Final Report
Tracking Trends in Undersea Autonomy

PI: Thomas B Curtin, Ph.D.
Applied Physics Laboratory
University of Washington

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Introduction

The annual Autonomous Underwater Vehicle Student Competition (AUVSC) (now called RoboSub) celebrated its 25th anniversary in 2022. RoboSub has been very successful gauged by the tens of thousands of students who have participated over the years and graduated to productive careers.

AUVSC was originally envisioned as a competition in which students learn and practice system engineering, exercise creative problem solving, forge collaborative relationships, and develop interest in autonomous underwater vehicles. Student competitors learn:

- System engineering design involving multi-disciplinary, problem solving teamwork
- Competitive-collaborative balance in accomplishing goals
- Underwater autonomy skills measured by specific tasks
- Underwater application of methods from the robotics community
- Hands on engineering skills meeting the challenges of an underwater environment
- Documentation/presentation skills and peer networking including technical conferences
- Opportunities to apply new technologies not yet incorporated into core academic curricula

Sponsors learn:

- Trends in autonomy software within communities of practice
- Trends in autonomy hardware driven by 3D printing and cross-domain components
- Measures of autonomy based on task design and diversity of performance
- Best practices for identifying and attracting engineering talent to underwater autonomy

The evolution of RoboSub is a success story in many ways. In the original partnership, AUVSI (subsequently AUVSI Foundation, now RoboNation) provided logistical support and ONR provided technical direction. Without exception over 25 years, the logistical support has always been excellent. The event itself has always enjoyed an energetic vibe with a healthy balance between competitiveness and collegiality. People enjoy participating, interacting with the students and embrace their assigned roles with enthusiasm (judges, staff, divers, volunteers). The format, tasks, in-water performance (consistently disappointing), and prizes have all settled into a routine.

Valuation Analysis

The International Autonomous Underwater Vehicle Competition, inaugurated in 1998, was subsequently re-branded RoboSub (RS) in later years. For brevity, the event regardless of year will be referred to as RS throughout this valuation analysis.

During the first half of its lifetime (1998 - 2010), RS was of increasing value to the Navy. The UUV Master Plan was revised to include lightweight and man-portable systems. New start-up companies (e.g., Hydroid, Bluefin) emerged from Academia. Three new underwater gliders made their debut and were successfully assimilated into the academic and Naval oceanographic communities. MCM, EOD and SOF operators embraced and refined the technology for a range of missions. Software and hardware standards were few and component technologies were decreasing in size and power.

Government and industry employers actively recruited many alumni of the competitions who could often save a year of training for them due to their system engineering and teamwork experience in RS. These alumni can be found today in mid-career positions throughout Navy Labs and industry. During this period, RS was relatively small (< 20 teams), almost all teams were from the US or Canada, and the logistics overhead cost was manageable. Tasks and venues varied from year to year (for a awhile). The creativity of the competitors was reflected in the wide diversity (sizes and shapes) of vehicles fielded. With the combination of modest cost, changing challenges and productive interaction with Navy-related employers in the rapidly growing field of unmanned systems, RS proved to be of substantial value to the Navy with a high return on investment.

During the second half of its lifetime (2011 - 2022), RS's value to the Navy has decreased.
Four factors contribute to the diminishing value.

The first factor is inefficient management of growth. From its humble beginnings (4 teams), RS has expanded to over 50 teams in recent years. RS is a competition, first and foremost. RS today accepts any registrant regardless of competency. The result is an annual event fielding vehicles that range from inoperative to highly sophisticated. Qualifying is done on the spot extending the event by several days, necessitating several practice courses to be set up, and eliminating many teams from further in-water participation.

No doubt, the range of team expertise on-site provides a great learning opportunity for less experienced students and creates a collegial atmosphere that can be energizing and contagious. Essentially RS has evolved into more of an international summer camp than a capstone world-class competition. This hybrid identity is confusing. Both summer camps and high-level competitions have merit and serve different purposes. Doing both together well is difficult in less than a week. Operating educational summer camps can be a laudable and lucrative business itself. Financial sustainability is attained for summer camps typically by participants paying a substantial fee (tuition) to attend. What has evolved in RS is a hybrid in which sponsors pay the fee for a truncated camp culminating in a weak competition.

All world-class competitions are based on a qualifying process to insure only the best teams participate in what should be a capstone, showcase event. Such a process enables the event to be run efficiently with less supporting resources than the hybrid version. Additionally, the championship event is much more spectator friendly with more action and less dead time. Also the qualifying process provides an opportunity for involvement of ocean engineering and technology professional societies (see factor three below).

The second factor is that the chosen tasks, which have not changed substantially in recent years, represent only a small subset of potential autonomy tasks, many of which are of more relevant to Navy missions. The current tasks are primarily vision-dependent (optical) putting a large premium on image processing algorithms. Reliance on this perception modality is attractive since cameras are cheap and sophisticated software is available. The downside of this approach is that teams tend to spend considerable amounts of time and energy training and tuning vision algorithms while often neglecting the basic navigational competency of their vehicle. Symptomatic of task invariance is the similarity of vehicle design. Almost all vehicles now take the structural form of an ROV with six or more thrusters and a high drag frame, ideal for hovering-type tasks such as salvage operations and some mine neutralization techniques. However, many operational Navy AUV's are not in these categories and their challenging limitations are not being addressed in the competition. RS's return on investment for the Navy increases to the extent that participants (the future workforce) gain insight and experience related to diverse and mission-relevant tasks.

An important missing component of RS has been a technical advisory committee or board of professional maritime engineers to vet and help design the tasks that are the heart of the competition. This event is singular among robotic competitions in its focus on underwater autonomy. Many tests of underwater autonomy can be imagined and the ones of most interest to the sponsors should take priority. In the case of the Navy, tasks relevant to real ocean missions are of primary interest. What has evolved is that the competing teams of students themselves serve as an ad hoc advisory committee to the TD providing input (through an online forum) about their likes and dislikes of proposed tasks. This incestual process is completely independent of sponsor input and has resulted in only incremental changes to the tasks over the last decade. The current tasks are heavily vision oriented, and while they include some functional tests of underwater autonomy, they leave most of the challenges in underwater autonomy unaddressed. That the current process leads to incremental change is to be expected since most students (the advisers) prefer to tweak their existing designs rather than create something new. This tendency is reinforced by the fact that there is no qualifying infrastructure to work through (debug the design) before showing up at the main event. Ironically, the consistently excellent logistical support has grown in many creative ways but has masked the stagnant technical evolution imbedded within it. Clearly, the lesson learned is to support sponsor-oriented technical guidance and task development separately from support for logistics.

The third factor is a disconnect with the professional community of undersea roboticists who define the state-of-the-art through their research as reflected in peer-reviewed journal publications and conference proceedings. The potential for participants to graduate into professional career paths will be significantly enhanced with the involvement of MTS and IEEE/OES in the qualifying process through their local chapters and in the awards process through opportunities for journal publication, travel to conferences and visits to laboratories in academia, government, and industry. RS has evolved to date devoid of this formal involvement, and has instead encouraged a parallel community of robotic enthusiasts. Such communities have merit in stimulating early education STEM interest, an important national goal. Given that such basic STEM education is being supported by many organizations, the specific return on investment for the Navy is at higher levels and is related to the seeding of existing communities of practice at the professional level.

