Digital Twin: a bridge between simulation and real world in the Maritime Environment

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ABSTRACT

This publication describes the CMRE effort on the development of the Digital Twin (DT) architecture for Maritime Unmanned Systems, with the goal for the DT to serve as a bridge between modelling and simulation and the real world applied to MUS technologies and to explore how cyber-physical bridging is achieved during the execution of two NATO exercises.

The maritime domain, especially underwater is a complex, "non-human-friendly" domain. MUS applications face challenging environmental conditions. Nonetheless, there is an increasing interest in MUS from the operational community; MUS can perform dangerous missions without putting people in harm's way. New MUS capabilities are developed and these systems are becoming more advanced and autonomous, being able to take over tasks normally performed by expensive manned platforms. Industry, together with research institutes and academia are developing new MUS (prototypes) in a rapid pace. This combination makes MUS a demanding but also a very relevant research topic in support of NATO exercises and operations. The Digital Twins concept provides a cost-effective means to analyse the operational capability and interoperability of existing MUS while at the same time reducing the risks involved with actual deployment and use of MUS. Digital Twins further facilitates the development of requirements for future MUS by providing the opportunity to easily change or upgrade MUS capabilities using modelling and simulation. For the above reasons DT is a very active and evolving research area for CMRE, and also an area that has high interest and visibility within the technical and operational community.

CMRE developed a DT prototype and deployed it during two NATO exercises REPMUS22 and DYMS22. These exercises took place in Portugal, September 2022. This DT prototype, which is currently further being developed and expanded, serves as the first DT framework prototype for the nations involved. An important development within the DT is the implementation of the Collaborative Autonomy Tasking Layer (CATL) interoperability protocol. CATL (emerging in the standardization agreement STANAG 4817) makes the DT system seamlessly interoperable with existing Command and Control (C2) systems on-board ships.

This study reports on the technical feasibility of cyber-physical bridging and describes the prototype *developed by CMRE. It also discusses current gaps and next steps. It paves the way for future development of the technology proposed.*

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1.0 INTRODUCTION

Underwater is a complex, "non-human-friendly" domain. Complexity arises amongst others from difficult environmental conditions, the need for remote sensing, and limited communications. Nonetheless, maritime is a strategic domain: above and on the water surface, underwater, and on the seafloor. Underwater operations cover a wide spectrum of applications, from offshore industry and oil and gas production to the layout and maintenance of underwater cables and pipelines (currently over a million km of underwater cables and underwater pipelines ensures internet, communication, and provide energy to the whole world [1]), environmental science, archaeology and, not least, defence. The adoption of unmanned systems is growing fast, reducing risks to operators and increasing persistency at sea.

The concept of Digital Twins was first publicly introduced in 2002 at a Society of Manufacturing Engineers conference, but its first practical use was by NASA in 2010 for the simulation of a digital Twin spacecraft. Today the Digital Twins concept is widely used in industry and engineering for many purposes, such as reducing time-to-market, reducing risk of complex systems (of systems), predictive maintenance and many more use cases. Also in the maritime domain, e.g. for ship design, Digital Twins is a well-known concept. However, to the best of our knowledge, Digital Twins, specifically, for research on Maritime Unmanned Systems (MUS) operations it is an as of yet largely unexplored topic.

Having a DT capability for MUS has clear benefits for the technical and operational community. Some of the most prominent are:

- Use the DT as a situational awareness tool to improve insights into the execution of a maritime operation using human-interpretable visualisation and augmentation of vehicle and sensor data.

- Being able to investigate the effectiveness of different alterations of deployment and tasking of a MUS.

- Being able to assess interoperability between different MUS in a larger scenario.

- Being able to simulate communication network performances to analyse the most effective configuration of different MUS for different tasks.

- Reducing the risk to equipment and personnel by being able to analyse scenarios and trials before execution in the real world with the real systems.

- Facilitating the design and the drafting of new system requirements, and reducing R&D costs, when developing new MUS by being able to analyse the effectiveness of possible different system improvements beforehand. For example, improvements in sensor capability, steering control system or on-board processing. Thereby being able to weigh the costs of system improvements against their effectiveness before investments.

- Reducing costs by reducing trial exercise iterations by using a DT simulation to alter deployment, mission and being able to analyse and select the most promising methods before trial execution.

- Reducing time-to-market for new MUS.

- Using DT to post-process and analyse the data collected by the MUS during live exercises to assess and improve the overall performances.

Within the framework of the Supreme Allied Command for Transformation programme on M&S, aiming at the exploration of DT use-cases for MUS applications, NATO STO CMRE and Italian Navy CSSN (Centre for Maritime Support and Experimentation) collaborated to investigate scenarios and target architectures for the future DT applications. The use case addressed in this paper is the improvement of the situational awareness for a maritime scenario with a relevant underwater component.

Based on the state of art of the interoperability with Command and Control (C2) environments and the Live-Virtual-Constructive concepts for maritime exercises.

With the work described in this paper, the authors focus on proving two main ideas:

- There is an end-users’ community interest on concrete applications of DT in the underwater domain.
- The rapid development and deployment of working DT prototypes have a solid basis.

