A Wave Adaptive Modular Vehicle (WAM-V) for George Mason University participation in RobotX 2022

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1.0 Technical Approach and Justification

To accomplish the challenge tasks enumerated in the 2022 RobotX Task Ideas document, three senior-level, multidisciplinary, capstone design teams will be formed, supplemented by extracurricular student volunteers and mentored by technical experts listed in Section 2.1 of this proposal. One capstone team will focus on navigation, taking the lead for Tasks 1 and 5, and providing support to Tasks 2-4. A second capstone team will focus on sensing, thus leading for Tasks 3 and 4, and supporting Tasks 2 and 5. The third capstone team will emphasize UAV integration, taking the lead for Tasks 2 and 6, and supporting Task 3. A multidisciplinary team of faculty will lend unique expertise toward the core technology areas needed to accomplish the prescribed tasks, as described in more detail in Sections 1.1-1.5.

1.1 Vision, Sensing, and Sensor Fusion

Drawing off historical team designs (Norris *et al*, 2019; Oksne et al, 2020), as well as the sensors available in the Virtual RobotX competition (RoboNation, 2019), it is anticipated that a baseline sensor suite for vision and sensing will include stereoscopic camera(s), LiDAR, sonar, a global positioning system (GPS), and an inertial measurement unit (IMU). Additional accelerometers may be used for structural monitoring and in support of motion predictions.

We will utilize the Joint Directorates of Laboratories (JDL) Data Fusion Model to systematically implement multi-model sensor fusion capabilities for sense making and perception. The JDL Data Fusion Model lays down a framework for collecting low-level raw and processed data from sensors of different modalities and fuses it to reduce uncertainty in estimates and establish high-level situational awareness in a sensed domain. First, we will develop an ontology of the sensed domain of WAM-V operations and establish situational awareness requirements such as detecting and classifying wildlife, codes, landmarks and images. Second, we will implement both the low-level and high-level information extraction and fusion algorithms to meet these requirements. Finally, the situational awareness obtained from sensor fusion will then passed on to the planning and guidance functions.

1.2 UAV Integration

The inclusion of an operationally independent UAV shifts the problem domain of WAM-V capability development from a monolithic system design to a system of systems engineering (SoSE) challenge. SoSE principles recognize the operational independence of multiple geographically distributed systems that collaborate to achieve novel goals. Here, both the UAV and WAM-V are operationally independent and have their individual goals (e.g., UAV must maintain stable flight within its operational environment) but remain interdependent to achieve the overall mission success.

SoSE focuses on the subtleties that emerge from independent operational environments of interdependent systems and examines the compound impact on mission outcome of various consideration such as different functional allocations and information availability/connectivity requirements in distributed systems. We will combine the SoSE approaches with well-established systems engineering techniques to study, design, implement, and test the UAV integration with the WAM-V. This approach will allow us to include a wider set of design consideration for implementing solutions and assessing their efficacy and robustness, e.g., these considerations include questions such as what level of hyperspectral imaging processing is performed on-board the UAV (raw data vs fused information or situational awareness) and how it interacts with the communication requirements between UAV and WAM-V; how far the UAV may venture out before losing connectivity (range) and how far in advance the WAM-V needs access to UAV information (timeliness); how are range and timeliness requirements impacted by the nature of information provided by the UAV (raw data vs situational awareness) *etc.*? We will examine these and other similar questions using Model-based Systems Engineering methods.

Furthermore, the UAV-integration challenges provide opportunities for demonstration of concept of previous host vessel motion prediction for launch and recovery operations research (e.g. k-NN algorithms, neural networks, etc…) conducted by members of this WAM-V proposal team (see, for example with surface vessel launch and recovery, Cooper and McCue, 2017).

1.3 Planning

The team has extensive expertise in planning having developed numerous state-of-the-art approaches to plan collision-free and dynamically-feasible motions that enable UAVs, surface vehicles, and ground vehicles to accomplish increasingly complex tasks (McMahon and Plaku 2021; Warsame, Edelkamp, and Plaku, 2020; Le and Plaku 2018; Wallar, Plaku, and Sofge 2015). These methods have been shown to work not only in physics-based simulations but also in field deployments.