The fourth factor is a significant shift over the years in the ratio of US citizens to non-US citizens among the participants. Since its inception RS has always been billed as (and initially named) "International". (RS has spawned similar competitions in Asia and Europe.) While diversity is clearly advantageous in many acknowledged ways, the potential for Navy workforce development derived from the pool of participants clearly decreases as the citizen/non-citizen ratio decreases. This ratio has been decreasing steadily in recent years. For example, in recent years, Chinese, Russian and Singapore teams have consistently outperformed their US competitors and been awarded Navy-funded prize money. This trend could be meaningful or at least informative if there were a common performance baseline (e.g., universal qualifying procedures) for entry. In reality, some international teams are subsidized by their governments, whereas US teams tend to be self-supporting. Regardless, if the above ratio goes to zero, the Navy's workforce return on investment in RS will also go to zero.

Without some corrective action (e.g., as described in the third factor above), RS data from recent years indicate the ratio continues to decrease.

Valuation Analysis Conclusion

In today's world, the need for skilled system engineers to maintain the Navy's competitive advantage in unmanned systems has not diminished. Competitions remain an extremely effective way of identifying, encouraging, and capitalizing on talent. Reversing the trends of RS's deceasing value to the Navy has proven to be difficult. This is exacerbated by the cultivation of a RS brand identity, which is resistant to change. A more productive path for the Navy is the initiation of a new competition with its own focused identity that accounts for the four factors above and has a value proposition that once again justifies the investment. Possible foci include micro-vehicle performance, vehicle-vehicle interaction, energy limitation and management, underwater navigation, adaptive behavior with environmental uncertainty, and sparse, latent communication. Elements of a new competition (AUVSC-NEXT) are described below.

Venue

The AUVSC venue changed annually for the first few years, and many lessons were learned. In recent years, the event was staged at TRANSDEC, which is logistically and environmentally comfortable, but increasingly unaffordable. The 25th event was held at the University of Maryland. Much effort has been expended over the years in searching for suitable, if not ideal, venues. The challenge involves combining water body size, availability, supporting infrastructure, competitor- and spectator-friendly access, affordable accommodations and convenient travel options. Size/weight penalties were introduced in the rules (one of the early lessons learned) and have been progressively adjusted downward. With smaller vehicles, the tasks and overall mission layout can be made more compact, enabling a wider range of possible venues.

Vehicle Size

Advances in technology continue to support more compact designs with their associated ease of deployment in affordable venues. These trends are driven by advances in smart phone technology, 3-D printing, small, efficient brushless motors, miniaturized inertial and GPS navigation units, inexpensive cameras, multi-spectral electromagnetic and acoustic sensors, high energy density batteries, digital radios, wi-fi bandwidth, open source software and libraries of downloadable applications. These trends are likely to continue. A highly capable underwater vehicle can now be constructed in a form factor not much bigger than a cell phone or tablet computer. As the size of a vehicle decreases, teams are challenged to be creative in their designs. Large, expensive components are eliminated, thus leveling the playing field. Multiple vehicle solutions to accomplishing tasks become feasible and attractive. In-water testing becomes easier and available in more places, thus increasing reliability. Useful toolboxes are more affordable and more likely to be available. The cost of shipping and associated potential damage is greatly reduced. AUVSC-NEXT maximum vehicle weight will be 23 kg in accordance with National Institute for Occupational Safety and Health lifting guidelines (https://www.cdc.gov/niosh/docs/94-110/).

Tasks

Initial AUVSC missions consisted of tasks demonstrating a vehicle's capability to navigate a well-defined course and perform basic maneuvers. Missions in subsequent years have been derived incrementally from the previous year's experience, with tasks added to include in-situ decisionmaking and some intervention (e.g., dropping/picking up objects). In recent years themes have added narrative coherence to the tasks and provided identity to the annual events. While this evolution has been successful in attracting teams, it has not been constructed in the context of a comprehensive autonomy framework and has not directly addressed many current Naval and commercial applications. AUVSC-NEXT will consist of nine tasks, one in each of nine successive years. The complete set of tasks will be published initially so teams can plan years ahead.

Toolkits

Size considerations aside, there are advantages and disadvantages to both common platforms and free-form platforms. Common platforms shift creativity from hardware innovation to control skill, strategy and tactics. Free-form platforms allow a full range of imaginative hardware designs, perhaps at the expense of robust control algorithms when development time is limited. Hardware diversity is more spectator and media friendly. For student competitions, a disadvantage of free-form platforms is the tendency for teams to re-invent standard components. While re-invention is pedagogical, such learning has opportunity costs in time, a precious commodity for full time engineering students. Better for students to direct their energies toward high-level system engineering and autonomy programming. A compromise between standardized and free-form vehicles can be achieved through the use of toolkits. Teams will have the option of purchasing (or perhaps being awarded) a basic developer's kit containing building block components of a compact underwater vehicle.

The process of determining the contents of a developer's toolkit is an exercise in defining vehicle modularity and interface standards. As with all aspects of the competitions, feedback from users will help refine and debug this process. The combination of greater reliability and less cost for vehicle components will enable teams to be more competitive from the start. Since the components can be assembled in different ways, design flexibility is retained. The kits themselves also provide a convenient mechanism for sponsorship. Vendors can contribute kit components at a discount or sponsors can finance an entire kit for a team. Possible contents of a developer kit include: thrusters, underwater connectors, pressure cases with end caps, waterproof actuators, low level software (e.g., motor controllers, open source algorithms), navigation components (e.g., compass, IMU, pressure sensor), acoustic homing device, wireless communication device and various sensors. Part (or all) of a developer's toolkit could also be simply downloadable CAD files for a 3-D printer. AUVSC-NEXT will define the contents and costs of basic and advanced developer's toolkits and identify sponsor candidates to populate these toolkits.

Growth

AUVSC has grown significantly over the years, despite minimal marketing. Currently, some effort is expended during the year in defining the mission, drafting and refining the rules, constructing task-related apparatus, and arranging for logistics and media, but the primary effort by far is concentrated during the weeks of the main event. Managing growth sustainably, improving team performance and reaching a wider audience calls for a more evenly distributed effort over the year than has been implemented to date. Each team is required to submit a journal paper that describes the design of their vehicle and the rationale behind their design choices. The paper is a valuable element of the competition and improvements in content and style have recently been implemented. Harmonization with IEEE poster paper requirements will facilitate presentation and citation of these papers at Conferences. Each team is also required to submit a video that introduces the team and their approach to the event. AUVSC-NEXT will establish qualification milestones that can be achieved locally (facilitated by IEEE/OES and MTS Chapters) throughout the year leading up to a final capstone event for pre-qualified teams.

Management Structure

Analysis of RoboSub cost growth over the years reveals an increasing imbalance between the level of effort supporting technical development (autonomy tasks) and the level of effort supporting administration and logistics. Some of the latter costs are related to the increasing number of teams. The rules and tasks that measure underwater autonomy and the design, fabrication and testing of associated in-situ equipment are the heart of the competition, yet receive relatively little support. The RoboSub management structure in recent years (Fig. 1) may explain this imbalance. Technical development has resided with the Technical Director who, while highly competent, has been somewhat isolated with little support throughout the year except during the event itself. Some communication and feedback are provided by online forums, but this falls far short of the potential input available from the global community of AUV professionals.

