Title:
LSSU- UniBZ Collaborative Proposal for the 2022 RobotX Maritime Challenge

Prime Offerer:
Lake Superior State University, 650 W. Easterday Ave., Sault Sainte Marie, MI 49783, USA

Technical Contact:
Edoardo Ivan Sarda, Ph.D.
Assistant Professor, School of Engineering and Technology
Affiliate Faculty, Center for Freshwater Research and Education (CFRE)
Lake Superior State University, 650 W. Easterday Ave., Sault Sainte Marie, MI 49783, USA
Phone: (906) 635-2738 Fax: (906) 635-6663 Email: esarda@LSSU.edu

Administrative Contact:
Erica Newland
Office of Sponsored Programs
Lake Superior State University, 650 W. Easterday Ave., Sault Sainte Marie, MI 49783, USA
Phone: (906) 635-2272 Fax: (906) 635-6663 Email: enewland@LSSU.edu

1. Technical Approach and Justification

In close collaboration with the students and faculty from the Free University of Bolzano, advised by Prof. Karl von Ellenrieder (complementary proposal entitled UniBZ-LSSU Collaborative Proposal for the 2022 RobotX Maritime Challenge), we propose to develop the instrumentation, hardware and software for an Autonomous Maritime System (AMS) to complete the competition challenges outlined in section 1.31.2. UniBz will focus primarily on the research aspects that tie into the competition, including the design and simulation of the various algorithms essential to complete the competition tasks, including non-linear control, localization, mapping, and path planning. LSSU, as an undergraduate institution, will focus on implementing and testing UniBz designs and algorithms on the vehicle, thus providing data from field trials, in addition to integrating all the various subsystems on the AMS.

Within this section, the general approach to the competition, including a brief description of the essential subsystems that will be designed and integrated on the AMS, is first introduced in subsection 1.1, the technical approach to each individual task is then described in subsection 1.2, finally the timeline for system development and testing is given in subsection 1.3.

1.1. Approach

A WAM-V unmanned surface vehicle (USV) and an unmanned aerial vehicle (UAV) will be part of the AMS to compete in the RobotX Maritime Challenge. A systems engineering approach will be taken for the design of the Guidance, Navigation & Control (GNC) system and the propulsion system for the USV. A detailed exploration of the available sensors and their capabilities will be performed to select the most viable combination of visual-based navigation, Lidar, GPS and acoustic sensors. Similarly, trade studies will be performed to determine the best combination of propulsion system and actuators for maneuvering. Due to the complexity of the competition's tasks, requiring a high level of maneuverability, an over-actuated thrust configuration will likely be necessary.

The USV base platform, from which the UAV will be launched and recovered, will be propelled with twin electric drive propellers. Each hull will contain one stern-mounted thruster. The engine speeds will be controlled via pulse-width-modulated servo control. A 12 channel servo controller will be used to switch the control authority of the vehicle between a hand-held Remote Control (RC) transmitter and onboard computer control. Thus, it is possible for a user to override onboard computer control of the USV and manually control the vehicle if it is not operating as expected, or in an emergency situation. Depending on the final safety requirements, a second RC with similar functionalities will be devoted to the UAV, when it is flying.

The use of LiFePo or lead acid batteries will be explored for USV propulsion. Lead acid batteries will also power the electronics in the GNC box on the USV. Although LiPo batteries are lightweight and well-suited for unmanned systems, they are considered hazardous materials and can be difficult and costly to ship. Since the 2022 competition will be held at the Regatta Center, the magnitude of the wind and wave disturbances should not be as large as in previous venues, like in Hawaii, thus more alternatives in terms of power capacity can be considered. Lightweight LiPo batteries are still essential to fly the UAV, therefore such system will be shipped to Australia without batteries and the team will arrange to have the batteries purchased there before arrival.

LSSU will develop an in-house-built controller box for sensing and control. A Siemens Programmable logic controller (PLC), an embedded-processor, sensors, power monitoring and conditioning and communications electronics will be integrated within the control box. Wireless communication between a shore-based laptop and the AMS will be via RF transceiver and/or WiFi.