1.1 State of the Art

Scientific and technical publications provide various definitions of DT. In this paper, authors consider DT as a digital representation of a real-world entity or system/sub-system or in this case system of systems. It is an evolving digital representation of states and behaviours of a physical asset or process and it is implemented as a software model replicating the status and characteristics of a system/subsystem. Clearly, this concept makes DT vastly reliant on real-time flow of measurements from systems, sensors, and processes across multiple domains [2].

The DT conceptual model adopted for this study is the Five-Dimensional DT model constructed and described by the Beihang University [3] [4]. According to this model, DT are made of five components: Physical Entity, Virtual Entity, Service System, Connection and DT data as per Figure 1.

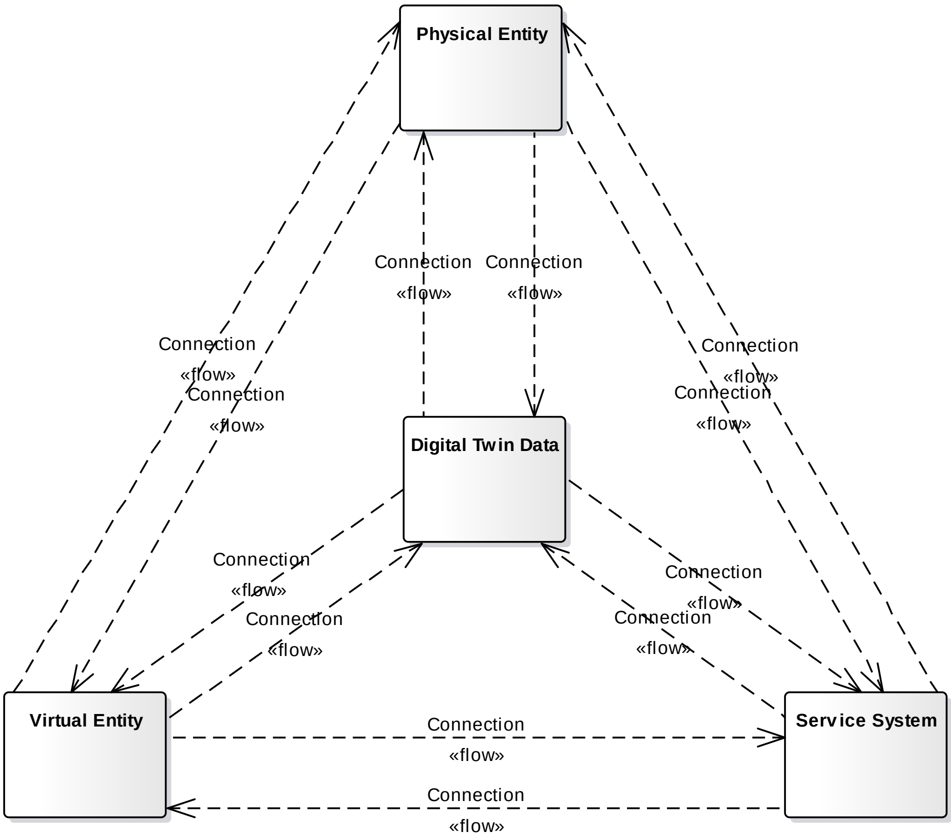

Figure 1 – DT 5 Dimensional conceptual model

Following a brief summary of the five dimensional DT model according to [3] and [4]:

- Virtual Entity: the replica of the physical system, hence the core of the DT. During the usage of the system (e.g. a mission), it maintains a bi-directional flow of data with the physical entity, storing data.
- Physical Entity: the "real" system that benefits the adoption of a DT approach. According to this definition, two subcomponents constitute it: the physical entity and a "vision" physical entity, which are estimated status (e.g. future status) of the physical entity.
- Service System: the interface with the human. Services operate with the data coming from the virtual and real systems.
- Connection: the structural element that allows data flow from the components of the DT.
- DT Data: consists of all the data existing in the DT system. To study a specific DT means to study the exchange and processing of its data.

In the "Science & Technology (S&T) Trends: 2020-2040" the NATO Science and Technology Organization (STO) assessed emerging and disruptive S&T applications and their potential impact on NATO military operations, defence capabilities and political decision space. The report outlines the use of DT as a growing approach over the next years, relying on extensive platform and sensor networks deployed in the future operational environments, in support of predictive analysis, experimentation and assessment [5].

Focusing on the underwater maritime domain, there is a growing interest in the application of DT. In the US, DARPA (Defense Advanced Research Projects Agency) issued a program named Defining and Leveraging DT in Autonomous (DELTA), to understand whether DT technology can be effective for unmanned undersea vehicles [6].

Current applications in the maritime domain are being experimented also by the US DoD Naval Surface Warfare Center, with a typical industrial application DT of supporting maintenance of ships (damage identification, corrosion and alignment issues). The technology is also used to digitally mirror the capabilities of weapon systems and support the maintenance and upgrades of aircraft, engines and government facilities. The Office of Naval Research (ONR) is developing the "Navy Platform DT" [7]. The platform aims at fusing data measured from the ship sensors and by using physics-based models predict platform performance, material conditions and battlespace susceptibility.