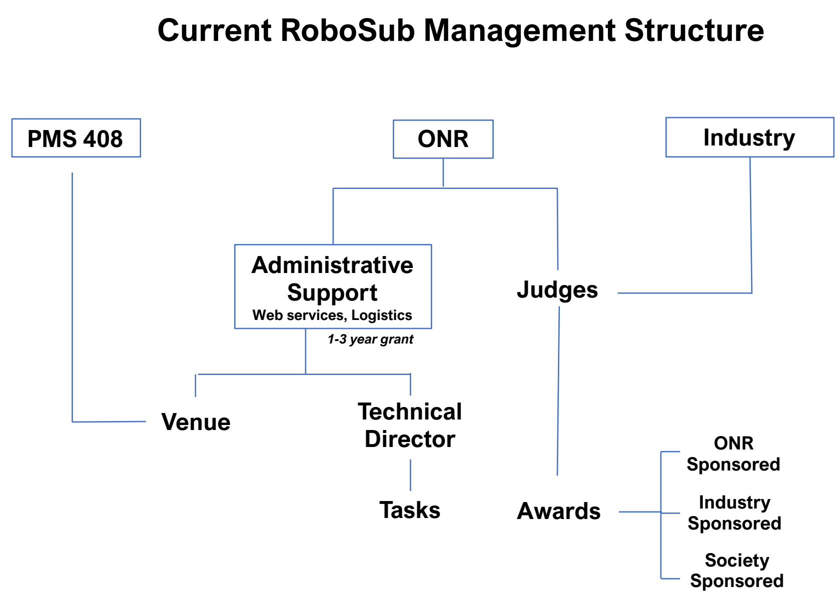


Figure 1. RoboSub management structure in recent years.

The management structure for AUVSC-NEXT (Fig. 2) is designed to better maintain a balance among the technical, logistical and financial aspects of the competition. Funds flow through a selected grantee or contractor. All sponsors, as well as academia, have representation on the Technical Executive Board in proportion to their level of support. The Board plays a pivotal role defining strategic directions: science and engineering challenges, geographic distribution of venues, rules/Technical Director, judges, awards, policies, and procedures. Sponsors will likely want to field tasks most relevant to their applications, and also to nominate judges to help identify promising student prospects. The Technical Executive Board is the avenue to achieve these goals.

The Board contracts with an Event Management Company via a master management service agreement for all general contractual and legal terms, and with individual Statements of Work or Services Purchase Orders for business aspects of each event (deliverables, itemized costs, responsibilities of parties). The budget includes liaison with qualifying events. Qualifying events are facilitated by local chapters of IEEE and MTS. The Technical Executive Board also coordinates with other related AUV competitions.

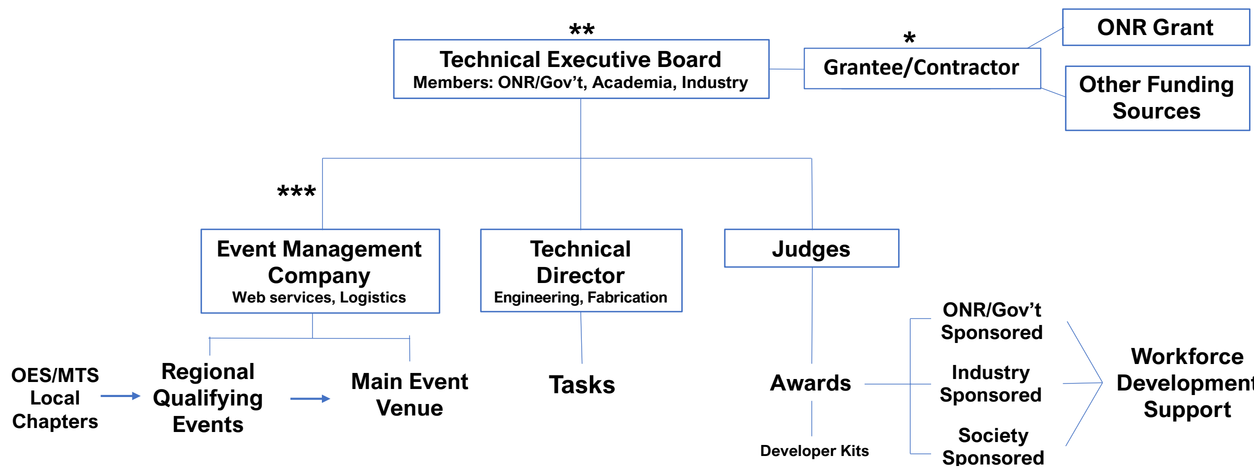


Figure 2. Proposed AUVSC-NEXT management structure.

Partnering

A natural partnership to explore going forward is one with MATE, a long-running, highly successful underwater competition with related logistical, administrative and technical needs. Many ROV and AUV tasks are complementary, and it is not hard to imagine constructing tasks best accomplished with a range of vehicles working together. MATE already has a Divisional Structure based on performance capabilities and regional qualifying events. This infrastructure could be capitalized on in a partnership.

The MATE 2019 competition was held at the King County Aquatic Center in Seattle. Discussions with MATE organizers and the Director of the Aquatic Center have indicated enthusiastic support for a coordinated event. The entire facility could be made available for a week for a very reasonable cost. MATE competitions are typically held at different venues in subsequent years. Recently, various municipalities across the country have been bidding to host the event which they view as greatly benefiting local schools and businesses. Since there is competition to host the event, the cost has been low and much local support is provided. AUVSC-NEXT should explore partnering with MATE and other related competitions as part of a long-term sustainable business model.

Budget

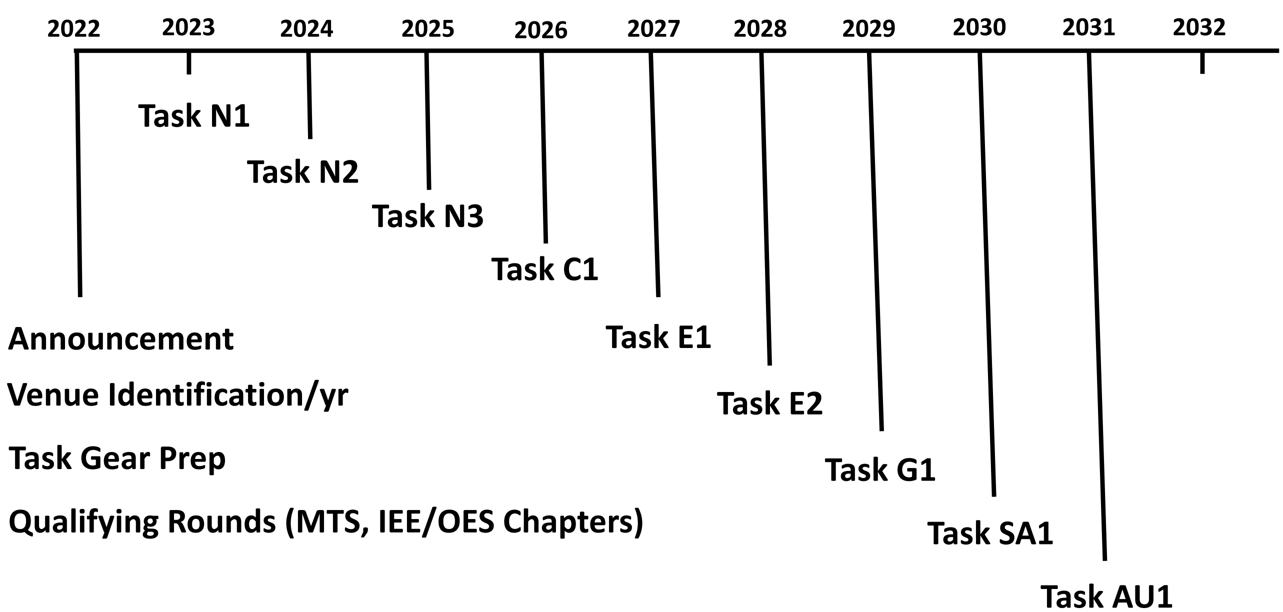
Line items:
Competition venue
Publication charges
Travel
Website

Advertising
Awards
Career tracking efforts
Internships
Yearly Report
Task-related hardware
Event-related hardware (e.g., large monitors, cameras)
Equipment Rental (e.g., tents)
Journal costs: flat fee for open access
(Total: about $300K)

Rules

AUVSC NEXT tasks change significantly year to year. Teams electing to compete in successive years need to substantially re-design their systems to meet new challenges. AUVSC NEXT will focus on one primary task each year. The primary task schedule will be published up to ten years in advance enabling teams to plan and build for specific tasks. Teams that score points in nine successive years will be recognized with a distinguished special award including lifetime memberships in MTS and IEEE/OES for all participants.

