Multidisciplinary standard-based architecture for underwater autonomous systems

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ABSTRACT

This paper describes the research conducted by NATO STO CMRE (North Atlantic Treaty Organization Science and Technology Organization Centre for Maritime Research and Experimentation) on the development of an architectural framework based on standards that bridge the Robotics, Command, Control and Communication (C3) and Modelling & Simulation (M&S) communities.

The use of autonomous systems in real operations, in particular in the underwater domain, requires preliminary phases of testing (*Does it work?*) as well as experimentation and analysis (*How does it work?)* under accurate and realistic scenarios. CMRE is answering these questions with interoperable M&S. This work uses interoperable M&S to fill a cultural and educational gap in the underwater autonomous system operational communities, preparing the way for new concepts such as serious gaming for the analysis of the human decision-making process and "M&S-based training environments for robotics", by including machine-learning algorithms in the loop.

CMRE's work has addressed the development of multi-layer interoperable High-Level Architecture (HLA) federations to support operationally relevant research and engineering activities for cooperative and collaborative teaming of autonomous systems in the maritime domain. The use of HLA federations also enables Live, Virtual and Constructive simulations following the Distributed Simulation Engineering and Execution Process (DSEEP) standard.

To date, the federations consist of ROS (Robotic Operating System) based underwater autonomous systems (hardware- and software-in-the-loop), virtual simulators to display and manage interactions among assets, and federates for the environment, communications, dynamics as well as mission-specific federates. Furthermore, the architecture supports over-the-internet distributed experiment, embracing the Service Oriented Architecture concept.

The paper presents the result of the work done to support the experimentation on autonomous collaborative algorithms for Autonomous Underwater Vehicles (AUV) for Mine Counter Measure (MCM). Currently the team is focusing on Anti-Submarine Warfare scenarios and on the design of new application of Augmented and Virtual Reality for surface and underwater to enhance situational awareness by the integration of multiple layers of information.

ABOUT THE AUTHORS

Alberto Tremori an Electronical Engineer with a PhD in Modelling and Simulation (M&S). He worked for ICT companies (IBM, Xerox, IDC…) and in 2007 he co-founded and managed a university start-up. In 2010, he became a researcher at the University of Genoa completing his PhD in 2012. Since 2014, he is a M&S Scientist at NATO STO CMRE, where he is currently Project Leader focusing on future trends of simulation in NATO, interoperability, autonomous systems and standards.

Arnau Carrera is a scientist at the NATO STO CMRE since 2015. He received the B.S. and M.S. degree in Computer Science from the Universitat de Girona in 2012 and a PhD in 2017 at the same university. His PhD was devoted to the development of artificial intelligence algorithms, specifically in learning by demonstration methods, to perform underwater intervention tasks using autonomous underwater systems (AUV). His current research activities are related to the integration of autonomous system in complex simulated environments.

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INTRODUCTION

Underwater operations, like Antisubmarine Warfare (ASW) or Mine Counter Measures (MCM), are beginning to realize the benefits of the use of autonomous robotic systems. These benefits include, among others, the possibility to work for extended periods of time with limited human intervention, reducing risks caused by human operator stress and fatigue during complex and long-term operations that could be potentially harmful for the people or systems involved. In spite of the broad consensus about the strengths of autonomous systems, their potential to support underwater operations has not been fully exploited, and there is still room for improvement.

The Persistent Autonomous Reconfigurable Capability (PARC) project aims to address technology and engineering requirements, enabling future unmanned systems of systems to reach their full potential in the maritime domain. PARC, a NATO STO Centre for Maritime Research and Experimentation (CMRE) project started in 2014, is focused on increasing autonomous robotic system capabilities, persistence, interoperability, and scalability whilst addressing standardization and information assurance considerations. To achieve this, Modelling & Simulation (M&S) methodologies have been identified that can support the testing, experimentation and analysis of the Autonomous Underwater Vehicles' (AUVs). Further, M&S capabilities provide an opportunity to improve the training of both humans and autonomous systems.

PARC M&S activities focus on linking the three different communities involved in the scope of the project. First, M&S as a facilitator and enabler for concept development, experimentation, and testing. Second, the robotics community, today represented by the AUVs, as the matter of investigation. Finally, the Command and Control (C2) and Communications community, supporting the operators for planning, conducting, supervising, managing, and analyzing operations.

To facilitate the links between these communities, the design and implementation of a multi-layer interoperable simulation capability that allows the inclusion of hardware- and software-in-the-loop has been proposed. By leveraging M&S methodologies to allow the "immersion" of real systems, the Robotics and C2 and Communications communities have been able to take advantage of M&S based Verification and Validation (V&V) frameworks, carry out Concept Development and Experimentation (CD&E) activities and incorporate virtual and augmented reality to better understand system capabilities.