The increased use of UUVs, the costs/efforts and the notoriously difficult communication between above and below the surface of the sea pushes scientists and engineers from domains other than military. Novel engineering processes are developed for determining the subset of components from a UUV that, when monitored through DTs, yield the maximal increase in total system reliability and minimize the cost entrance hurdle for implementing the DTs [8]. It is worth mentioning that mature use cases found in literature, to the best of the authors` knowledge, cover classical engineering aspects and Verification and Validation (V&V) [9] [10] [11] [12], whereas application of DT for Concept Development and Experimentation (CD&E) is currently still embryonal [8].

1.2 Collaborative Autonomy Tasking Layer (CATL)

As previously stated, communication and data exchange have a key role to achieve a key concept behind DT: the continuous link with the real systems. Especially important considering the limited communication bandwidth available in the underwater environment is to define a common protocol and data-model to exchange data, information, and tasks. A NATO working group belonging to Systems Concepts and Integration (SCI) entitled "Enabling Federated, Collaborative Autonomy" is working to build up a common language between heterogeneous assets to create a system of task generation and exchange. This system has a dual purpose. Firstly, the system connects heterogeneous assets independent of the actual command and control in use. Secondly, the system orchestrates the data flow between the assets as efficiently as possible, taking into account the limited bandwidth available in the underwater domain.

CATL was not developed intentionally for the DT use-case but parallel developments, with the study on DT being applied to MUS, resulted in a productive collaboration.

The use of DT for MUS is an excellent case study from several perspectives: especially for underwater assets, the acoustic channel is particularly limited, being noisy and affected by multi-path, while DT require a constant and comprehensive exchange of information. It is possible to recreate a representation of the evolution of the underwater environment by exploiting the data collected from a multitude of sensors. Moreover, the currently used assets are not required to abide by specified standards and are therefore extremely heterogeneous in terms of navigation capability, decision-making capacity and sensors used.

REPMUS22 and DYMS22 represented an interesting opportunity to test such capabilities: indeed, different research groups, following a general architecture, independently implemented the ability to receive and transmit different tasks in a common language called Collaborative Autonomy Tasking Layer (CATL).

1.3 MUS

MUS encompasses a broad range of unmanned systems. In this study we use Underwater Unmanned Vehicles (UUV), typically equipped with a payload of acoustic sensors (Hydrophones, Synthetic Aperture

Sonars, Side Scan Sonar, linear/volumetric-active/passive sonar arrays), acoustic telecommunication modems for underwater communications, and navigation sensors. The MUS are capable to follow missions autonomously while collecting data, mainly, from acoustic sensors. Data, collected during missions, is processed and used for the generation of contacts and/or tracks; some evolved MUS can adapt to the evolution of the scenarios modifying their missions and tasks, adopting cooperative behaviour, and as such autonomously improve its mission performance.

Operating most of the time underwater, communication is severely limited by physical and technological constraints, and/or by operational considerations. The limitations on communications, imposed by the underwater environment, surely is a driver for more autonomous MUS capabilities. Developments such as the use of artificial intelligence on-board, designed to automate sensors raw data processing to generate target detections and tracking, redesign the mission assigned by the operator and automate the tasking of the cooperative/collaborative[1] fleet, leaving the UUV operator unaware of the situation underwater for considerable portions of the mission duration. When possible, underwater communications are limited to vehicles telemetry at low sampling frequency and mission updates from the operator to the vehicle.

Once emerged, the user connects the control station through Wi-Fi and radio antennas with the MUS and can download the collected underwater data for post-processing and analysis.

2 METHODOLOGY

The CMRE M&S team follows a methodology for M&S solutions defined in 2018, in a project a SACT funded project (SAC000812 [13]). This methodology follows the NATO guidelines for the implementation of M&S capabilities stated in the NATO M&S Master Plan [14], it applies the IEEE 1730 Std. – Distributed Simulation Engineering and Execution Process (DSEEP) [15] and IEEE 1515.4 Std. – Recommended Practices for Verification, Validation and Accreditation (VV&A) of a Federation [16]. The execution of the DSEEP methodology was supported with the use of model-based systems engineering approaches, such as the NATO Architecture Framework (NAF) v4.0 [17], in the design of the simulation environment