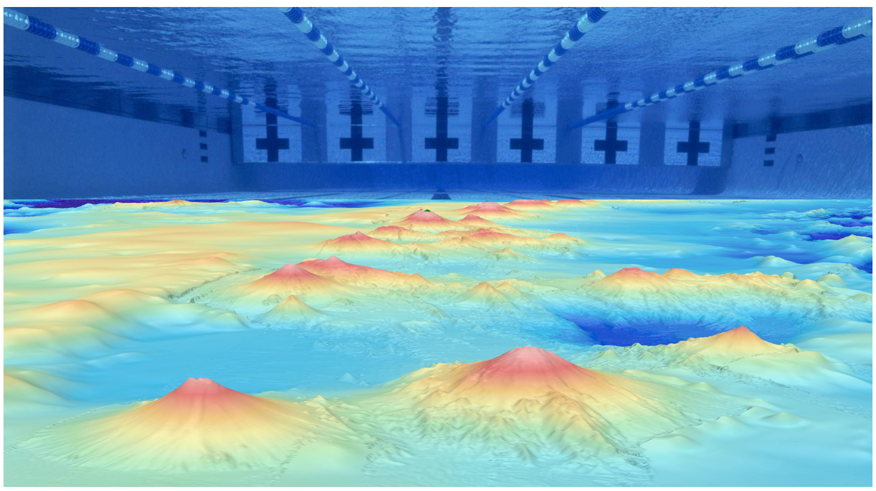
Schedule of Events



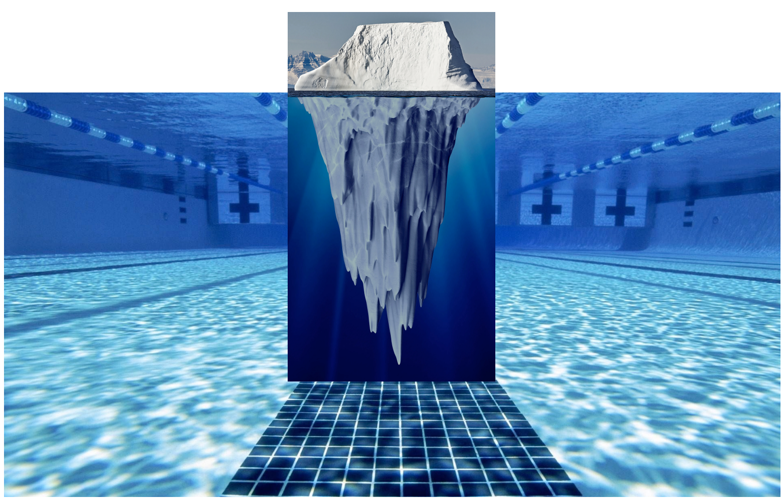
Navigation-Related Tasks

Underwater navigation can utilize magnetic fields, gravitational fields, and bathymetric features. Variable bathymetry can be used in several ways to test the navigation skill of a vehicle. For example, a bottom area could be fabricated with a known roughness spectrum and singular anomalous features. Mapping such an environment to the degree necessary for accurate location may be fundamental to a vehicle's operation.

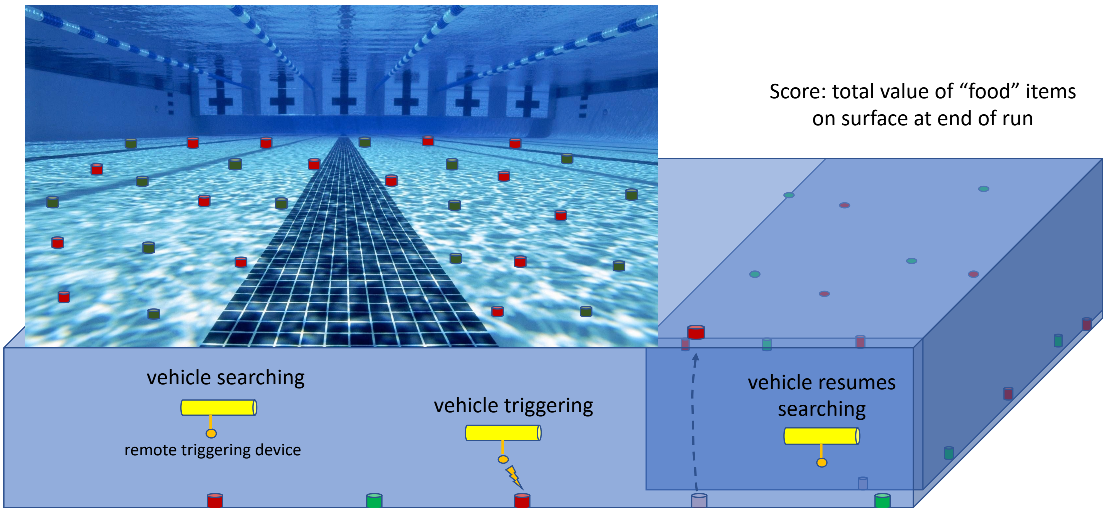
Task N1: locate and mark the deepest (or shallowest) point in the arena in the fastest time. Embedded patterns may provide clues.



Task N2 : determine the mass of a surrogate iceberg floating in the arena. The density of the "iceberg" is uniform and given.



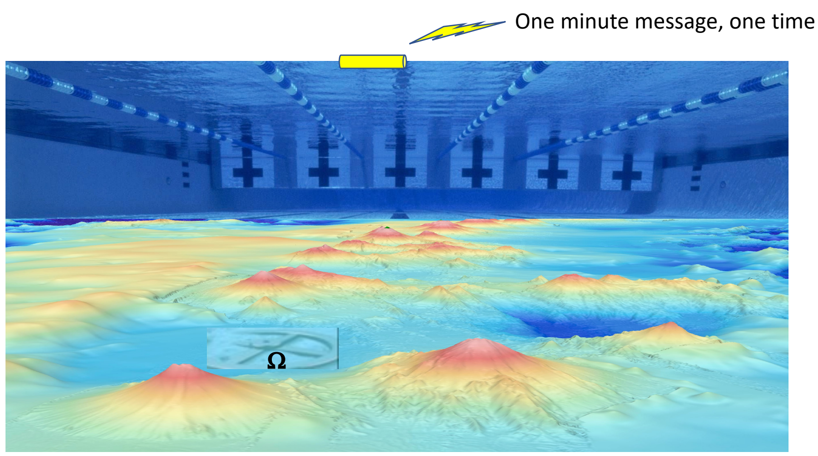
Task N3: Forage for "food" distributed on bottom. Some items have more value than others. Vehicles assume the role of hunter/gatherers. The team with the most "food" survives and wins.



Communication-Related

What distinguishes autonomous from remotely operated vehicles (ROV's) is the amount of communication between the operator and the vehicle. Total autonomy with no communication is of limited practical utility. Clever use of sparse communication in achieving a mission is a test of the interplay between vehicle and human intelligence.