The content of this paper is structured as follows. Section 2 summarizes the exiting standards for each of the PARC communities. Section 3 describes the achievements made so far by analysing the major building blocks of this capability. Section 4 is devoted to the description of those scenarios where the M&S testbed capability has been and is being used. Section 5 includes a summary of possible future developments and envisioned challenges. Finally, the conclusions drawn and the lessons learned during the development of this work are summarised in the last section of the paper.

THE MULTIDISCIPLINARY APPROACH: STANDARDS INVOLVED

As stated before, the M&S testbed capability is achieved by bringing together the three communities (see Figure 1) using the M&S standards as a baseline. Interoperability, exchange of data, and sharing information are some of the most critical aspects when dealing with the integration of different approaches, regardless of the fact that these approaches can belong to the same or different community of interest.

Individually, each of the areas under consideration has developed specific approaches to deal with information exchange issues. Figure 1 shows the set of interoperability standards (or *de*-facto standards) renowned in each domain. As our intention is to preserve the existing methodologies and approaches, in order to implement the required links, our developments, where possible, shall be based on these standards.

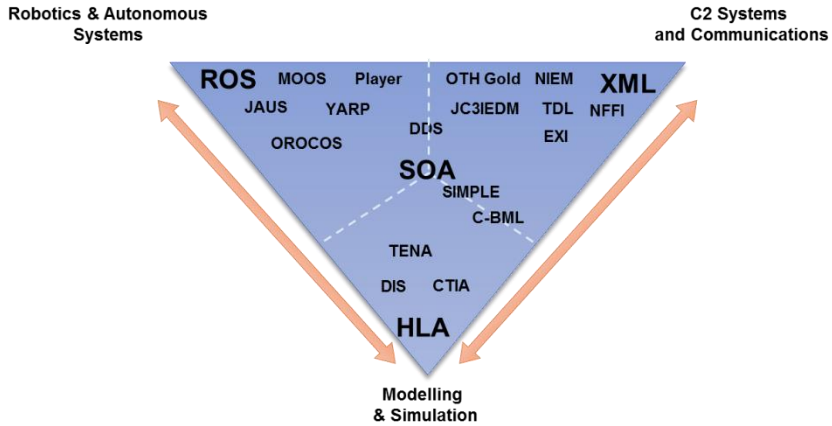

Figure 1 – Subset of standards devoted to data exchange, sharing information and interoperability standards of the three considered communities.

Regarding M&S, there is a list of standards devoted to facilitate the development of interoperable distributed simulations. This list includes Distributed Interactive Simulation (DIS) (IEEE, 2012), Test and Training Enabling Architecture (TENA) (US DoD, 2002), Common Training Instrumentation Architecture (CTIA) (ACB, 2003), or High Level Architecture (HLA) (IEEE, 2010). Even though each of them uses different protocols for communication and data sharing format, their common goal is to facilitate the task of executing distributed simulations and the synchronization of events and actions.

Robotics and Autonomous Systems is, in terms of standardization, the community with the lowest level of maturity and is still in a state of evolution. In fact, there are no available standards and the majority of the developments are carried out based on “de-facto” standards. In order to simplify the research in the robotics field, to provide hardware abstraction, and to enhance the development of modular, scalable, and distributed robotics systems, several frameworks have been developed in the last years. The most known in the Robotics field are Robot Operating System (ROS) (Quigley, et al., 2009), Mission Oriented Operating Suite (MOOS) (Newman, 2001), Player (Gerkey, Vaughan, & Howard, 2003), Joint Architecture for Unmanned Systems (JAUS) (Wade, 2006), Yet Another Robot Platform (YARP) (Metta, Fitzpatrick, & Natale, 2006), Data Distributed Service (DDS) (Object Management Group, 2015), and Open RObot COntroller Software (OROCOS) (Bruyninckx, 2001).

Concerning interoperability for C2 systems and Communications, the efforts of the community are focused on the development of formal ontologies and protocols for data exchange and information sharing in order to achieve syntactic and semantic interoperability levels. In that sense, the following standards and recommendations have been identified: OTH Gold (Dorion, Matheus, & Kokar, 2005), JC3IEDM (MIP, 2013), NFFI (NATO Friendly Force Information), National Information Exchange Model (NIEM) (NIEM ESC, 2013), Efficient Xml Interchange (EXI) (W3C, 2014), or Tactical Data Link (TDL). The majority of these formats are based on XML syntax, and XML itself is also used for data exchange purposes by some C2 and Communications systems. In this case, we have also identified some activities aiming to link this domain with M&S – Standard Interface for Multiple Platform Link Evaluation (SIMPLE) (NC3B, 2010) and Coalition Battle Management Language (C-BML) (SISO, 2014).