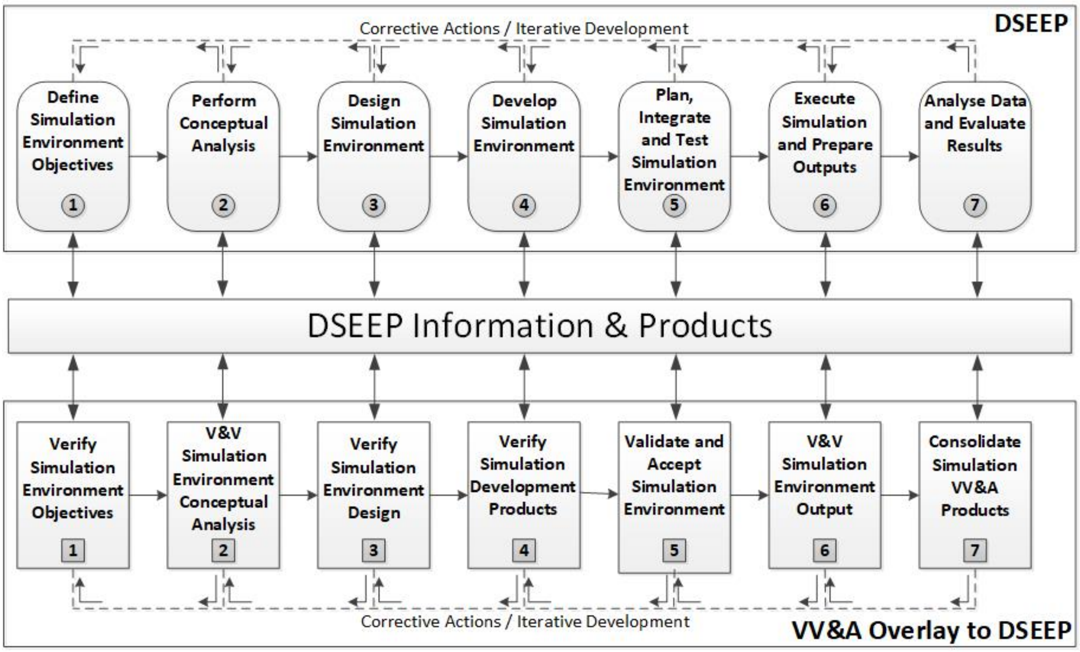

Figure 2 – STANAG 4603 DSEEP and VV&A overlay processes

3 RESULTS

This section specifies different scenarios for the application of DT. As per standard definition, a scenario is a bounding mechanism for modelling activities. It includes the types and numbers of represented entities and a functional description of the capabilities and the relationships of these entities over time [15]. Scenarios can address different kind of use-cases: for Operational users, to clarify the operational picture, compensate data incompleteness, and to develop new experiment and tests. Other types of scenarios can be designed e.g. for training human operators or MUS developers to manage the health status of different assets and to test, evaluate, verify, and validate new components, algorithms, or behaviours.

Thus, the scenarios identified are as follows:

- Clarify the operational picture;
- Compensate for data incompleteness;
- Concept Development and Experimentation (CD&E);
- Training;
- Health Monitor Systems (HMS);
- Test and Evaluation to Verify and Validate (TEV&V).

Figure 3 is a pictorial representation of the *Clarify Operational Picture* scenario, this scenario is used to demonstrate the DT prototype, for a better understanding to the reader.

