentially doubled)
- Externally: Software costs and support have more than doubled, almost tripling (!)
- Efficiency and output slowdown from vendors and loss of work force, chip design delays of as much as 8 months that effects everything.

Beaches were closed which inhibited testing progress. Many vendors and parts suppliers were either shut down or operating at reduced capacity so long lead items became longer in many cases greater than a full year.

Demonstration Results: A full system was not demonstrated. After preliminary testing the cost of development and the technical risk of the original plan for excavation and hole stabilization was too much. Alternate methods were tested such as direct vibratory placement aided by water jetting showed great promise in certain soil types. It was decided that the best low risk plan was to develop a dispenser that could place a range of surrogate munition sizes on the surface (solve the simple problems first).

A larger wheelbase vehicle was developed (5-ft x 6 ft) than the originally planned 4 x 4 ft vehicle. It was found that a higher torque motor system was needed which as well had ripple effects in the motor controller design. Once built the dispenser was tested on land at Crow island, Stow, MA and subsequently at First encounter Beach in Eastham, MA using GPS as an aid and without GPS. Placement accuracies of 8x 155mm inert rounds (or mass equivalent cylindrical models) were placed within 4 centimeters of the predicted location. A 5-point pattern representing 4 corners spaced 1 meter apart and a center location was tested in a GPS denied condition and placement accuracy was within 5 centimeters, after a 500 m out and back transit.

The results showed that transport, dispensing and placement accuracy goals were achievable.