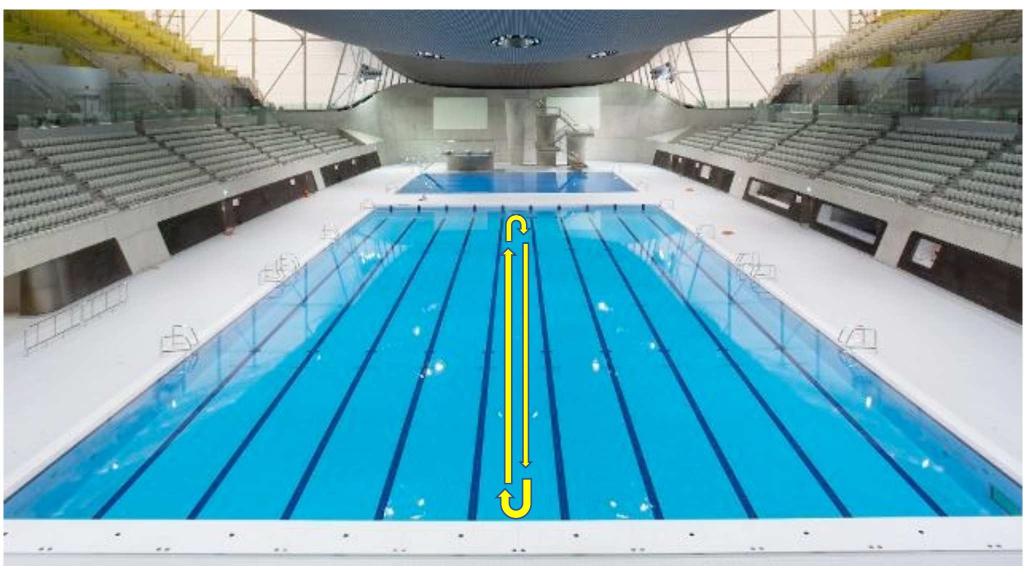
Task C1: while surveying the bottom looking for "anomalies", the vehicle is allowed to surface once at any time to communicate with the operator for one-minute only. The signature of the anomaly will be made available to the operator only after the vehicle initially submerges. Identifying the anomaly will likely require multi-modal sensing. Single mode false alarms will be present The goal is to locate the anomaly.



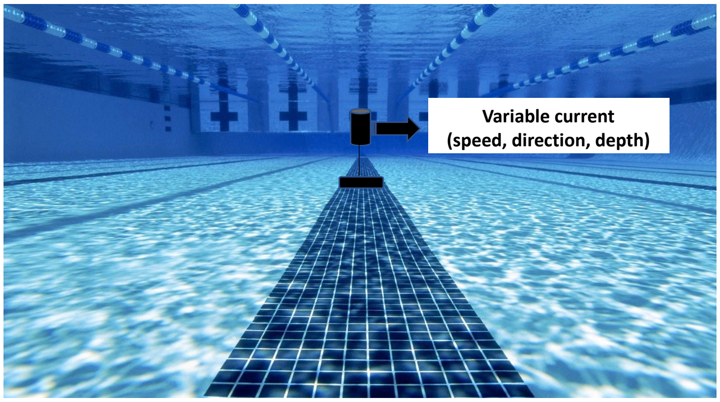
Energy-Related

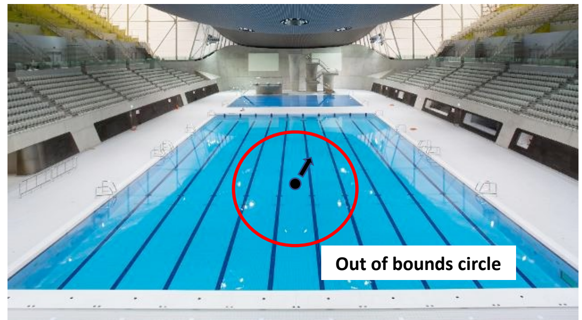
Energy is a limitation for all mobile platforms. Competitions to date have used COTS batteries, and missions have been short enough that onboard energy has not been a limiting factor. In contrast, competitions focused on energy conversion, energy distribution and energy efficiency can be envisioned. Energy is commonly stored in one form for ease of transport, and then converted to another form to do work. Energy is also a spatially distributed quantity. Sources include other mobile platforms (e.g., tankers), caches at fixed positions (e.g., gas/docking stations), the kinetic and potential energy of the surrounding medium (winds, currents, buoyancy), radiation (e.g., solar, geothermal, nuclear), and chemical, electrical and thermal potentials (e.g., redox gradients in mud, electrical fields, thermal gradients). Some sources are easier to harness than others. Energy management in practice is a combination of mobile and fixed sources. Given a fixed amount of onboard energy, transport efficiency (kilogram/joule/meter) is governed by drag, propulsion efficiency and buoyancy control.

Task E2 (energy conversion): swim the highest number of laps in a swimming pool powered solely by 100 grams of glucose with no constraints on the size, shape or configuration of the vehicle.



Task E1 (energy conservation): stay within a 5 meter circle centered on a fixed subsurface buoy in a pool with a variable, ambient current for the longest period of time utilizing all available energy sources. Crossing the circle perimeter ends the run.

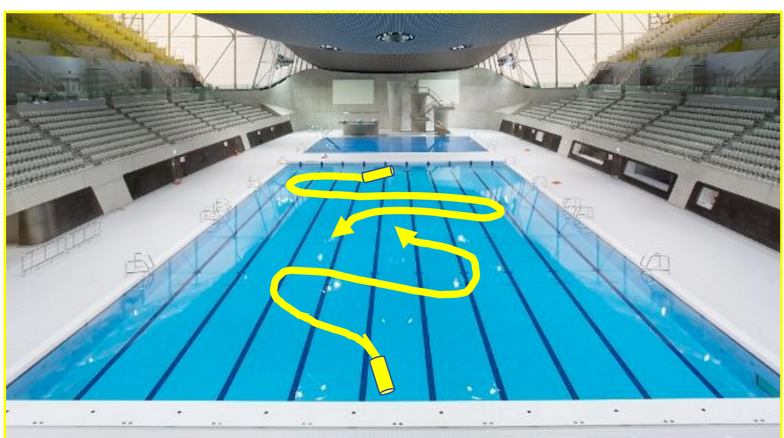




<u>Gaming-Related</u>

The introduction of multiple vehicles enables gaming possibilities in which competing vehicles from different teams interact simultaneously to gain an advantage.

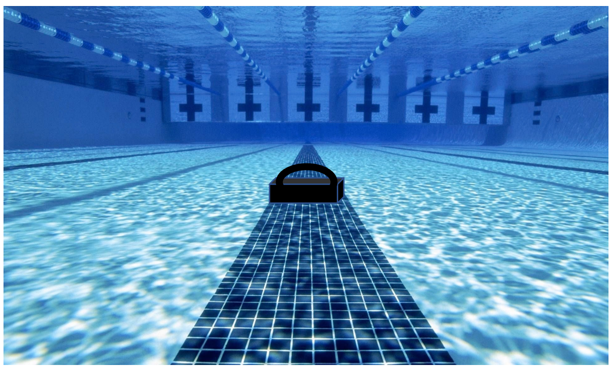
Task G1: one vehicle attempts to traverse the pool from one end to the other, while the opposing vehicle attempts to prevent it from reaching the goal line in the time allotted .

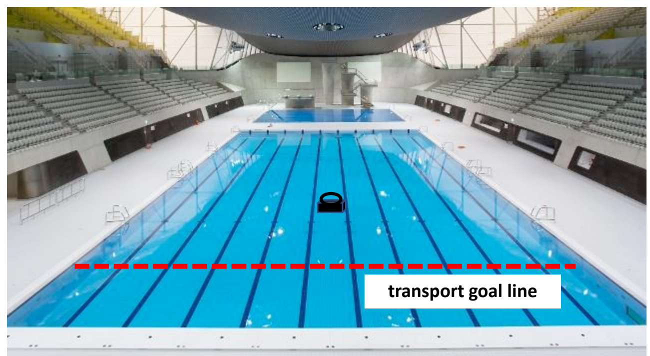


Self-Assembly-Related

The deployment of large platforms in the field is often logistically demanding and expensive. A more manageable approach is to construct a large platform in-situ from smaller components that are capable of self-assembly and re-configuration.