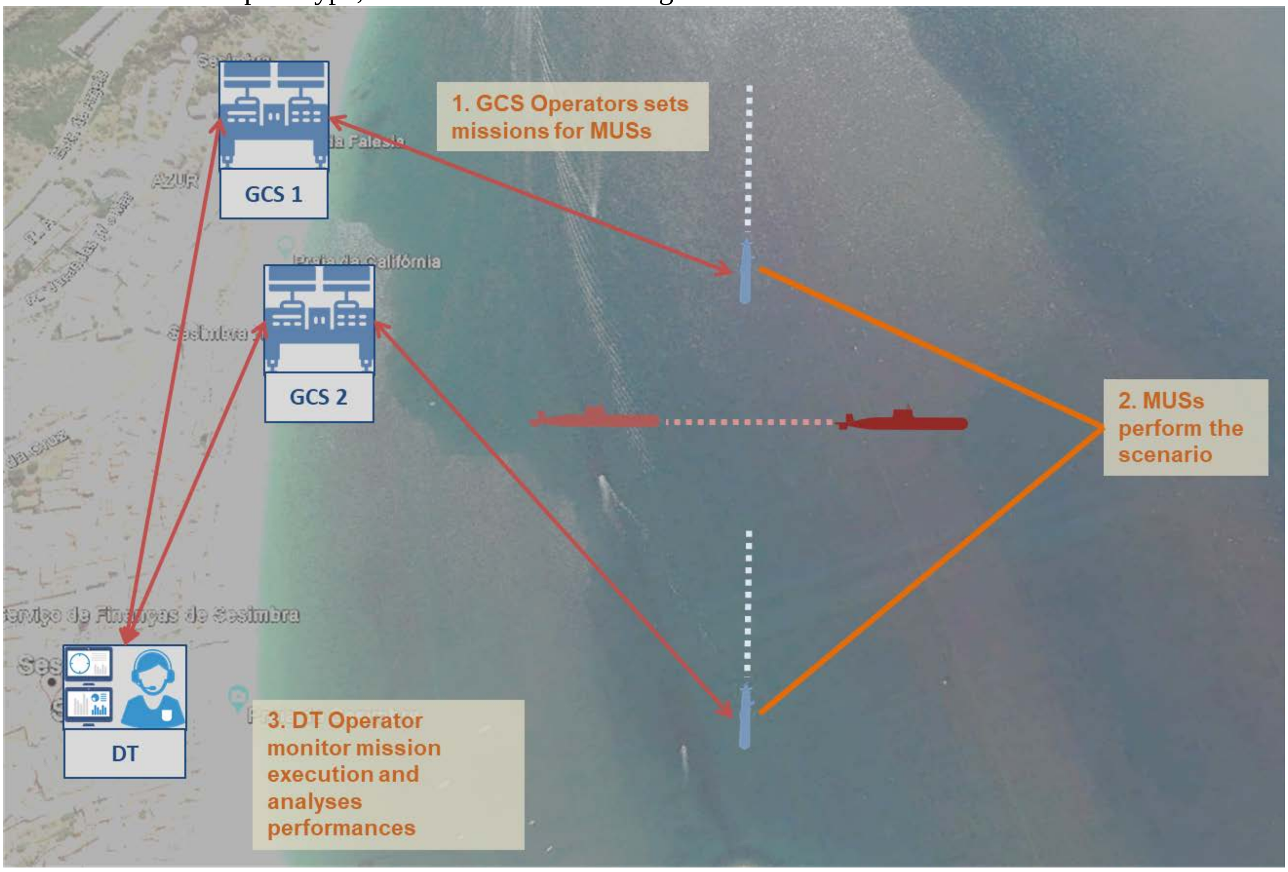

Figure 3 - MUS DT Clarify Operational Picture Scenario

Scenario Scope: Provide the MUS operator with a common operational picture fusing partial data shared by the vehicles.

As mentioned before, the lack of communication during (part of) underwater operations leaves the operator of a MUS fleet blind for considerable portion of the mission duration (even hours). In this case, the Operator uses the DT services to reconstruct and visualize a hypothetical underwater situation based on partial data from telemetry or contacts, which is synchronized when vehicles are able to communicate. The virtual entity includes the autonomy engines installed on board the vehicles and the simulator of the sensors, to work out the underwater situation based on the partial data shared by the vehicles.

3.1 Prototype

A specific instance of the reference architecture introduced in the previous paragraph has been deployed during REPMUS 2022 and DYMS 2022 (Figure 4). The architecture was implemented and deployed to fit the Clarify Operational Picture scenario described above; specifically to:

- Visualize real assets in a 3D realistic environment;
- Augment the mission, where real assets and simulated assets execute a parallel missions (ghosting) to highlight discrepancies between realistic operational conditions and initial planning conditions;
- Augment real assets with simulated sensors to simulate sensors performances;
- Inject simulated events in the real scenario.

The crucial component of the DT is by far the Interoperability Federate. The M&S team at CMRE developed and deployed a bridge that allows the exchange of C2 messages between the M&S federation and the C2 environment (real systems). To achieve this C2 interoperability, the team relied on the C3MRE infrastructure based on the CATL data model and an MQTT broker. The result of these implementations produced an enabler for a prototypal DT, used as a service for situational awareness, TEV&V, and CD&E.