In addition to the individual activities of each domain, the software engineering community is evolving to a service oriented and cloud computing based approaches due to the proven benefits that this solution has in terms of scalability, reusability, modularity, or flexibility. This fact is reflected in the Service Oriented Architecture (SOA) (OASIS, 2006) paradigm and its implementations. The relevance of this approach in the M&S community is underlined by the NATO interest expressed by the M&S groups on the "As a Service" approach (NATO Modelling and Simulation Group 131, 136 and 164). Each of the three considered domains are investigating and working on the adoption and fostering of interoperability and reusability. Therefore, it has been subject of our investigations.

Once the list of solutions in the scope of each domain has been identified, the next steps consist of the design, implementation, and validation of the capability. The achievements made so far and the challenges that will be faced in the next phases of the work are described in the following section of this paper.

M&S TEST BED CAPABILITIES WITH HW- AND SW- IN -THE-LOOP

The initial steps of M&S in PARC project have been focused on the establishment of the baseline architecture for the integration of HW and SW-in-the-loop. The main efforts have been in the analysis, design and implementation of a set of building blocks which provide the link between the Robotics and the C2 and Communication communities.

The following sub-sections are devoted to explaining the details of the development of a core HLA federation, with HW and SW in the loop. Further, the possibility of distributed experiments over the Internet and the addition of virtual reality (VR) and augmented reality (AR) functionalities are also described.

Modelling & Simulation - Robotics & Autonomous Systems

From the Robotics perspective the Robotics Operating System (ROS) is, currently, the framework most widely used in the field, and this fact had led to its selection. From the M&S point of view, High Level Architecture (HLA), an IEEE standard adopted by NATO (STANAG 4603), is the chosen M&S interoperability standard. HLA for robotics has been also used by NASA and the ESA (Möller, Crues, Garro, Skuratovskiy, & Vankov, 2016) (Arguello, Dwedari, Lauderdale, Vankov, & Chliaev, 2001) allowing the creation of heterogeneous and complex simulation environment, thereby increasing the richness of the simulation.

Simulation is widely used in the Robotics community in almost all the phases of a robot development for defining, designing and testing systems. Even though, to the best of the authors' knowledge, there is no previous work published with the intention of connecting ROS-based developments with HLA-based federations. There have been other developments involving non ROS-based robotic systems and interoperability using HLA. For instance, for testing sensors and actuators by means of simulation in the field of Unmanned Underwater Vehicles (Lane, Falconer, Randall, & Edwards, 2001), for the integration of simulation capabilities in a discrete event simulator involving aerial and terrestrial assets (Joyeux, Alami, Lacroix, & Lampe, 2005), and for testing the performance of a heterogeneous system (including real and simulated assets) for agricultural tasks (Nebot, Torres-Sospedra, & Martínez, 2011).

All these works are based on the injection of simulated events directly in the operating system of the robot. Conversely, the presented proposal is derived from M&S community ideas, like virtual reality and immersive environments, where real systems are "immersed" in simulated environments. While this concept is still not widely spread among the robotics community, the first results and the preliminary feedbacks from the different communities engaged in the dissemination of the results seem to confirm the potential of this approach.

The main purpose behind the development of this connection is to try to minimize the effort required for including existing autonomous ROS-based systems in complex, interoperable, and standard-based simulated scenarios. In that sense, this proposal preserves the existent control architecture in the system and, by adding a layer or middleware, it enables the interoperability of the desired system at SW or HW level. In this way, it will avoid the need of re-designing the entire robotic system and it maintains the manufacturers' SW "as it is", i.e. without modifications. Figure 2 shows a simplified version of the ROS-HLA middleware design.