The low-level controller would be interfaced through Ethernet with a high-level planner and vision based navigation system through the PLC or the Robot Operating System (ROS) or a combination of both. While using ROS makes the GNC system modular, an industrial controller like a PLC would increase the overall robustness and it is often preferred in the industry, thus both alternatives will be explored.

The PLC will also control the actuation systems for the deployment and retrieval of the hydrophones during task 1 and for the payload delivery during task 5. The hydrophones' deployment and retrieval system will be based on the design of retrievable landing gear on planes. Therefore the hydrophones will be lowered in the water during the search, and retrieved out of the water when they are not being used, thus reducing the drag and the control effort on the USV. The payload delivery system will consist of a variable elevation "cannon", enabling control of shooting range. The "cannon" will be manually loaded and it will utilize the friction of rotating wheels to shoot the racket ball.

The high-level software is a real-time system with multiple threads: video processing, navigation, and task management happen concurrently. To deal with the complexity, a PLC will be used to determine which task needs to be executed and at what time. The PLC decides which task to activate and what to do when it is completed. The PLC will also manage the safety aspects of the system, including RC and E-stop.

The guidance control approach will consist of both reactive and deliberative elements. Reactive control uses only current information and can be computed quickly. Deliberative control requires full knowledge, may need longer time to compute, but can implement global optimization. Our approach will be an overlay of deliberative control with reactive control.

The AMS will sense its environment through the use of a modularized LIDAR and vision system, distributed between the UAV and the USV. The fusion of these sensors with other localization sensors, such as inertial measurement units (IMUs) and GPS, will enable the AMS to have a detailed understanding of the environment around it, as well as its state within the environment. Industrial grade Cognex vision systems will be utilized to extract and process visual information, which will be accessible by the PLC and through ROS. Lastly, the use of artificial intelligence algorithms to perceive the environment, localize with respect to objects (e.g. buoys, objects, docks, etc.) and avoid obstacles will be explored.

1.2. Competition tasks

The final goal is for the team to attempt each task with some level of confidence. A brief description of the autonomy challenges associated with each task that will drive the development of a navigation and control system for the vehicle is given below.

Task 1 - Entrance and Exit Gates: There are three major challenges associated with this task: 1) the WAM-V USV has a fair amount of windage, thus a fairly robust controller and trajectory planning system will be needed if there is a significant cross wind; 2) estimating the location of a beacon underwater requires data processing using multiple hydrophones, in addition to custom designed filters to eliminate sound reflections and reverberation; 3) Red/White/Green/Black color recognition may be difficult as the light conditions change throughout the day, thus some self-tuning image processing techniques will need to be integrated with the vision system.

Task 2 – Follow the Path: In addition to requiring robust performance of the path planner and low-level controller, it will be necessary to use a combination of vision, LIDAR and GPS to localize the USV with respect to the buoys and to correctly identify the closest set of buoys. Enabling the UAV to localize the USV within the buoy channel (map) should simplify the process, as the simultaneous localization and mapping is split in two separate tasks that don't necessarily need to be performed simultaneously (e.g. UAV creates the map first, then the USV is continuously localized within the map, thus reactive obstacle avoidance would enable the USV to avoid dynamic obstacles.) However, launching and recovering the UAV on the water represents a complex control problem that requires coordination and precision. Additionally, Red/Green color recognition must rely on slightly different image processing algorithms as compared to task 1, when observing the buoy channel from the top, but it is subject to the same level of disturbance due to lighting conditions.

Task 3 – Wildlife Encounter and Avoid: Identifying objects on the water surface is a challenge itself, which relies on the physical characteristics (color, shape, material, etc.) of the object, but distinguishing between different objects may require the combination of machine learning and image processing, thus a probabilistic approach. Since the UAV must again stay in the air to locate the wildlife, it is anticipated that it will be launched at the start of task 2 and it will not be recovered until task 3 is completed. Such approach would eliminate the need to launch and recover the UAV twice, but it would add a strict time constrain to perform task 2 and 3, as the UAV flight time is limited to its battery life.