Task SA1: assemble a vehicle capable of lifting a heavy object off the bottom and transporting it underwater to a fixed location.





Adaption with Uncertainty

Most tasks to date have involved localizing, recognizing and interacting with an active beacon, light, or visual pattern independent of other tasks. With correlated tasks, what is learned in completing a task, is necessary or helps in completing other tasks. One simple test of autonomy is executing a decision tree by completing conditional or correlated tasks in a benign environment. This test is essentially solving a cueing problem. Another test of autonomy is optimally completing several uncorrelated tasks in a noisy, uncertain environment. This test is essentially solving an adaption problem. Both problems are critically constrained by time.

Task AU1: the goal is to traverse from one end of the pool to the other through a field of "ghost" fishing nets that are drifting randomly and extend vertically to various depths.

Oscillating (side-to-side) nets. Random variables: oscillation frequency, net depths)

Appendix A
Frequently Asked Questions

What are the differences between RoboSub and AUVSC NEXT?

How do teams qualify for RoboSub and AUVSC NEXT?

RoboSub is an annual, catch-all event with no required pre-qualification to enter. Qualification to advance can be accomplished on-site at the event or through an optional video submission. AUVSC NEXT is an annual, capstone event in which only pre-qualified teams compete. Pre-qualification is accomplished through certification by a participating MTS or IEEE/OES Chapter.

What underwater autonomy skills are needed for RoboSub and AUVSC NEXT?

The primary skills needed for RoboSub are visible image recognition, object manipulation, and acoustic homing. Minor details vary annually, but the basic skill set remains the same. The primary skills needed for AUVSC NEXT include adaptive navigation and perception, maneuvering with under-actuated platforms, energy efficiency, response to environmental uncertainty, obstacle avoidance and multi-team gaming. The primary skill set needed for AUVSC NEXT varies with each capstone event.

How do the awards differ between RoboSub and AUVSC NEXT?

RoboSub awards have ranged from $7K for first place to $2-3K for third and fourth places. Smaller amounts are sometimes awarded for noteworthy achievements. AUVSC NEXT awards will include full-time graduate student support, and fellowships for visits to AUV labs around the world. A goal of the AUVSC NEXT awards is to provide opportunities for outstanding students to develop professional relationships with leading researchers in autonomous systems.

How do teams prepare for RoboSub and AUVSC NEXT?

RoboSub tasks change only incrementally from year to year, so teams tend to develop a multi-year plan of development leading to platforms of increasing complexity with accumulated expensive components and expanding software. AUVSC NEXT tasks change significantly year to year, so the teams competing in successive years need to substantially re-design their systems to meet new challenges. AUVSC NEXT will focus on one primary task each year. The primary task schedule will be published up to ten years in advance enabling teams to plan and build for specific tasks. Teams that score points in nine successive years will be recognized with a distinguished special award including lifetime memberships in MTS and IEEE/OES for all participants.

How much do RoboSub and AUVSC NEXT represent real-world scenarios?

RoboSub tasks relate to typical work performed by ROV’s as reflected by the open frame, multi-thruster configurations that dominate. AUVSC NEXT tasks relate to sampling, surveillance and reconnaissance missions in the ocean that are typically performed with streamlined vehicles with single or dual thruster configurations. AUVSC NEXT tasks and time constraints will be constructed to reward efficient designs.

What are the venues for RoboSub and AUVSC NEXT?

RoboSub in recent years has been held exclusively at TRANSDEC in San Diego, an attractive venue for many reasons (but increasingly expensive). AUVSC NEXT will be held at various locations hosted by MTS or IEEE/OES Chapters or other supporting sponsors or municipalities. AUVSC NEXT arenas will be Olympic-size swimming pools and vehicle sizes will be limited to one-person portable.

How are the competitions scored?

RoboSub teams are primarily evaluated on task performance in the water, according to a published rubric including subjective metrics ("judges' discretion"), plus a "static judging" score based on a written paper and oral (including video) presentations summarizing the design approach. AUVSC NEXT teams will be evaluated based on a written paper, objectively measurable accomplishments in the pool, and originality as assessed by the publication criteria of MTS or IEEE/OES conferences and journals.

What is the intended participant demographic of the competitions?

RoboSub, originally targeted at university undergraduate/graduate students, has evolved to include a wide range of students including an increasing number of high and middle school teams as the underlying COTS technology becomes more accessible and affordable. AUVSC NEXT is primarily targeted at university graduate students interested in using the competition to develop, test and evaluate publishable work in autonomous maritime systems and establishing a career in the field.

What are the design constraints on entries?

RoboSub entries are weakly (via penalty points) constrained in volume size (54 cubic feet) and weight (125lbs). There is no defined limit to a vehicle’s on-board power reservoir. AUVSC NEXT entries will be more tightly constrained in size and weight, which will motivate design choices regarding energy efficiency and endurance. There may be additional explicit design constraints for each specific event.

Appendix B
AUVSC NEXT Among Robotic Competitions

Since AUVSC's inception 25 years ago, the world of robotic competitions has expanded immensely. In general, robotic competitions test machine performance with defined rules of play. At least, four major Types of competitions can be identified (Fig.A1):

(1) Learning Exercises designed to teach system engineering through task accomplishments;
(2) Grand Challenges that push performance envelopes with extreme objectives;
(3) Games in which robots compete against each other simultaneously to score points; and
(4) Combat in which robots battle against each other to disable the opponent.

Robots in each type of competition may be autonomous or under human control. Autonomous robots primarily test programmed behaviors and independent adaptability, whereas those under human control test operator skill and the human-machine interface. AUVSC is a Type 1 robotic competition based on autonomous, constrained free-form, underwater vehicles.

Some competitions use a common vehicle for all participants, primarily testing the strategy, tactics and skill of the operator. Others allow free-form vehicles which tends to heavily weight the design and performance of the vehicle itself. A middle ground that tests both design and skill utilizes a constrained free-form vehicle. Integral to vehicle specification are the dimension and location of the competition arena, which must be logistically manageable. AUVSC requires a body of water large enough to field several underwater tasks, yet small and accessible enough for task performance to be observed and judged conveniently. To provide more options for viable venues, AUVSC vehicles have been constrained in size and weight, but have otherwise been free-form.