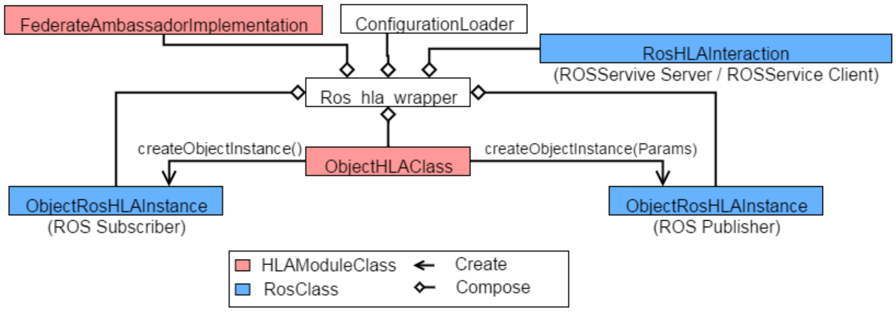

Figure 2 - ROS-HLA Middleware design

The specific strategy adopted to tackle the problem consists in the development of a ROS-HLA wrapper, which guarantees the technical and conceptual interoperability between the robotic system and the simulated environment. A hybrid component composed of an HLA Federate and a ROS node is created in the robotic system or platform, converting all the ROS-relevant messages to HLA interactions, and vice versa. Thus, the exchange of information between these two vertexes of the triangle is centralized in one node, keeping the vertexes specific software independent. More detailed information about this development could be found in (Carrera, et al., 2016).

Modelling & Simulation – Service Oriented Architecture (SOA)

The M&S testbed capability has been enriched with SOA-related concepts. SOA is an architectural design approach that enables a specific implementation of a SW architecture to the usage of services, where a “service” can be defined as “a logical representation of a repeatable business activity that has a specific outcome, that is self-contained, and may be composed of other services, being a ‘black-box’ to consumers of the service” (The OpenGroup).

The SOA paradigm is based upon five principles: abstraction, loose-coupling, reusability, composability, and discovering. In the context of M&S, the focus is on providing a framework supporting the discovery, the composition, and execution of services in order to enhance the flexibility, accessibility, and scalability of the simulation, so as to reduce both the development cost and time.

Building upon both SOA principles and the HLA-ROS bridge concept, the CMRE M&S team developed a middleware aimed at connecting an HLA-based federation to a Command and Control (C2) system according to the service-oriented paradigm. The purpose of this is twofold. First, the integration of SOA with M&S for C2 capabilities is the basis upon which to implement the M&S-C2 leg of the “standards for interoperability” triangle (Figure 1). Second, introducing SOA concepts into the federation architecture permits the plugging of services in the existent federation, offering the simulation as-a-service through a standard interface.

OpenCPN software has been chosen to add C2 capabilities to the federation. The software provides support for multiple assets and data visualization, allowing the combination of the information coming from deployed assets into an integrated geo-referenced picture. It also provides tools for the identification of areas (e.g., survey areas, inspection points, etc.) and executes associated commands, such exporting information in standard formats (e.g., GPS eXchange Format). These features enable the management of a fleet of heterogeneous assets for different types of operations.

Following to the SOA paradigm, the technology-independent interface implementing the HLA-SOA middleware plays both the roles of server and client. The former is in charge of offering data outside the federation in standard formats, and it is used by the C2 system to obtain the asset-related information according to the NMEA standard, while the latter is in charge of delivering the user-defined commands from OpenCPN to the federation.

SOA-over-HLA, introduced through the integration of C2 capabilities in the PARC federation, plays a major role in the definition of a standard and technology-independent interface to be used as a basis on which to enhance interoperability with standard C2 and communication systems. Indeed, thanks to the flexibility of the adopted SOA paradigm, the integration of other interfaces is straightforward. As an example, the NMEA-based data exchange may be substituted with other standard formats, as with Tactical Data Link (TDL), whose connection with M&S has been already tackled, leading to the definition of the SIMPLE (NC3B, 2010) protocol.

Core federation with HW and SW in the loop

As a result of the effort in bridging the three communities, a core HLA federation with HW- and SW-in-the-loop has been created, see Figure 3**.** This federation allows the integration of real and simulated assets in a complex and realistic environment and it constitutes the core federation to which scenario-specific federates may be connected.

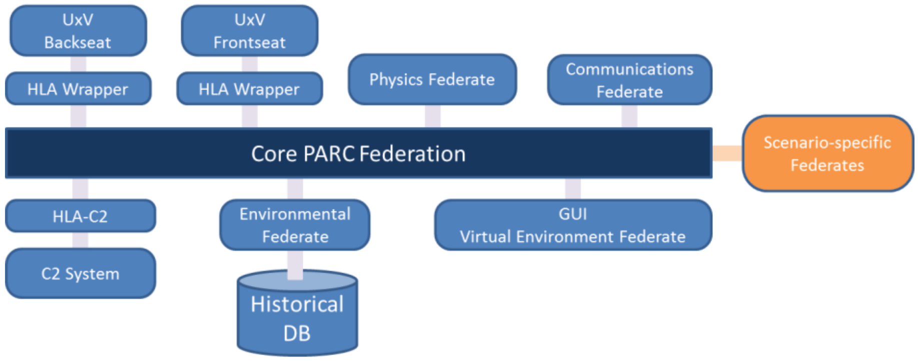

Figure 3: Representation of the core PARC Federation.