Task 4 - Scan the Code: Identifying a color sequence is difficult for vision systems, depending on the frequency of light flashes, but it is even more challenging when the system is moving. For such task to be accomplished correctly, it is essential that the USV is able to autonomously station-keep and track the buoy slow motion, by positioning itself normal to the light. A fully actuated configuration is therefore mandatory for such maneuvers.

Task 5 - Dock and Deliver: In addition to the correct dock identification challenge, which could be solved by positioning the vision system at the right distance from the dock, performing the docking maneuver requires a collaborative effort from guidance, navigation, control and propulsion. In other words, the correct dock where the USV must go has to be extrapolated from the image, the control effort must be distributed to accomplish the desired maneuver with minimal error and the population must be powerful enough and fully actuated to sustain the control output. Finally, an additional actuation system must be implemented to deliver the payload.

Task 6 – UAV Replenishment: This task is by far the most challenging as it requires autonomous collaboration of a heterogeneous set of systems. Additionally, a UAV equipped with some form of manipulator or device to recover the item, will affect the UAV dynamics during and after the recovery, thus non-linear adaptive control techniques to accommodate for the changes in mass, inertias, drag and center of gravity is essential for the UAV to accomplish this task.

Lastly, the USV must be capable of autonomously avoiding obstacles, while also maintaining a steady connection to a ground station and the UAV, thus requiring safety and robustness.

1.3. Timeline

A summary of the work plan and associated timeline for this project is shown in the table below.

Phase - Time frame	Milestones
Phase 1: Analysis and Planning June-August 2021 (Summer 2021)	• Students recruitment: integration of RobotX projects within the curriculum at LSSU, through classes, labs, senior project and student's organizations • Research of technology and methodologies relevant to the tasks • Marketing and fundraising strategy • Development and acquisition of industry partnerships • Budget and other administrative tasks • Design and fabrication of propulsion system
Phase 2: System Development, Initial Testing, Fundraising and Virtual Competition September-December 2021 (Fall 2021)	• Design and development of navigation hardware, including power management and distribution and ground station • Design and implementation of the "payload" (racquetball) delivery system and hydrophones deployment and retrieval • Small scale manual tests in open waters: system identification and data collection • Basic development of low level autonomy • Research and strategy development for each task • Simulation of systems' performance • Software development for Virtual RobotX, including low and high level autonomy • Data collection for training/testing AI algorithms for basic obstacle avoidance • Initial AI testing in indoor pools • Website development geared towards fundraising and donations • Virtual RobotX competition
Phase 3:	• Design and development of control system • Design and development of guidance system

Final System Integration and Fundraising January-May 2022 (Spring 2022)	• Integration of all hardware for GNC • Improvement of algorithmic approach to the challenges, based on performance at Virtual RobotX and control optimization through research • Station-keeping control testing in indoor pool using artificial markers (no GPS) • Acoustic trials indoor, without the USV • Obstacles and support equipment fabrication and testing • Mirroring the construction of some LSSU-designed systems at UniBZ to support the development of the control and planning algorithms
Phase 4: Final Testing and Fundraising June-August 2022 (Summer 2022)	• In-water control tests: speed and heading control, trajectory tracking control test, optimized Station-keeping control (GPS + IMU + vision) • UAV trials on land and data acquisition • Acoustic target and navigation through gates field trial • Scan the code on the light buoy field trial • Autonomous docking and payload delivery field trial • UAV launch from the WAM-V on the water and landing on land • UAV launch and recovery from the WAM-V on the water • Follow the path, wildlife encounter field trials using the fully integrate AMS • UAV replenishment field trial
Phase 5: Shipping and Competition September - November 2022 (Fall 2022)	• Complete course field trials • Wrap up Journal article • Testing wrap up and last fund raising effort • Competition strategy definition, based on observed strengths • WAM-V shipped to Australia at least 30 days prior to the competition • RobotX Maritime Challenge

2. Team Qualifications

The proposed team will consist of students and faculty from UniBz and LSSU working together to address the technical and logistical challenges of the Maritime RobotX Challenge. Dr. Edoardo Sarda and Dr. Karl von Ellenrieder will be the faculty advisors from LSSU and UniBz respectively.