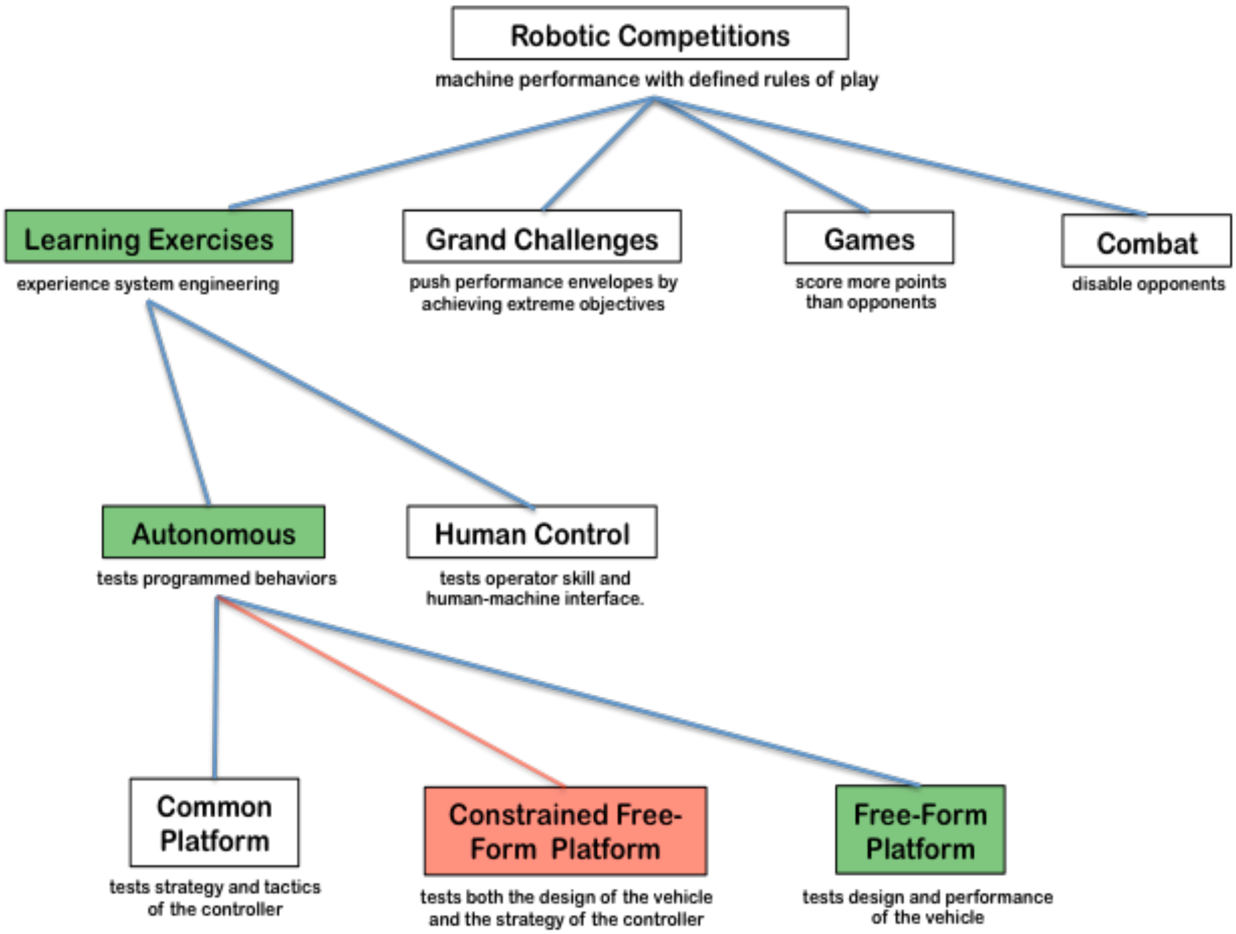


Figure A1. Taxonomy of Robotic Competitions.

Appendix C
Tasks as Measures of Autonomy

A common thread through all definitions of autonomy is independent, adaptive behavior. In real, complex environments, various combinations of autonomous behaviors can prove to be effective in accomplishing a task. Is there a best set of such behaviors (best practices) that is most effective? Since all mobile platforms consume energy, one measure of “best” might be accomplishing the task with minimum energy. Another measure might be accomplishing the task in minimum time. Another measure might be accomplishing the task safely in a hazardous situation or contributing positively to the survival of a group.

Accomplishing a specific task generally requires a combination of core competencies that characterize a vehicle’s autonomy. At the highest level, these core competencies are navigation, perception, object deployment and retrieval, survival, planning and communication (Fig. B1). Examples of familiar tasks requiring combinations of primary and secondary core competencies are shown in Fig. B2. Tasks in a specific competition will test different core competencies, and different competitions can be compared in this way. The international growth in size and number of autonomous underwater vehicle competitions motivates the establishment of a set of benchmark tasks that serve as common measures of autonomy. Such a set of tasks can provide a basis to compare different competitions, and perhaps normalize them as qualifying events for a world championship.

Autonomous Mobile Vehicle Competencies													
Navigate			Perceive Objects			Deploy Objects		Survive		Plan		Communicate	
Localize	Transit Toward Objectve	Maneuver	Identify Stationary Objects	Identify Moving Objects	Interact with Objects	Deliver Payloads		Adapt to Environment		Prioritze Tasks Decide to Act		Transmit / Receive Data	
			map fields	track, target	manipulate	spatial coverage	precise location	avoid obstacles	withstand extreme events	single objective, simple constraints	multiple objectives, complex constraints	remote montoring and control	local cooperative behavior

Figure B1. Autonomous mobile vehicles core competencies.

				Tasks					
Autonomous Mobile Vehicle Competencies	1	Navigate	ability to localize, transit to a waypoint and maneuver	**X**	x				
	2	Perceive Objects	ability to sense and identify stationary and moving objects and recognize patterns (maps, tracks, targets)	x	**X**	x			
	3	Deploy/Retrieve Objects	ability to deliver payloads and recover items of interest		x	**X**	x		
	4	Survive	ability to sense and adapt to the environment, avoid danger and weather extreme events	x	x	x	**X**	x	x
	5	Plan	ability to optimize cost/benefit and plot a path ahead in complex, uncertain situations.	x	x		x	**X**	x
	6	Communicate	ability to distill data remotely, transmit critical information on demand and coordinate with other platforms					x	**X**
				pass though a constriction (e.g., "go through a gate")	identify piece-wise continuous features (e.g., "pipeline") with clutter	deliver an object to a specific location (e.g., drop a marker in a bin, hit a target)	develop a search pattern based on observed structure (bootstrap search)	multiple tasks with changing priorities as functions of time and risk	adjust communication frequency and latency based on detections
Level of Skill	A	Expert		follow a bottom feature (e.g., ridgeline, isobath)	identify anomalous discrete features with clutter	pickup an object at a specific location (e.g., "back box" ELT)	sample in sensitive locations to maximize forecast skill (targeted observations)	energy management (onboard, distributed, renewable)	
	B	Competent		develop a map based on features (e.g., self localization)	fuze perceived features into patterns and maps		adjust track based on wind and currents (fuel efficiency)	coordination of multiple, cooperating vehicles	
	C	Functional		maintain a course with no reference frame input (e.g., dead reckoning)	map a complex object (e.g., ship hull inspection)			maximize system persistence	
				path planning (waypoint navigation)	identify an object with a unique signature by multi-sensor fusion			optimize sensing modalities to decrease false alarms	
				search as a function of available energy	follow a discontinuous or transient track			adjust spatial sensing aperture to increase gain and focus	
				terminal homing on a fixed object (dock)	coordinate with other autonomous vehicles			intercept a target from several directions simultaneously	
				terminal homing on a moving object (re-fueling)	change the position of an object (e.g.,turn a valve)				
					repair or service an object (e.g., clean an anchor chain, connect new unit)				
					destroy an object (e.g., neutralize a mine)				

Figure B2. Examples of tasks requiring combinations of primary and secondary core competencies.

AUVSC missions to date have been structured around the world of discrete objects. Future missions should address the challenges of interacting with continuous fields and of managing performance limitations (Fig B3), and include a wide variety of tasks that are closely aligned with real-world autonomous underwater vehicle operations, as well as future research directions in autonomy.