We will build upon these approaches to develop our planning module, which will incorporate information from the UAV and plan the vehicle motions so that they can accomplish their assigned tasks safely and efficiently. Specifically, our vision is for the UAV to build a map of the environment that includes the location of the red/green buoys as well as any of the obstacles. The path-planning module will rely on state-of-the-art sampling-based approaches to build a roadmap that captures the connectivity of the environment. The roadmap is constructed by sampling waypoints at random throughout the environment, and connecting neighboring waypoints with edges, discarding those waypoints and edges that are in collision. Afterwards, the path-planning module searches the roadmap in an A* fashion to find a path that goes through the red/green buoys while maximizing clearance from the obstacles/buoys. Once the path is computed, it will be converted into a (dense) sequence of waypoints that is passed to the controller module, which will then navigate the WAM-V from one waypoint to the next. The advantage of this approach is that the computation is done in real-time (based on our experience the roadmap construction and path search can be done in the order of milliseconds). This allows the path-planning module to adapt the path as new information comes in from the UAV, e.g., when detecting new obstacles or updating the location of the buoys.

1.4 Guidance & Control

A mature body of research exists to build upon for modeling, guidance, and control of an autonomous catamaran (Caccia *et al*, 2008) and a WAM-V in particular (Baldini, *et al*, 2019; Klinger, 2014; Klinger *et al,* 2017; Pandey & Hasegawa, 2017, 2018; Qu, 2016; Sarda *et al*, 2016). Amongst the first operational decisions that will directly affect controller design will be selection of propulsion system. The RobotX Resource Library (RobotX, 2021) provides a valuable summary of propulsion examples including waterjets, integrated trolling motors, and external trolling motors (RoboNation, 2014). Those selections will have a direct impact on controller design and system cost.

Amongst the team of faculty listed in Section 2.1 supporting this effort, there is deep expertise in guidance and control of subsurface, surface, and air vehicles, including for underactuated nonlinear systems such as lighter-than-air vehicles competing in the 99++ LuftBalloons competition hosted by ONR shown in Figure 2, right (McGinnis, 2021) and with perception and interpretation functions (Sherry *et al,* 2020). A canonical guidance and control architecture for this project, adapted from Sherry *et al* (2020) is shown in Figure 1.

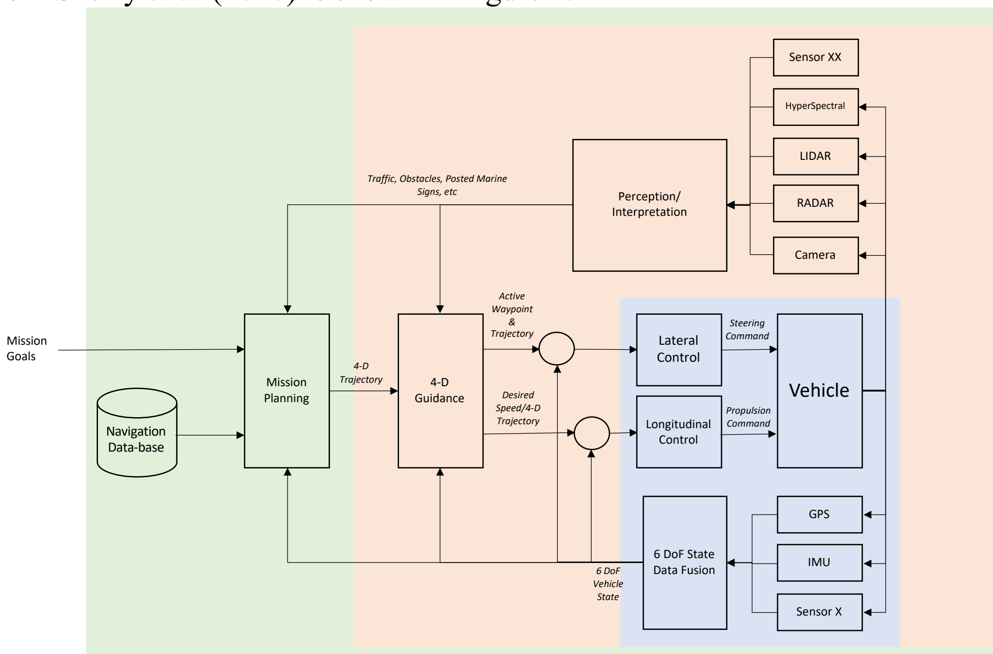

Figure 1: Guidance and control system for non-sterile environment, adapted from Sherry *et al* (2020)

1.5 Application to Challenge Tasks

To accomplish the six challenge tasks, three capstone teams will be formed with specific emphasis on navigation and obstacle avoidance, sensing, and UAV integration. Each team will require integration between the four functional areas described in Sections 1.1-1.4, though particular emphasis will be delineated as follows:

Functional Area	**Team**	**Task Leadership**	**Task Support**
1.1 Vision, Sensing, and Sensor Fusion	Sensing	Challenge Task 3: Wildlife Encounter and Avoid Challenge Task 4: Scan the Code	Challenge Task 2: Follow the Path Challenge Task 5: Dock and Deliver
1.2 UAV Integration	UAV Integration	Challenge Task 2: Follow the Path Challenge Task 6: UAV Replenishment	Challenge Task 3: Wildlife Encounter and Avoid
1.3 Planning 1.4 Guidance and Control	Navigation	Challenge Task 1: Entrance and Exit Gates Challenge Task 5: Dock and Deliver	Challenge Task 2: Follow the Path Challenge Task 3: Wildlife Encounter and Avoid Challenge Task 4: Scan the Code

2.0 Team Qualifications
Mason has existing strengths within the Volgenau School of Engineering and School of Computing with respect to autonomous systems and robotics in air and maritime domains. This proposal represents a collaborative effort leveraging the expertise of faculty in Computer Science, Electrical and Computer Engineering, Mechanical Engineering, and Systems Engineering and Operations Research, as well as existing student organizations with a passion for robotics.

2.1 Participating Faculty
- Monson Hayes, Chair, Department of Electrical and Computer Engineering. Area: digital signal processing.
- Jana Kosecka, Professor, Department of Computer Science. Areas: visual sensing, object recognition, scene parsing, and human-robot interaction.
- Leigh McCue, Interim Chair, Department of Mechanical Engineering. Areas: naval engineering, maritime autonomous systems, testing.
- Cameron Nowzari, Assistant Professor, Electrical and Computer Engineering. Areas: dynamics, robotics, analysis and control of complex systems and spreading processes, artificial intelligence, machine learning.
- Erion Plaku, Associate Professor, Department of Computer Science. Areas: motion planning, marine robotics, computational robotics, human-machine cooperation, artificial intelligence, logistics operations.
- Ali Raz, Assistant Professor, Systems Engineering and Operations Research and Visiting Faculty for Naval Surface Warfare Center (NSWC) Crane. Areas: sensor fusion, systems of systems integration, requirements, and testing
- Lance Sherry, Associate Professor, Systems Engineering and Operations Research. Areas: requirements, interface design & control, system integration, testing, planning, guidance and control.
- Daigo Shishika, Assistant Professor, Mechanical Engineering. Areas: cooperative control, swarming.
- Gregory Stein, Assistant Professor, Department of Computer Science. Area: robot planning.

2.2 Potential Participating Student Organizations
- SciTech Robotics (VEX Robotics), Department of Mechanical Engineering hosted, based out of Mason's SciTech campus in Manassas. Faculty advisor: Daigo Shishika
- BOT Robotics and Automation, Registered Student Organization, based out of Mason's Fairfax campus. Faculty Advisor: Cameron Nowzari

3.0 Facilities
The Mason departments and faculty referred to in the prior section have access to multiple mechatronics and robotics laboratories and test facilities between the Fairfax and SciTech (Manassas) campuses to enable sensor prototyping, development, and testing. These facilities have been used to successfully prepare teams for ONR competition (Figure 2, right). The Department of Mechanical Engineering has a full-service machine shop on the SciTech campus staffed by a professional machinist to support fabrication needs associated with student capstone and research efforts (Figure 2, left). The waterfront facilities of Mason's Potomac Science Center on the Occoquan River provide an optimal open-water testing ground for the full system in preparation for competition (Figure 2, center).

Figure 2: Department of Mechanical Engineering Machine Shop (left), Potomac Science Center (center), remotely controlled blimp retrieving and moving a green ball through the orange square hoop identified by the QR code as part of the 99++ LuftBalloons competition hosted by ONR (right)

4.0 Sponsorships and Partnerships

The Mason team expects to reach out to members of the College of Engineering and Computing advisory board, as well as the represented departments' advisory boards for potential industry partners on this activity. Members of these advisory boards are listed at the following websites: College of Engineering and Computing, https://volgenau.gmu.edu/partners/advisory-board; Computer Science, https://cs.gmu.edu/community/advisory-board/; Electrical and Computer Engineering, https://ece.gmu.edu/connections/advisory-board; Mechanical Engineering, https://mechanical.gmu.edu/people/advisory-board; Systems Engineering and Operations Research, https://seor.gmu.edu/people/advisory-board.