Dr. Sarda is experienced in the design and development of autonomous systems, including system integration and field testing. He teaches courses in mobile robotics, automated systems, machine vision, robotics technology and ROS. He was the team captain for the FAU/Villanova RobotX team in 2014, during which the team won 4 awards and he has competed in multiple RoboNation and ASME competitions, when he was a student. He was part of Dr. von Ellenrieder's research group at Florida Atlantic University, designing and testing non-linear controllers, including multiple station-keeping controllers for the WAM-V USV. He also developed an AUV launch and recovery system for the WAM-V USV. He has worked as research and development engineer in the field of mobile robotics, since 2016.

This partnership would combine UniBz's advance research in control and UAV autonomy; and LSSU's expertise in robotics engineering, systems integration, and applied education through technology. Furthermore, the cross-fertilization of ideas and technological approaches will be fostered by the international collaboration of students at UniBz and LSSU. The team will be very multidisciplinary and will include graduate and undergraduate students from multiple departments at both universities. At LSSU, students are represented from across three distinct schools: School of Engineering and Technology, including Robotics, Mechanical, Electrical and Computer Engineering; School of Business, including Marketing, Management, and Finance; and the School of Computer Science and Mathematics. Each participating student will be given the opportunity to contribute to the competition in areas related to his interest.

The team will also be able to draw upon the technical expertise of faculty, post-doc and engineering staff at both UniBz and LSSU, who have agreed to help as Team Associates in areas critical to the competition, such as mechanical and electrical engineering, control, vision, and systems engineering.

3. Facilities

The competition vehicle will initially be based at LSSU in Sault Ste Marie, MI as the facilities there make it more convenient to house and test the relatively large WAM-V USV. Specifically, LSSU's strategic location in the middle of the Great Lakes will allow students to explore novel USV applications. The Center for Freshwater Research and Educations (CFRE) on the St Marys River in between Lake Huron and Lake Superior will house the WAM-V USV.

CFRE possesses 4 boats that can be used to support testing in open waters, along with multiple trucks and trailers that can be used to tow the WAM-V USV and other equipment to different test sites. The nearby engineering building at LSSU also includes an electronics workshop staffed by an electrical engineer (Travor Bryant), and a Mechanical Shop with one full time engineer and machinist (Ron Throener). Both Travor and Ron will act as Team Associates for the effort. Lastly, a state of the art robotics laboratory includes more than 30 industrial, collaborative and mobile robots, equipped with vision systems and other sensing devices that can be used for the development of the AMS and to continuously progress on the RobotX project without having to be on the water. Specifically, 10 turtleBot 3 Waffle Pis and 4 MiRs, both running ROS can serve this purpose. Multiple identical industrial PLCs (Allen Bradley and Siemens) and vision systems (Cognex) are also available in the robotics lab and can be used for subsystems testing, without the need to disassemble the equipment on the USV.

In addition, two indoor swimming pools are available for basic USV testing: an Olympic style pool and a deeper dive pool. Obstacles pertaining to the various challenges could be set up in these pools for testing certain subsystems during the winter. To support the collaborative development of the autonomy, LSSU and UniBz will collaborate on the RobotX virtual competition as well. The simulation models developed for the virtual competition will aid the development of the guidance system and the low level controller that will then be integrated on the AMS.

4. Sponsorship and Partnerships

Partners and sponsors for the team that have agreed to support this effort thus far are listed below. Letters of support are also attached to this proposal.

