Report Detailing the Installation, Operation, and Demonstrations of the Sea Machines Robotics SM-300 Autonomous Control System aboard the

MSRC Kvichak MARCO Boom Skimmer Vessel

U.S. Department of Transportation Maritime Administration

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Acronyms Glossary

AI	Artificial Intelligence
ASV	Autonomous Surface Vessel
CONOPS	Conditions of Operation
DC	Direct Current electrical transmission
GPS	Global Positioning System
IMU	Inertial Measurement Unit
ML	Machine Learning
META	Maritime Environmental and Technical Assistance Program
MPA	Marine Pollution Association
MSRC	Marine Spill Response Corporation
MARAD	Maritime Administration
MMA	Maine Maritime Academy
OPA	Oil Pollution Act 1990
OSRO	Oil Spill Removal Organization
ROM	Rough Order of Magnitude
SMR	Sea Machines Robotics
UI	User Interface
VPN	Virtual Private Network

1.0 Introduction

Boston-based, Sea Machines Robotics (SMR) was awarded a cooperative agreement under the US Maritime Administration (MARAD) Maritime Environmental and Technical Assistance (META) program to demonstrate their remote and autonomous control system aboard a Kvichak MARCO Boom skimmer that is owned and operated by the Marine Spill Response Corporation (MSRC).

The intended benefit of automating the Kvichak MARCO Boom skimmer is twofold: to improve operator safety by having an option to control the boat from a safe location and to automate controls for some of the mundane, repetitive operations such as boom operations and grid navigation. All of this was in an effort to improve safety, efficiency and productivity.

The Sea Machines SM-300 remote and autonomous systems were installed on the skimmer in Portland, Maine during the Summer of 2019. Two field demonstrations were conducted to highlight the capabilities from manual operations to autonomous and robotic operations. A requirement of the conversion project was to document lessons learned from system design, installation, and training through to the mock demonstrations.

Nearly 200 Kvichak MARCO Boom skimmer vessels are strategically deployed in US inland and coastal areas where rapid spill response is mandated. (Image 2 Marco Boom & Belt). With the Marco boom, the system can recover a wide range of spills, from light sheens to thick weathered oils contaminated with debris.

In addition to remote and autonomous piloting, SMR automated manually controlled systems such as the boom control, skimming belt, water pump, and tank level monitoring.

Image 2: MARCO Collecting Grate, Boom and Belt Assembly

2.0 Background

Hazardous material spills can occur anywhere commercial and industrial scale operations take place including inland waterways, coastal waters and offshore. Rapid spill response minimizes serious environmental damage that can occur. Spill response is mandated by federal and local authorities and implemented by organizations such as the Marine Spill Response Corporation (MSRC). MSRC employs skilled personnel trained to mobilize quickly in times of need. As first responders, they are often put into harm's way. The crew members may be exposed to toxic fumes from spilled fuels or chemicals which can make their working environment intolerable. It is scenarios such as these that prompted Sea Machines, MARAD and MSRC to automate such a skimming operation to demonstrate its ability to help keep crew members safe and to enable faster response which would in turn minimize environmental impacts of a spill.

Representatives of SMR and MARAD have been researching applications of autonomy for use in the maritime sector. A principle motivation behind automating the oil skimming operation was to see if SMR's technology could be used to control the boat as well as the boom skimming mechanism. The concept of applying SMR's autonomy to the well known oil spill clean up operations aboard the relatively small Kvichak Boom Skimmer was appealing and met the criteria of MARAD's Maritime Environmental and Technical Assistance program. Working with industry partners such as SMR and MSRC leveraged government resources (funding) with company assets and skills for productive collaboration.

Sea Machine Robotics (SMR) is headquartered in Boston Massachusetts and is pioneering autonomous control and advanced perception systems for the maritime industry. Founded in 2015, the company builds autonomous vessel software and systems, which increases the safety, efficiency and performance of ships, workboats and commercial vessels.