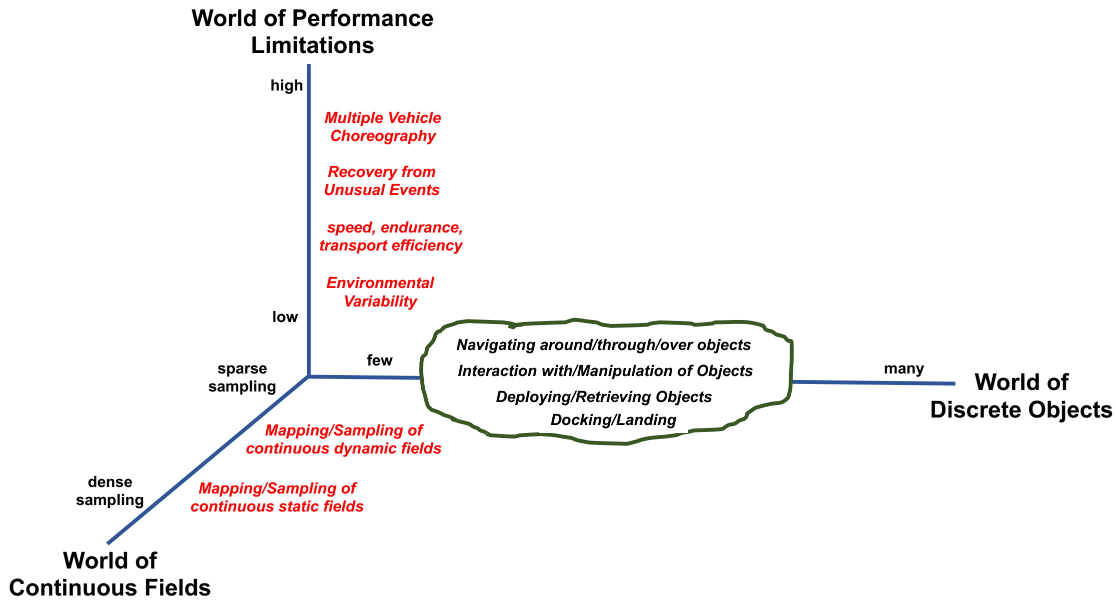


Figure B3. A world view of autonomous underwater vehicle tasks. Most competitions to date Have occurred in a benign world of well-defined discrete objects.

Appendix D
Autonomous Marine Vehicles Competition Committee

Normalization of autonomous vehicle competitions is being pursued through the Autonomous Marine Vehicles Competition Committee (AMVCC) formed in March 2017. The committee grew out of informal discussions at recent Oceans conferences about the growth of robotic competitions over the past 20 years and their demonstrated value. The U.S. Office of Naval Research (ONR) has supported the competitions since their inception. Recently, the IEEE Oceanic Engineering Society (OES) has restructured internally to focus more on marine robotics competitions, reflecting the interests of OES membership. At the AUV Symposium (AUV 2016), University of Tokyo, OES agreed to fund a two-day kickoff meeting and University of Porto was selected as the location.

Participants in the initial meeting included competition organizers and technical directors, industry experts, research engineers, government laboratory personnel and past participants. Attendees spanned the globe with representatives from India, Singapore, Japan, China, Australia, Canada, Scotland, France, Germany, Spain, Croatia, Scotland, Sweden, Ireland, Italy, Chile, Argentina, Portugal and the United States. Attendees included representatives from the following competitions:

- Eurathlon/SAUC-E/European Robotics League (ERL) - Europe
- Students Autonomous underwater Vehicle - India (SAVe)
- RoboBoat – U.S.
- RoboSub – U.S.
- Maritime RobotX Challenge – U.S.
- National Marine Vehicle Design and Development Competition - China
- OI China Underwater Robot Competition - China
- Singapore AUV Challenge - Singapore
- Student Autonomous Underwater vehicles Challenge - Europe (SAUC-E)
- Underwater Robocon – Japan.

Working together, the group established a governing board and drafted a charter: "*the international Autonomous Marine Vehicle Competition Committee is a group with a committed interest in coordinating, improving and expanding the quality and value of autonomous marine systems student competitions.*" Autonomous marine systems include vehicles in, on or above the water. Members of the newly formed board identified efforts for the group to initially focus on: a common lexicon, benchmarking fundamental tasks of autonomy, guides for uniformly scoring tasks, common procedures and metrics for static judging, technical resources for competitors and mentors, and mechanisms for knowledge transfer as teams turn over.

The AMVCC is envisioned to be a forum for the exchange of knowledge and ideas among all involved in sponsoring, managing and supporting autonomous marine vehicle student competitions around the world. Involvement of OES strengthens the connection to professional development and provides a place for peer-reviewed and other recognized technical publications. Participation in the competitions has clearly impacted the careers of a generation of engineering students to date, and that trend is likely to continue. The Committee is committed to supporting student professional development and community interaction through special sessions and events at conferences and a website hosted by OES. Consistent with this approach, the Committee plans to convene at existing symposia, conferences and competitions each year, capitalizing on established community events.

All members of the Committee contributed to the Workshop discussions and output. They are acknowledged here in alphabetical order. Greado Acosta (U. Buenos Aries), Gianluca Antonelli (U.di Cassino), D. Atmanand (NIOT), Ralf Bachmayer (Memorial U.), Anne Bajart (EU), Julie Banner (US Navy), Dick Blidberg (Consultant), Zoz Brooks (Consultant), Marc Carreras (U. Girona), Kelley Cooper (US Navy), Nuno Cruz (Porto U.), Thomas Curtin (APL/UW), Janelle Curtis (AUVSI Foundation), Daryl Davidson (AUVSI Foundation), Daniel Deitz (US Navy), Vladimir Djapic (Consultant), Tom Drake (US Navy), Esteban Escobar (5:00 Films), Shuangshuang Fan (Zhejiang U./ U.Tasmania), Fausto Ferreira (CMRE), Gabriele Ferri (CMRE), Hayato Kondo (Tokyo U.), David Lane (Heriot-Watt U.), Richard Mills (Kongsberg), Rick Nagle (Consultant and Workshop Scribe), David Novick (RoboSub), Felix Pageau (RoboBoat), Venugopalan Pallayil (Nat.U. Singapore), Yvan Petillot (Heriot–Watt U.), Bill Porter (US Navy), Aamir Qaiyumi (Robot-X), Pere Ridao (U.Girona), Robert Simmons (US Navy), Hanu Singh(NEU), Asgeir Sorenson (U. Norway), João Sousa (Porto U.), Jason Stack (US Navy), Ivan Stenius (KTH), Andy Stewart (APL/U. Washington), Tom Swean (Consultant), Doug Todoroff (US Navy), Giancarlo Troni (Pontifica U.), Zoran Vukic (U. Zagreb), Christoph Waldmann (U.Bremen), Alan Winfield (U.West England),

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4333 Brooklyn Avenue NE
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14. ABSTRACT

Trends in undersea autonomy have been tracked and assessed using the 25 years of the Autonomous Underwater Vehicle Student Competition (aka now RoboSub) as a source. Included is a valuation analysis pursuant to the US Navy's return on investment. The need for skilled system engineers to maintain the Navy's competitive advantage in unmanned systems has not diminished. Competitions remain an extremely effective way of identifying, encouraging, and capitalizing on talent. A productive path for the Navy is the initiation of a new competition with its own focused identity and a value proposition that justifies the investment. Possible foci include micro-vehicle performance, vehicle-vehicle interaction, energy limitation and management, underwater navigation, adaptive behavior with environmental uncertainty, and sparse, latent communication. Competition elements described include venue, vehicle size, tasks, toolkits, growth, management structure, partnering, budget, and draft rules. A number of appendices are included: Appendix A: Frequently Asked Questions; Appendix B: AUVSC NEXT Among Robotic Competitions; Appendix C: Tasks as Measures of Autonomy; Appendix D: Autonomous Marine Vehicles Competition Committee.

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