Organization	Contact	Email	Phone
CFRE	Ashley Moerke, Ph.D.	amoerke@lssu.edu	+1 906 635-2153
NIWC Pacific	Travis Moscicki, Ph.D.	travismoscicki@gmail.com	+1 561 613-5316
L3Harris	Mario Miranda	mario.mirandaII@L3Harris.com	+1 407 766-6744
LSSU SET	Paul Weber, Ph.D.	pweber@lssu.edu	+1 906 635-2031

Additionally, every year, the School of Engineering and Technology at LSSU receives multiple project proposals, funding, equipment donations, scholarships from different industry partners, such as Textron Aviation, Corning, Nexteer, 3M, Continental, 4D Systems, AMT, JR Automation and others. All of these companies regularly hire LSSU graduates and support LSSU engineering financially, and providing technology and human resources. Given the nature of the project, system integrators such as JR Automation and AMT can often be of assistance for application or integration specific challenges.

5. Management Approach

LSSU and UniBz have complementary expertise and have divided the functions accordingly. They will have shared web folders for exchange of all data, repositories for parallel software development on GitHub, and host virtual meetings via Zoom twice a month. The use of ROS will make it possible to develop modular software, thus both partners can contribute to this aspect of the project.

Testing of the subsystems on the vehicles will go through a parallel process, during which the hardware will be designed and implemented on the USV, while guidance, navigation and control software is simultaneously developed and tested using the virtual environment. UAV launch and recovery trials will first be performed on land. By the time all subsystem hardware is ready to go in the water, the software should be at a level that will enable for minimal low-level autonomy.

At LSSU, students will be recruited through the integration of RobotX-related tasks within regular classes, labs, senior projects, student's clubs and community engagement through the Career Technical Education and FIRST robotics program at the local high schools. Specifically, Engineering Research Methods is a course that we often use at LSSU to attract students in specific area of research. This will be the starting point from which students that are passionate about RobotX and the WAM-V will decide to bring their class project into student's clubs thus exposing RobotX to a broader group of students, including other majors. This aspect is crucial to raise the necessary amount of funding, as marketing, management and finance students can boost the efforts in this area. Lastly, the integration and testing of the WAM-V autonomy for the competition can be made into an internal senior project, which would guarantee academic rigor and a complete solution, as students in senior project at LSSU are required to meet an acceptance criteria defined by the faculty before they can graduate. In this regard, other student competitions projects have been successful at LSSU when tied to a specific senior project.

The majority of testing of the integrated AMS will be performed nearby the CFRE facility of LSSU as it is located directly on the St Marys River with immediate access to calm, sheltered freshwater. The team will alternate the University where the USV is based after every competition. This would allow for the vehicle to be equally shared between both parties, providing opportunities for students' hands-on experience at both Universities, and equally splitting the costs associated with shipping the AMS.

6. Rough Order of Magnitude Cost

Considering the resources already available and/or invested at LSSU and UniBz (labor, hardware, software), the total estimated cost for LSSU to attend the competition is about $80K, as shown in the table to the right. Additional funds will be raised through fundraising and University support to bring 2 or 3 team members to the RobotX Forum in 2021, if held in person. The opportunity to participate in the RobotX Forum will be used to attract students and stimulate interest in the Virtual RobotX competition, thus supporting the overall RobotX challenge. About the same amount of funding is expected to be raised every two years, to keep the systems up to date and develop the technology for new challenges and tasks associated with the competitions.

Item	Cost ($)
Airfare (10 members)	20000
Hotel (10 members - 12 days)	11000
Shipping to Sydney	7000
Food (10 members – 12 days)	7500
Transportation in Sydney	1500
Motors	6000
Electronics	5000
Acoustics	5000
Mechanical hardware	2000
UAV related items	10000
Batteries	2000
Misc.	3000
TOTAL:	**80000**

7. Summary

LSSU and UniBz are proposing to collaborate on the design and development of an AMS to compete in the 2022 Maritime RobotX Challenge and to acquire the necessary resources to participate in the competition in Sydney, Australia in November 2022. UniBz will focus on the research aspects of the project, including some of the UAV control aspects, path planning and control of the AMS, whereas LSSU will lead the system integration and testing of the AMS. LSSU and UniBz also plan to form a competitive team for the 2021 Virtual RobotX Competition. This collaboration will be strengthened by partnership with representatives from the government, industry and other academic institutions. Overall, we believe that the combination of hands-on education and advance applied research can materialize in this international collaboration, therefore we look forward to working towards this effort.