SMR offers two controller modules, the SM-200 remote controller and the SM-300 autonomous controller. The SM-200 communicates with the boat via a radio frequency (RF) link and is controlled by a person located within line of sight of the skimming vessel (1-2 miles). In the case of the live demonstrations that took place in Portland, Maine, a person was stationed on the dock within view of the vessel and used the belt pack to control the boat remotely. (see: Image 3 - SM 200 belt pack remote controller)

Image 3: SM 200 Belt Pack Controller

The SM-300 autonomous control system operates via a communication link that sends information to the boat via Wi-Fi or 4G cellular signal. Use of the SM-300 also allows pre-programmed instructions on survey tracks, waypoints, operational speed, and direction that are controlled through a computer-based user interface (UI). This type of controller can be installed inside an office or aboard a tending vessel where personnel can monitor the vessel's operations in real-time. These systems allow minimally manned autonomous operations which permits operators to respond to spills 24/7 depending on recovery conditions in the event that crew are limited or restricted. These configurations also reduce or eliminate exposure of crew members to toxic fumes, dangerous sea states and other safety hazards.

Marine Spill Response Corporation (MSRC) is a not-for-profit, U.S. Coast Guard-classified Oil Spill Removal Organization (OSRO). MSRC was formed in conjunction with the Marine Preservation Association (MPA) in 1990 to offer oil spill response services and mitigate damage to the environment. MSRC provides a full range of oil spill response capabilities intended to meet the criteria of the Oil Pollution Act of 1990 (OPA 90). This is made possible through a combination of MSRC's own dedicated response capability and contracted resources. MSRC's client base is comprised of integrated oil companies, refiners and terminal operators, pipeline and rail operators as well as both domestic and international shipping companies.

Since its founding in 1990, MSRC has evolved to meet new regulatory requirements and the ever-changing needs of a diverse customer base. Over the years, MSRC has broadened its scope of services to include:

- Remote sensing and aerial observation
- Oil spills of any size
- Shoreline cleanup
- Hazardous material spill response (case by case)
- Response to spills outside the U.S. (case by case)
- Response to other emergencies

MSRC's Portland Maine facility was chosen due to its proximity to Sea Machines engineering campus located in East Boston, Massachusetts

3.0 Methodology

The Kvichak MARCO Boom skimmer was selected for this project because of its relatively small size (31ft), its dependable performance, and its availability for retrofit.

Installation of the SM-300 aboard the MSRC vessel took approximately three and a half weeks giving the skimming vessel the following new capabilities:

- Remote control from an onshore location or secondary vessel, via the belt pack controller
- Data-driven waypoint following and mission planning
- Autonomous operation
- Programable grid routes and tracking
- Collaborative vessel operations
- Remote payload control to deploy boom, drive the belt and monitor holding tanks
- On board video monitoring of belt and boom operations
- Minimally manned configurations
- Obstacle detection and collision avoidance

SMR installed remote automation of the vessel's MARCO Boom™ controller, belt operation, and holding tank level monitoring. These three items are key components of the spill recovery process that SMR's technology is uniquely suited to automate. SMR added float switches to the collection tanks to provide operators with a reading on whether the tanks are 50% full and 80% full. This way the operator can better gauge when to pause collection operations for off-loading product more efficiently.

The outfitting of this vessel is intended to enable constant run time in dangerous situations, extreme weather conditions, and during overnight operations. Accommodations aboard these skimmers are limited to a small pilot structure with no life support functionality or climate control. Crews must switch out more frequently in the extreme weather, therefore, automating operations for these boats will enable them to operate on station longer.

The SM-300 system provides Level 3 Autonomy (human-in-the-loop) and semi-autonomous navigation abilities through a connection to a shore station or to another vessel nearby. This provides operators the ability to control a vessel using streaming video, audio, electronic charts, radar, live environmental sensors and machinery condition feedback. The system was installed in the lower deck beneath the pilot house. Included with the system are the sensors which are described in detail in the Installation Section (3.1).

The SM-300 vehicle controller may also interface with vessel machinery and instruments to provide remote command/control and monitoring capabilities. The system can receive a wide variety of software interfaces including: Serial, CANBUS, Profinet, Profibus, NMEA, Ethernet and more.

The SMR user interface (UI) System uses a Windows-based graphical display that provides real-time chart reference that will result in remote situational awareness using navigation sensor data and a remote feed of vessel equipment data.

Once the SMR system and associated devices were installed on the boat and it was deemed to be a safe working environment, SMR personnel provided onsite training to the MSRC staff throughout the installation, tuning and calibration of the vessel. This stage of the project involved testing all communications from the UI to the boat and from the belt pack to the boat. A customized tuning of the vessel speed and steering controls coincided with pre-programmed tracks that were created in simulation mode. Similarly, all sensors and interfaces were checked to verify everything was operating as anticipated.