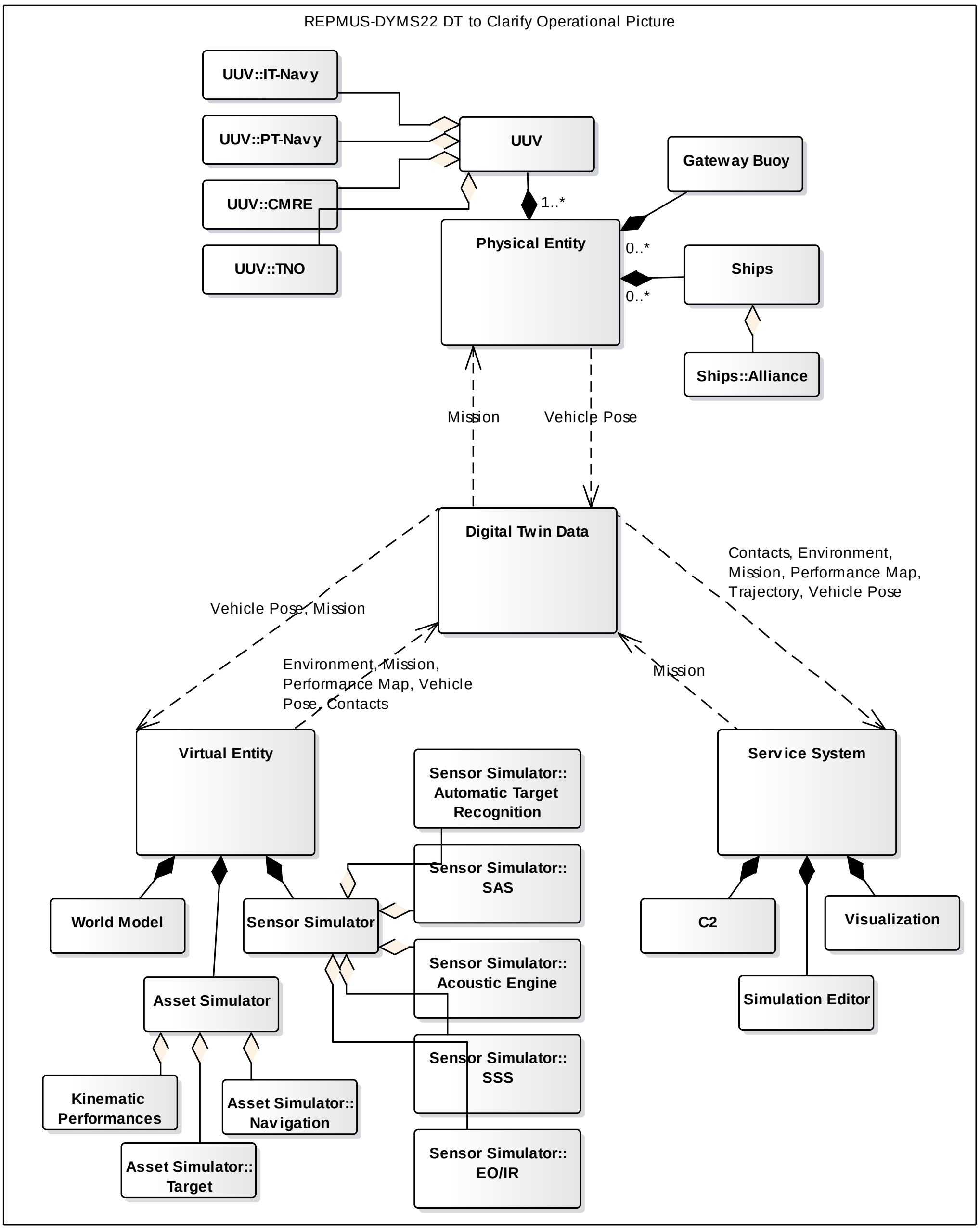

Figure 4 – DT architecture deployed during REPMUS and DYMS22 for MCM team

As mentioned in the introduction, the M&S capability (federation) is based on the IEEE standard/Stanag, High Level Architecture, HLA [18]. Authors have also investigated the possible usage of the RPR V2.0 FOM [19], adopting a specific instantiation of this data model to comply with the characteristics of underwater scenarios. One of the objectives of the M&S team at CMRE is to use M&S as a bridge between communities, especially between Robotics and C2. The Interoperability Federate is designed to support this integration, with software-in-the-loop simulations, with a particular focus on verification and validation of non-real time (fast time) simulation.

A more detailed explanation of the functionalities developed in the past years of the Interoperability Federate can be found in [20] and [21].

In 2022, the M&S federation was upgraded with the capability to support MCM teams to use the federation during REPMUS22 and DYMS22 as a situational awareness tool. For this capability, A CATL Bridge was implemented that allows any CATL and C3MRE compliant asset to exchange information with the M&S federation, hence allowing the federation to move towards the implementation of the DT concept.

The bridge allows the exchange of C2 messages between the federation and the autonomous vehicles C2 (Figure 5).

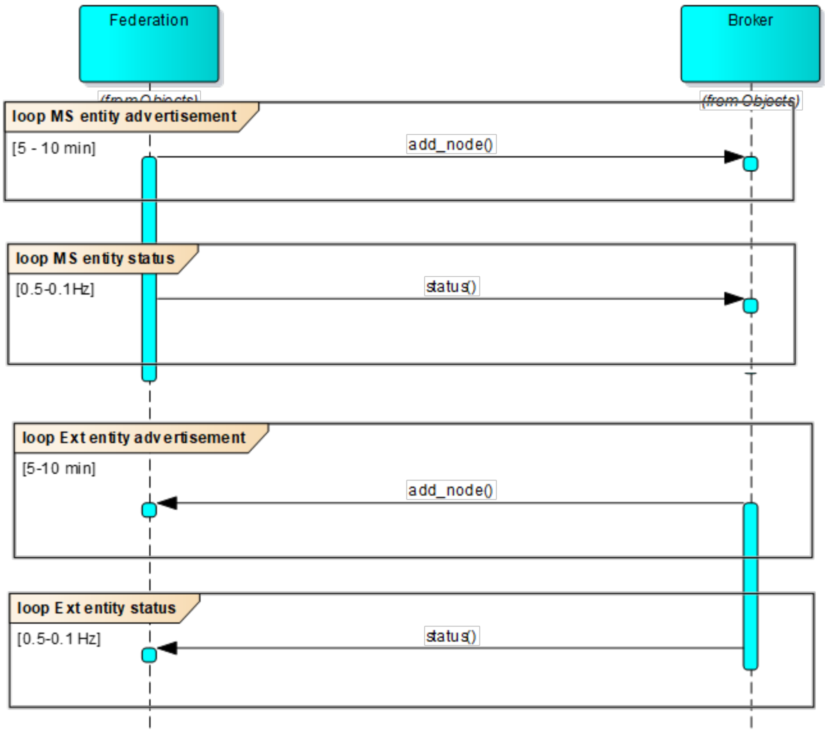

Figure 5 - Messages of interest for the CATL Bridge

To achieve C2 interoperability the federation connected to the MQTT broker infrastructure as per Figure 6.MQTT stands for MQ Telemetry Transport and it is the most commonly used messaging protocol for the Internet of Things (IoT) [17]. MQTT is an event driven protocol that connects the devices using a Publish-Subscribe pattern. Two clients were developed in order to connect to the broker using the Paho library. One is responsible for sending messages from the Federate to the client, while the other is responsible for receiving messages from CALT/C3MRE into the simulation (Figure 6).