Through an existing educational partnership agreement with the Naval Surface Warfare Center (NSWC), Carderock Division, the Mason team will seek to provide RobotX team members introductions to autonomy experts at NSWC Carderock; existing faculty relationships will be leveraged to provide introductions to personnel at NSWC Crane & Naval Research Laboratories. This project will support robotics student pipeline efforts in the region, as reflected in the attached supporting letter from Prince William County Schools. Faculty named in Section 2.1 have current or past research that could align to these activities from external sponsors including the Office of Naval Research (ONR) and National Science Foundation (NSF).

5.0 Management Approach

Approximately 15 senior level undergraduates will be recruited to this effort under the required two-semester capstone design course sequence during the 2021-2022 academic year. Three interdisciplinary teams will be formed to provide the ability to specialize in navigation, sensing, or UAV integration, with the faculty mentors named previously providing technical oversight and mentoring. Each capstone team will have a team leader, with the three team leads meeting regularly to ensure system compatibility and integration. The three team leads will be tasked with developing a plan of action and milestones (POAM) targeting development of a viable, competitive vessel for the 2022 competition. Furthermore, it is expected that extracurricular volunteers will be drawn from existing robotics clubs at Mason, who can further support development, integration, and fundraising activities. Due to logical synergy between the previously mentioned faculty members' research groups, it is anticipated that graduate student support and engagement will naturally align as the platform becomes a testbed for graduate level research activities, which further support participation in the competition. By aligning the project to the 2021-2022 academic year, the Mason team will have the summer of 2022 to resolve any integration issues and conclude testing prior to shipping the vessel to Australia for the November competition. Throughout the duration of the project, and working in partnership with Mason's Office of Research Integrity and Assurance, a tracker of all sensors, hardware, and software integrated onto the WAM-V platform with corresponding Export Control Classification Numbers (ECCNs) will be logged in order to facilitate documentation required for transportation outside of the United States.

6.0 Rough Order of Magnitude Cost

Expected costs are enumerated in Table 1 below.

Type	**Description**	**Approximate Cost**	
Travel	Shipping (by air to competition, by sea return)	$	10,000
Travel	Airfare for 10 people	$	20,000
Travel	Lodging for 10 people, 7 nights (2 to a room), using 2021 State Department per diem for Sydney, Australia	$	8,400
Travel	Meals and Incidentals for 10 people, 7 nights, using 2021 State Department per diem for Sydney, Australia	$	10,850
Hardware	Propulsion	$	20,000
Hardware	Sensors	$	50,000
Hardware	UAVs	$	2,000
Hardware	Replacement parts/spares	$	5,000
Software	Software licenses	$	10,000
Capstone	Navigation Team - Misc.	$	5,000
Capstone	Sensing Team - Misc.	$	5,000
Capstone	UAV Integration Team - Misc.	$	5,000
	Total:	**$**	**151,250**

Table 1: Rough order of magnitude costs for participation in RobotX 2022

7.0 Summary

While there would be significant catch-up required to be a top-performer against teams that have been participating in this program for years, we feel that the combination of expertise brought to this project by Computer Science, Electrical and Computer Engineering, Mechanical Engineering, and Systems Engineering and Operations Research faculty involved in robotics and autonomous systems, coupled with enthusiastic student support via capstone and extracurricular participation, will make for a competitive team. Drawing off established partnerships and research programs, we will effectively leverage current and future efforts to develop the Mason WAM-V into an effective autonomous vessel and versatile research platform.

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Subject: Support of the GMU WAM-V and the RobotX Challenge from K-12 student Pipeline
Date: Tuesday, April 20, 2021 at 3:20:02 PM Eastern Daylight Time
From: Denyse M. Carroll <CarrolDM@pwcs.edu>
To: Leigh Mccue-weil <lmccuewe@gmu.edu>

Prince William County Public School's robotics program has a monthly meeting with Engineering Department at George Mason University. The monthly meetings started because we discovered that we were both doing similar things but did not know the other was doing the same thing. Now we can work together in collaboration and resource sharing.

Our meetings have already increased communication between the K-12 schools (PWCS) and higher education (GMU) to not only share projects, but also to share resources, networking connection, and we have been able to brainstorm out of the box thinking between both the K-12 and the University level students. Interfacing with George Mason University is a way to hand technical students from our high school level engineering robotics students directly into the Engineering pipleline for future GMU students. Keeping our public-school students local at GMU, in conjunction with our local partners with engineering internships, will hopefully allow us to keep the engineering students in Northern Virginia vs. moving to other states like California and New York to find high paying technical jobs.

If Mason had a WAM-V to field teams for the RobotX challenge, this would further support our collaborative pipeline activities between the robotics students in K-12 to the college level and real-world engineering conceptions in industry.

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Tell me, I'll forget
Show me, I'll remember
Involve me, I'll understand