SMR trained the MSRC oil spill response staff to operate the belt pack (remote helm) and the autonomous UI. Trainings were conducted before, during and after the July 31, 2019 and August 21, 2019 demonstrations.

The basic elements that were covered during the MSRC training sessions included:

- Start-up of system and UI

- Planning/editing/deploying survey and waypoint missions
- Basic troubleshooting steps involving common connectivity issues (VPN)
- Status page features including auxiliary functionality specific to their boat
- User Interface including tools (measure, track, zoom) and what information is displayed
- Installing navigational charts
- Start-up and connecting belt pack
- Belt pack functionality including use of steering control, throttle control, and all auxiliaries specific to the boat.

Two on-water demonstrations located at the Portland Yacht Services yard (100 West Commercial Street) were scheduled from 9:AM-11:30AM and then a repeat at 1:30 PM-3PM on August 21, 2019. The demonstrations were focused on the basic elements listed above.

3.1 Installation Description

It was necessary to update some of the Kvichak MARCO Boom skimmer's sensors to be compatible with the SM-300 interfaces. SMR configured the SM-300 controller to operate in autonomous and remote modes and operate via Wi-Fi and 4G or via RF signals respectively. The components of the system that were installed on the vessel include a user interface (UI) laptop (onboard and for shore side station), and a remote-helm – user interface system. All components are industrial grade, Siemens hardware combined with a ruggedized Siemens autonomy computer mounted in an IP65-rated stainless steel enclosure.

Some of the sensors that were added to the boat included:

- GPS: Hemisphere E103 Differential GPS with a built in IMU
- RADAR: Furuno ERS 4 NXT Radar & Furuno Multi-function Display (TZT 12F)
- Steering: A hydraulic pump was added for the steering system that runs in parallel with the existing system to regulate hydraulic fluid to turn port or starboard.
- Shift and Throttle: The existing shift and throttle controls were replaced with a Sea Star digital control system. The Sea Star uses a maritime interface (NMEA 2000) system which communicates on an ethernet controlled network on board the boat.
- Marco Belt and Boom operation were controlled remotely via belt pack and autonomously via the user interface (UI)
- Holding tank level monitoring system was installed on both tanks to show 50% full and 80% full.
- Camera (s) for remote boom and belt observation were installed on top of the pilot house.

To retrofit the Kvichak MARCO Boom skimmer, most of the vessel control systems had to be replaced. This work was performed by Navtronics, the installation contractor. Detailed system components are included in this section.

Navigation Electronics: Existing equipment was replaced and rewired. The helm and steering controls were interfaced to the SM-300. (Furuno MFD, Radar, GPS, AIS, 200Khz Transducer, NMEA200 Data Interface, NMEA0183 Data Interface, Heading Sensor)

Cellular Communications: The Pepwave Cellular/Wi-Fi with SIM, External Omni Directional Antenna, Ethernet Interface 4G Cellular/Wi-Fi were installed on the hardtop, with power wiring from the DC panel and to the network interface located inside the SM-300 cabinet.

Steering: In order to install the type two reversable hydraulic pump, fittings, hoses and the SeaStar Smart Stick outboard position sensor were added. A two-way 12V DC hydraulic steering pump required hoses and fittings to tie the pump into the helm unit and then interfaced to the relay enclosure.

Throttle/Shift Controls: Installation of the SeaStar DTS system required upgraded control cables, replacement of the binnacle controls, interface to engines and ignitions as well as to the NMEA2000 interface. All these systems were then connected to the SM-300 cabinet.

Cameras: To provide visual feed control, four IP cameras were installed on the corners of the hardtop and interfaced to the SM-300.

Capture Tanks: The two waste holding capture tanks were each retrofitted with two float switches (50% full and 80%full). To attach the float switches, mounting plates had to be fabricated and the tanks had to have holes drilled to feed wiring from the switches to the SM-300.

Hydraulic controls: Hydraulic controls for the boom and belt required a bypass with momentary up/down interface, induction pump bypass with open/close - flow control interface, and a belt feed bypass with open/close - flow control interface. To operate, solenoids, hoses, fittings for control of both induction pumps and MARCO Boom belt operation had to be integrated. The belt up/down control was wired through current switching at the helm.