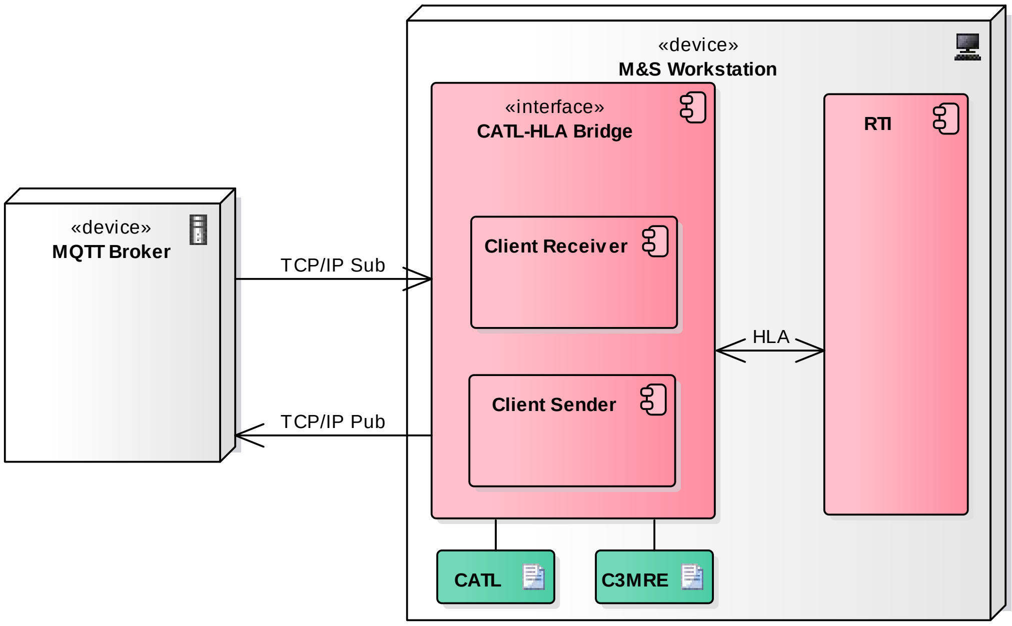

Figure 6 - CATL Bridge deployment schema

Figure 7 shows an example of the execution of the DT during REPMUS, where the simulated vehicles are acting in the same operative scenario as the real vehicle. On the north-east corner, a group of cooperative simulated vehicles perform survey tasks while on the south-west corner of the scenario area real vehicles are enhanced with simulated sensors. Both real and simulated vehicles share detection data among each other. The 3D visualization is provided as DT service to the user, displaying 3D reconstruction of vehicles, trajectories, assigned missions, sensors field of view and footprint in both a realistic 3D reconstruction of the scenario geography and on a tactical map.

The DT was continuously used during the two weeks of the exercise by both operators in Portugal and concurrently by scientists in Italy to reconstruct, monitor and test the performances of assets during the exercises.