The conceptual models of federates have been developed in close collaboration with the different departments at CMRE, each one covering specific domain: engineering and scientists working on autonomous systems, environment, and underwater communications. The core PARC federation includes the following federates:

- **UxV Frontseat:** it integrates the low-level software in charge of controlling the UxV. This federate receives the requests of the backseat and transforms them in commands for the sensors and actuators. Moreover, this federate may contain the real asset in the case of HW-in-the-loop simulation.
- **UxV Backseat**: it integrates the high-level software modules in charge of defining the behaviors of the UxV. This federate receives the mission requirements and commands from the C2 system and transforms them into commands for the UxV according to the environmental conditions.
- **Physics Simulator:** it is in charge of simulating all the movements and interactions of the virtual assets within the environment. Based on the commands and environmental information, it determines the new parameters (positions, directions, etc.) of the virtual assets. The dynamics of the AUVs are provided by the system producers. This approach is adopted for each system included in the scenario to enhance realism and minimize V&V efforts.
- **Underwater Communication Simulator:** it simulates the communication channels between the different assets, including noise, transmission time, and possible interferences. The underwater communications scientists (the team developing JANUS[1], standard for underwater communications) provided us simplified models to be used in this federate.
- **Environmental Simulator:** it simulates the surface and underwater conditions in order to determine the forces that would be applied to the different assets. These forces are mainly used by the physics simulator. EKOE (Environmental Knowledge and Operational Effectiveness one of the main programmers at CMRE) scientists helped us to define the parameters for the FOM and basic models for simulation of underwater environment (Oddo, Pinardi, & Zavatarelli, 2005) (Robinson, McCarthy, & Rothschild, 1999) (Woodham, 2011). It also simulates the seafloor types, being able to define sand, sand ripples, clutter, or posidonia.
- **C2 System:** it emulates the capabilities of a C2 system. It is designed to monitor the mission, visualize the assets' positions, and the assets' tracks over the federation execution. It is also capable of sending command messages. This federate is integrated by using a SOA approach and can be connected to C2 systems implementing SOA interfaces.
- **Virtual Environment:** its main purpose is to provide a graphical and 3D representation of the overall scenario simulated by the federation. It can be visualized using conventional screens or using VR devices.

[1] JANUS is a NATO standard, developed at the CMRE, to enable underwater communications systems to establish robust digital communications for node discovery and data exchange.

Distributed Experiment over the Internet

The architecture defined for the PARC federation supports over-the-internet distributed experiment, allowing the participation of external partners and third party software in the simulation. This provides a new environment able to simulate future missions with SW- and HW-in-the-loop in a cooperative and collaborative manner. Exercises and trials may be prepared in advance, with reduced cost and time, by testing the interoperability of deployed systems and assets through the internet.

Distributed experiments over the internet are realized through either HLA or SOA interfaces. Moreover, the network infrastructure is designed to prevent security and confidentiality issues, allowing the execution of NATO unclassified experiments.

Virtual and Augmented Reality to Support Operations

The usage of Virtual Reality is also under assessment with the intent to provide an environment that should support a better understanding of data coming from the underwater domain. The usage of VR and an “Augmented Reality”-like approach in support of operations should increase the situational awareness by

- providing an enriched representation of sensors data
- and a new way to interact with information and assets deployed in the field,

Figure 4 provides an explanation of this concept.

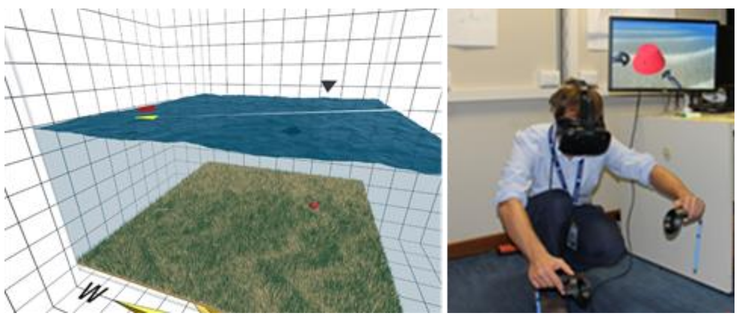

Figure 4: The image on the left depicts a 3D representation of the scenario in the VR environment, while the one on the right shows user exploring a 3D virtual operational area using the googles.