SM-300 Cabinet: The SM-300 cabinet was placed in the lower part of the hull accessible via a deck hatch on the port side of the pilot house. Placement of the cabinet required a fabricated mounting system in the engine space of the vessel. Power to the SM-300 was supplied from the main DC switch on the DC panel.

Relay Enclosure: This enclosure had to be custom designed, built, installed, interfaced in the lower forward storage cabinet. It contains latching relays and momentary relays with 12v DC supply power and 24v DC signal power.

Safety Light: A 2M yellow strobe autonomous operation warning beacon, sized for vessel length was installed on top of the pilot roof and interfaced to SM-300 cabinet.

Vessel Systems: All other vessel systems (navigation lights, deck lights, horn, bilge pump) were interfaced to the relay enclosure, fused and controlled through signal switching. This required the relay enclosure wiring to be in series with the existing switch wiring.

4.0 Results

4.1 Demonstrations

There were two on-water demonstrations conducted as part of the project featuring a series of simulated oil spill recovery exercises. On July 31, 2019 personnel from SMR and MSRC demonstrated the utility and functionality of the remote and autonomous operations aboard the Kvichak MARCO Boom skimmer. The second set of demonstrations, designed for the MARAD and other stakeholders, were conducted on August 21, 2019 with individuals from industry, government, and academic groups attending. .

The demonstration validated that this use of autonomy greatly minimizes factors that influence human fatigue and eliminates the need for personnel to be exposed to a potentially dangerous environment. For example, these factors were easily observed when the vessel is on task in a spill response situation. The vessel proceeds very slowly and it may be tethered to a floating boom while oil laden surface water is funneled through its collection blades. The spill material is pumped over the oil collection belt, which separates water from the spill waste and deposits the "product" into one of the (2) collection tanks. When those tanks are full the oil is offloaded to a collection barge or vacuum pumped into pier-side trucks and then the skimmer goes back out and resumes skimming. This can be a very mundane operation leaving crew fatigued, distracted and unnecessarily exposed to potential toxins in the environment.

Missions that SMR demonstrated successfully on July 31, 2019 included:

- Showing boat leaving dock using remotely operated system, belt pack.
- Showing skimming boom going up and down using belt pack.
- Showing skimming belt being turned on and off and running at one speed.
- Turning product intake pump on and off using belt pack.
- Showing tank level displays on user interface (UI) laptop (50% full and 80% full). Although the tanks were empty, the levels were simulated, and the float switches operated as expected.
- Configuring and executing an autonomous mission after the boat left the dock.

There was a simulation of an oil spill operation going in a tight survey grid course. The boat speed was designed to be 1-3 knots. On site it became apparent that the boat needed to go more slowly. Speed adjustments were made. (Image 4 Mock Demonstration Grid Pattern)

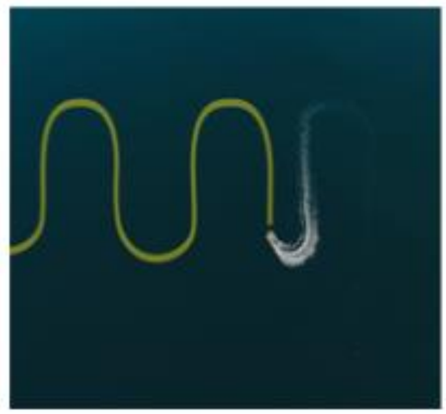

Image 4: Mock Demonstration Grid Pattern

The August 21, 2019 on-water demonstrations took place at the Portland Yacht Services yard located at 100 West Commercial Street. Two back to back demonstrations took place; the first from 9:AM-11:30AM and then a repeat at 1:30 PM-3PM. The morning program proceeded as planned. The weather deteriorated in the afternoon requiring the operations to be halted at least three times due to severe thunder and lightning for safety purposes. In an actual spill response situation, the autonomous functionality could have allowed operations to continue without endangering any crew.