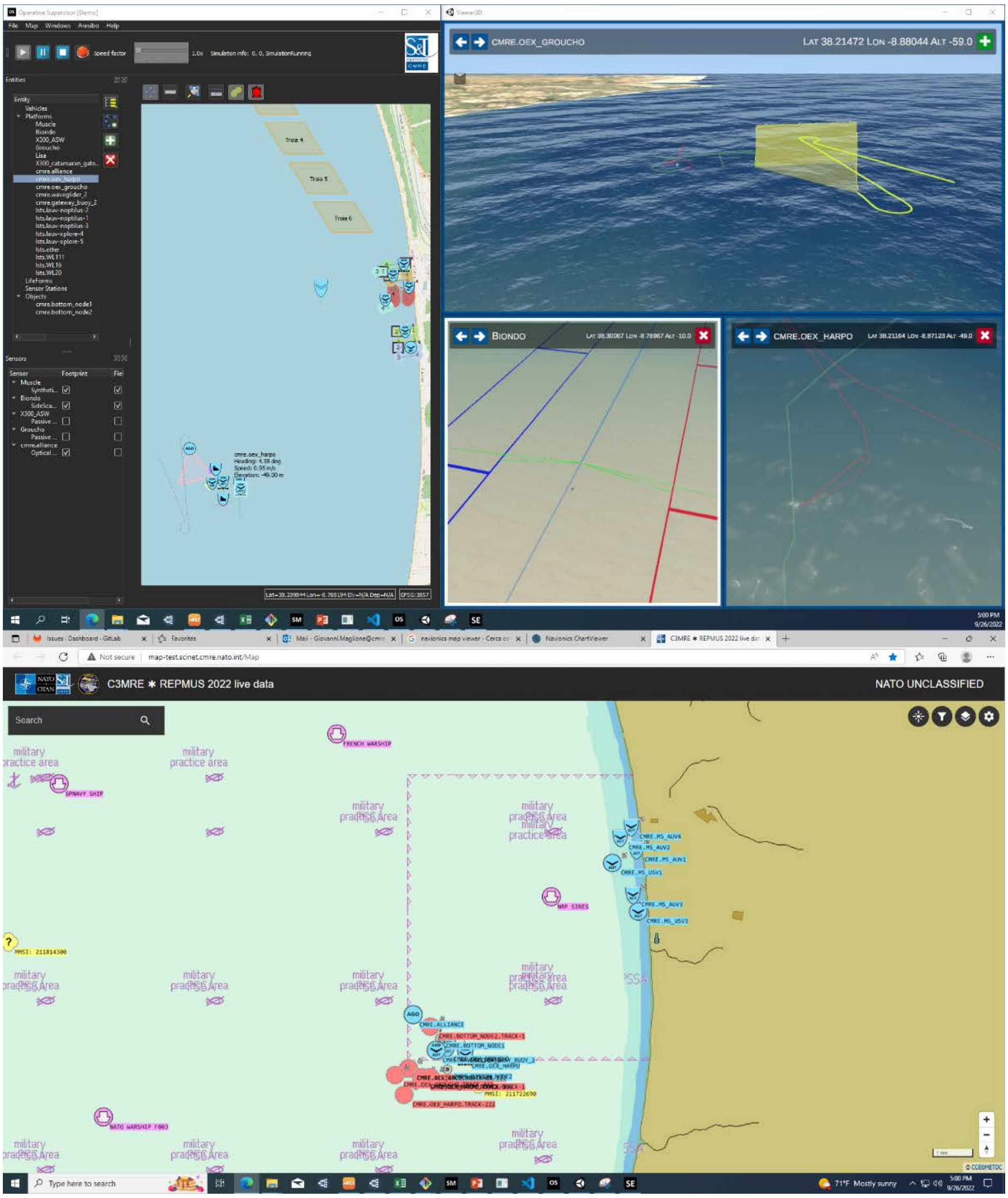

Figure 7 - Example from REPMUS. On the top the M&S federation GUI and the 3D visualizer, at the bottom the exercise C2

4 CONCLUSION

In this paper, the concept of Digital Twins for Maritime Unmanned Systems (MUS) is introduced. Although the concept of Digital Twins is not new, in the application area of MUS DT is not yet a commonplace. The work described aims to provide a valuable starting point for DT in this area for clarifying the operational picture and more in general using DT to provide valuable insight in the use of MUS for maritime underwater operations where it is difficult to monitor systems that conduct their tasks mainly unmanned and autonomously for several hours before servicing again. Mine countermeasures (MCM) and Anti Sub-marine Warfare (ASW) are taken as the use cases but the DT concept is valuable for many more use cases in the

MUS domain.

The authors designed and defined an architecture and several scenarios, based both on real-time data exchange and on data fusion, in order to compensate for the limited capacity of the acoustic links between different underwater assets. Next, the feasibility and potential of this technology was demonstrated in a real-life exercise. In 2022, the M&S federation capabilities where expanded to move towards the concept of DT. A prototype was deployed for experimentation during the REPMUS22 and DYMS22 exercises held in Portugal, September 2022, addressing specific user needs that resonated within the operational community and generated a stream of requirements for future developments.

The proposed DT concept is designed to aid and augment operations and exercises with autonomous underwater vehicles, applied to mine countermeasure (MCM), anti-submarine warfare (ASW) and environmental monitoring. One of the main aims of DT in MUS addressed is that of having limited underwater communication during prolonged periods of autonomous operation of AUV underwater. Operators are left mostly unaware of the mission execution at real-time: what is the position of the vehicle in the space? How is it navigating with respect to the sea bottom? What is the footprint of the imaging sonar on the sea bottom? What is the relative position of vehicles operating in the same area? Where are detection clusters from multiple vehicles located underwater? Is the current execution of the mission coherent with my planning or, in other words, did I consider correctly the operative conditions while planning this mission? These are all questions that can be investigated by the deployment of the proposed DT prototype.

The main limitation identified in this study is the scalability of the current architecture. The presented prototype was tested with about 30 real vehicles, all located in the same geographical area of about 40km radius. Recent tests showed that the 3D visualization capability has lowered positioning accuracy when vehicles are hundreds of kilometres away, mainly due to internal representation. It was identified that the 3D capability needs refactoring to have positioning accuracy independent from the actual absolute location of the vehicle.

Another topic of interest is that some of the simulation models are computationally intense (e.g. the acoustic engine that runs on dedicated servers). It was identified that the infrastructure needs to be improved in support of scenarios with a higher number vehicles present. At the same time, there needs to be a continuous effort to optimize the algorithms for processing efficiency.

The amount of data that is needed to have accurate (validated) models is another important issue. Obtaining relevant data and the validation of the developed models using this data is a time consuming job. Confidentiality and or classification can lead to further complications and this must be taken into account when identifying the data needs.

Areas of future investigation include simulators for the communication channels. Another aspect to improve is remote usability, i.e., the use of simulation services remotely (Simulation as a Service). This aspect, already investigated by the NATO Modelling and Simulation Groups [22], allows an external user, for example research centres, university laboratories, or private companies, to interact with the federation adopting an 'as-a-Service' approach. Starting from 2024, the team will investigate the potential use of the Digital Twin to analyse the performances of the vehicles in exercises.

A further possible investigation area is the generation of simulated raw sonar images. To date, the need for collecting extensive databases of sonar images is constantly growing. Indeed, artificial intelligence algorithms designed for autonomous target identification deeply rely on large collections of labelled sonar images. However, the collection of such images is a challenging and expensive endeavour. The generation of simulated sonar images has the potential to play a role in this challenge. Indeed, collecting large datasets would be easier, yielding simulated images that could be used for training artificial intelligence algorithms (e.g., initialize the training of AI models that can then be fine-tuned via a reduced collection of real images).

The authors, with the support of Italian Navy intend to explore and evaluate applications of Digital Twin in relevant operations at sea, outside the relatively controlled environment of an exercise.

In conclusion, this study aimed at providing an overview of DT in the underwater domain opening new perspectives for future research.

AUTHORS NOTE

This paper is an extract of a journal article wrote in collaboration with the Italian Navy. To date, the journal article is in its final review state.

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