Both VR and AR provide the capability to generate a common picture both at tactical or operational level including multi-source and multi-domain data. For example, acoustic and optical data, gathered by sonars and cameras, could be fused and represented in a more human-comprehensible manner. Furthermore, data may be structured on different levels for usability, security or organizational reasons, preventing all the users from viewing the whole piece of information.

The Federation as Testbed for Multiple Scenarios

The V&V of the core federation was accomplished in 2016 with an experimental mission. The outcome demonstrated the ability of the M&S testbed to assess the capability of the control system of an AUV to complete fully autonomous or human monitored missions. More specifically, the tested scenario consisted in a critical infrastructure protection mission in the CMRE harbor, including patrolling and docking tasks. The mission was performed several times, with different environmental settings, in order to find the range of safe conditions where it was possible to conduct the operations. The successful V&V and integration tests of the base federation demonstrate the capability to combine both real and synthetic environments by employing real assets at sea, and performing a simulated mission with other simulated assets Figure 5.

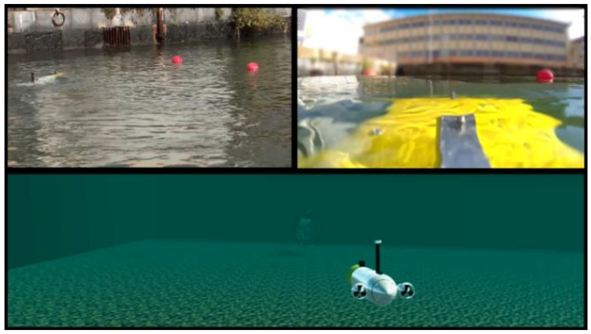

Figure 5 Images taken from the real world and virtual environment during the experimentation of the core federation with HW and SW in the loop.

The core federation needs to be specialized by adding scenario-specific federates or by extending existing federates to create realistic environments for the desired scenarios. The next section presents the two implementations of the federation that are currently under development. The former, which is currently at the final iteration of the development process, is related to an MCM scenario, while the latter is at the design stage and it is related to an ASW scenario.

OPERATIONALLY RELEVANT SCENARIOS

The aim of M&S PARC is to offer a testbed simulation capability for unmanned vehicles in operationally relevant scenarios. The usage is twofold. First, the testbed may be used to perform V&V of innovative algorithms; second, it may be used for supporting CD&E on scenarios that include autonomous systems. In a near future, another possible use case may be the usage of the developed simulation framework for training systems' operators and autonomous systems. This last concept is related to the possibility of including the software module in charge of the autonomous behavior as an element of the simulation loop. By relying on the simulation results, this software learns new strategies and behaviors that the autonomous systems shall reproduce to face different situations in real scenarios.

CMRE works in several warfare areas of the maritime domain. As of today, it has mainly worked on Mine Counter Measurements (MCM) in order to provide M&S testbed capabilities; in 2018 the team has also started the work with the Antisubmarine Warfare (ASW) experts. The following subsection will introduce the work done on MCM with the domain-specific problems and a description of the current federation.

MCM Scenario

In this scenario, the focus is on a team of AUVs collaborating to successfully complete an MCM mission, specifically the clearing of a Q-route. More in detail, the objective of this mission is the survey of a strategic area, usually the entrance of a harbor or a narrow passage, in order to identify and analyses possible threats and guarantee safe transit for vessels. The federation is used for two different purposes. First, the V&V of the algorithm responsible for the generation of the trajectories that the AUVs should follow in order to optimally survey the seabed. Second, the V&V of the algorithm responsible for the cooperative behaviors in multi-vehicles missions.

Figure 6 represents the federation developed for this purposes. The core federation is used as a baseline where a set of MCM-specific federates are connected. More specifically, one of the new federates, the target detection, is responsible for simulating the detection of targets illuminated by the sonars equipped on the deployed AUVs. Conversely, the other new federate embeds the autonomous engine responsible for the definition of the behaviors of the assets deployed in the mission. In particular, the autonomous engine replaces the generic backseat of the core federation and it corresponds to the software module under test. Finally, it is worth mentioning that the environmental federate of the core federation has been extended to include the seafloor characteristics of the mission area, necessary for the proper representation of an MCM scenario.