5.0 Conclusions

5.1 Lessons Learned

The conversion of a manually controlled oil skimming vessel to a fully automated controlled vessel offered an excellent opportunity to see how one could retrofit an existing work boat to operate autonomously. There are some important lessons learned resulting from this project that might be built into future workboat conversions and to other types of marine vessels such as tugs, first responder, service, private and recreational boats. Each type of vessel requires an initial survey by a qualified trained installer. The procedure should be based on a rough order of magnitude (ROM) approach. The overall condition of the vessel, previous modifications, damage and deterioration must be considered before installation. This ROM process approach is substantiated by the fact that the Kvichak MARCO Boom skimmer was the first installation of its kind. It would have saved time if the SMR personnel were initially accompanying the installation subcontractor in ascertaining the status of on-board systems prior to installing the SM-300. This would have prevented time lost in specifying interfaces and connections.

Another recommendation from the installers point of view was it would have been optimal to work on a boat that was not in “active service mode” so workdays could be longer. The installation process was greatly hindered by having to mobilize and demobilize the job site every time the installer worked on the boat. Ideally the installation process would have proceeded more efficiently if the boat was out of “active service mode” for at least a 2-week period. Now that the project is complete and all parts are cataloged, the next installation will go more smoothly and more quickly for this retrofit vessel selection.

It was extremely beneficial to have several practice sessions beforehand. The practice runs helped the team sort out unforeseen issues and adjust settings on all systems. The July 31, 2019 demonstration established a game plan and helped the team scope out the area for the August 21, 2019 demonstration. Every time the vessel went out on the water everyone became more knowledgeable and experienced with the new control systems.

5.2 Recommendations

Autonomous and remote technology is important for spill recovery operations.

According to the many parties involved in this project, autonomy and remote technology aboard a Kvichak MARCO Boom skimmer is a representative use case for illustrating the value of autonomy on boats. Autonomy can be adapted to specific tactical tasks, taking certain controls and leaving others for either manual intervention or for belt pack remote operations.

Demonstrating autonomy aboard this type of workboat successfully met the goal of this project. It illustrated the safety benefits of using autonomy systems in repetitive operations and particularly in unsafe areas.

The U.S. Coast Guard should evaluate and work to establish CONOPS for inclusion of autonomous spill recovery vessels.

Discussions at the demonstration illustrated the potential and enhanced value of using autonomy in spill recovery operations. It was suggested that Coast Guards worldwide work with their counterparts to envision areas of use by autonomous vessels in the current spill response operational plans.

There is a need for professional maritime education and training in autonomy.

Representatives of maritime academies attended the August 21, 2019 demonstration to evaluate applications for their programs for training and research. The integration of autonomous technology into their education programs is deemed critical. Many expressed the need to fund and enable the purchase and installation of autonomy aboard some of their training boats.

Maritime educators worldwide are seeking support for increasing autonomy training for various operations aboard ships. Applying Artificial Intelligence (AI) and Machine Learning (ML) to autonomously controlled surface vessels is a growing field. It is evident to those in attendance that the US must become more current technologically to remain competitive in the global maritime marketplace. Developing curriculum to address new systems, technologies and techniques is required. An important part of this process is for educators to evaluate and understand the applications of autonomy in order to effectively train students.

In some instances, there is reluctance on the part of those in the maritime industry to adopt autonomy because they harbor concerns that its purpose is to replace jobs typically staffed by merchant mariners. That is not the case, autonomy can make the mariner’s jobs easier because they will be better informed about the many systems that are simultaneously operating. It may be true that some traditional (low tech jobs) may drop off while many new jobs will be created that will require specialized training in advanced systems. This is an exciting time to be working with students in the maritime field. There will be a great deal of new learning that must take place to fully realize the potential of all the different tasks that robotics and autonomy can bring to maritime operations.

The key value proposition that the autonomous spill response demonstration illustrates is that there are widespread opportunities and applications that can enhance safety and operational efficiencies in the oil spill response sector.

6.0 Acknowledgements

This project was a first of its kind. A creative, collaborative team was put together to ensure all aspects were professionally designed and installed. The MSRC spill response team lead by John Swift and Eric Wyman was extremely helpful and patient during the installation process. The installation contractor, Navtronics, worked tirelessly to ensure all systems were wired and interfaced properly on the boat to ensure turnkey operations. The autonomy and engineering teams from SMR provided excellent guidance on SM -300 systems and operational issues. Finally, the vision and support leadership by Dan Yuska, Michael Carter, Richard Balzano and many others at MARAD made this project of real value. Adoption of such new technology by the maritime community will take some time. MARAD is truly pioneering the adoption of advanced autonomous technology that will enable many improvements in marine transportation and beyond.