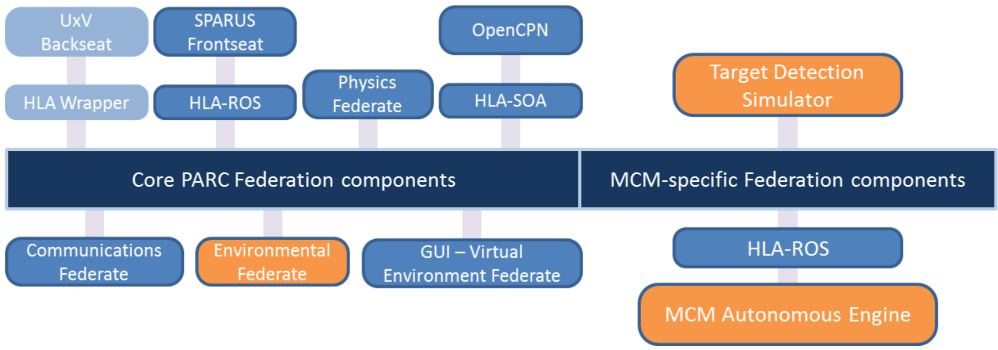

Figure 6: Representation of the federation responsible for the simulation of an MCM mission. The orange boxes identify either new MCM-specific federates or core federates that have been extended.

In November 2017, a live and distributed experiment over the internet was held at the 2017 I/ITSEC conference in Orlando. The goal was to demonstrate the MCM M&S federation in a distributed, over the internet, simulation. During the demonstration, the PARC federation was split into two groups of federates (see Figure 7, with CMRE and Mobile networks). The former was run in the CMRE network, and was composed of the Environmental, Physics, and Target Detector federates. The latter, composed of the remaining federates, was run in Orlando and was connected to the federation running at the CMRE.

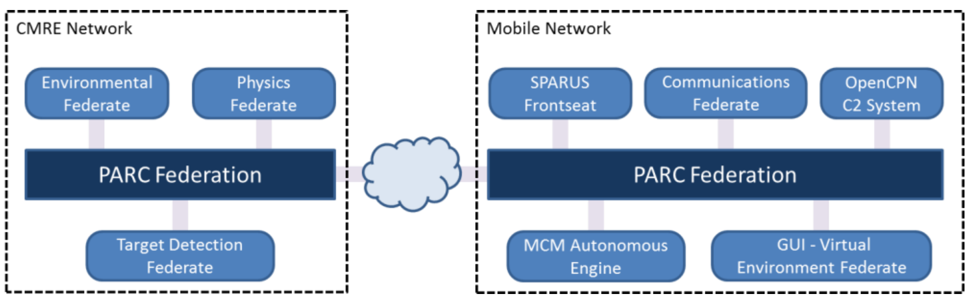

Figure 7: Topology of the PARC Federation during the distributed experiment over the internet. A set of federates run on a mobile network, while the rest of the federates run on the CMRE network.

ASW Scenario

The CMRE experts on ASW are developing new strategies related to the usage of autonomous vehicles in anti-submarine warfare scenarios. In this context, the role of the M&S team at CMRE is to offer support by developing a simulator aimed at testing the different entities involved. As a general introduction, the discussed scenario involves multiple autonomous vehicles cooperating to survey an area and identify, track, and classify possible threats.

More in detail, the specific scenario currently under design is the surveillance of a choke-point. A choke-point is a strategic narrow route providing passage through or to another region. Maritime choke-points are naturally narrow channels of shipping having high traffic because of their strategic locations. Three different categories of entities are identified: first, the assets deployed to survey the region, which may be either underwater or surface vehicles; second, the targets to be detected and tracked; and finally the possible neutral entities, that may be detected but classified as no-threat.

Figure 8 presents the federation that will be developed to support the ASW experimentation. Also in this case, the core federation will be connected to a set of ASW-specific federates. Similarly to the case of the Target Detection Federate in the MCM scenario, the Contact / Track Federate will be responsible for simulating the contacts received by the deployed autonomous systems and the subsequent tracks being generated. The other three federates will simulate the three categories of entities: the deployed assets (e.g., Unmanned Surface Vehicles (USVs) and AUVs), the targets of the mission (i.e., the submarine), and the set of neutral entities that may be present in the scenario and detected by the surveying vehicles.

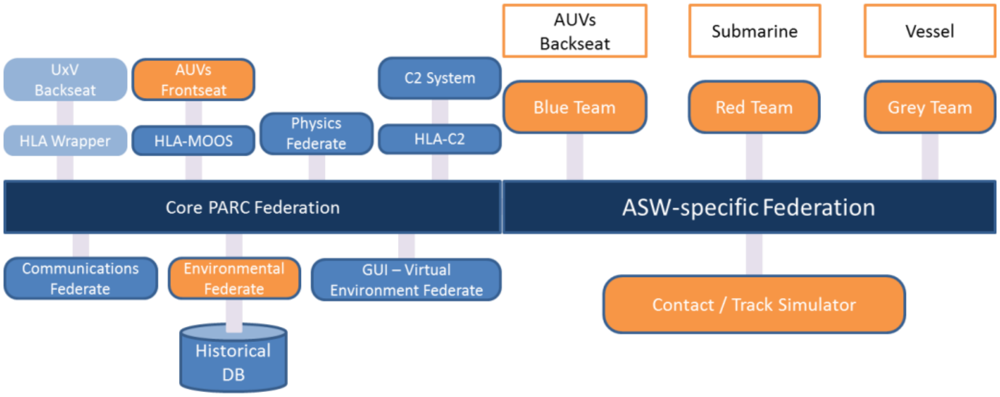

Figure 8: Representation of the federation responsible for the simulation of an ASW mission. The orange boxes identify either new ASW-specific federates or core federates that will been extended.

NEXT STEPS AND CHALLENGES

The CMRE M&S team is exploring new opportunities to enrich the M&S testbed capability. The end state goal of the next steps is to improve and utilize the standard-based M&S capability for de-risking sea-going activities, verification and validation, concept development and experimentation, and training. The future steps planned to achieve this result can be summarized in the following topics:

- The consolidation of the MCM and the development of ASW scenarios
- the extension to other warfare areas,
- the study and development of AR/VR applications for the maritime framework
- the investigation on the usage of serious games for the analysis of the human decision making process to be linked to the idea of using simulation for training autonomous systems, and also humans involved in autonomous systems missions.

The MCM federation is reaching a final stage of maturity; however, it still requires an extensive analysis from the user for the final validation. On the other hand, the ASW federation is at an initial stage of the development process. Until now, the requirements have been collected and the architecture of the federation has been designed. Moreover, in the future years, the PARC M&S team will continue working in the consolidation of the existing M&S capabilities and their extension to the remaining and possibly future warfare areas. This will also provide a common framework facilitating the cooperation between the different warfare areas.

Furthermore, the M&S capability will be extended to support the usage of machine learning algorithms to train the autonomous behaviors of the systems. On the other side, the simulation will be included into the training process of the operators of missions that include autonomous systems.

CONCLUSIONS

In this paper, we provided an overview of the M&S activities under PARC project. The product of these activities is a multi-layer, standard-based architecture for interoperable simulations. This has supported the implementation of a multi-disciplinary and cross-community testbed capability with M&S as its cornerstone.

Today CMRE has an HW- and SW-in-the-loop federation linking M&S, Robotics, and C2 and communications. The MCM federation will be validated by the end of September by means of extensive experimentation performed under the supervision of MCM experts. Simultaneously, the development process of the ASW federation will be finalized in 2019. As for the MCM case, after the completion of the development phase, an expert in the field will validate the ASW federation.

The future of the M&S developments in PARC project heads to investigate and develop new innovative solutions to underpin the adoptions of autonomous underwater systems to support naval operations. This will be achieved by further steps of consolidation of the standard-based Live/Virtual/Constructive federation.

The CMRE M&S team has an almost unique opportunity to leverage on a community of scientists and engineers with a wide and deep knowledge of the real world platforms, systems and environments in the maritime framework. This allows capsizing the point of view in Figure 1, where M&S was viewed as a baseline for the connectivity with other communities, to a new perspective, where M&S becomes the top of the triangle and the main enabler for the cross-disciplinary activities (see Figure 9). The joint involvement of the three communities provides an added value to the developments carried out. The CMRE experts on the two domains now base of the triangle provide accurate and well-founded conceptual models based on their knowledge and expertise of the real systems to the M&S efforts. Whereas, M&S provides them a rigorous and well-established methodology and process for V&V to support whole life cycle of systems and concepts, from testing, through analysis, CD&E, and training.

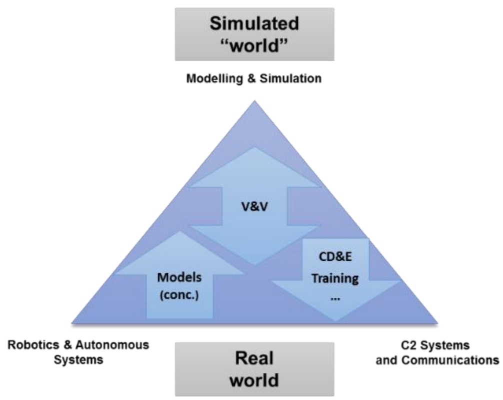

Figure 9 – Robotics and C3 as a foundation for M&S at CMRE

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