SYNTHETIC ENVIRONMENT FOR INTEROPERABLE ADVANCED MARINE SIMULATION

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ABSTRACT

This paper proposes a new virtual simulation environment designed as element of an interoperable federation of simulator to support the investigation of complex scenarios over the Extended Maritime Framework (EMF) including sea surface, underwater, air, coast, space and cyberspace.

The paper proposes different complex cases as examples to validate this approach related both to deep waters and to coast and littoral protection. These simulation environment involves different kind of traditional assets (e.g. satellites, helicopters, ships, submarines, underwater sensor infrastructures, etc.) interacting dynamically and collaborating with innovative autonomous systems (i.e. AUV, Gliders, USV and UAV). The proposed synthetic environment based on the use of virtual simulation supports validation of new concepts as well as the investigation of engineering and collaborative solutions. So the proposed approach enables the creation of dynamic interoperable immersive frameworks useful for Man-in-the-Loop training, education and tactical decision making by creating a support for the Man-on-the-Loop concept.

Keywords: *Interoperable Simulation, Maritime Simulation, Heterogeneous Networks, Autonomous Systems, Modeling & Simulation, Port Security, Man on the Loop*

1. INTRODUCTION

The research and development of the Autonomous Systems is continuously growing up because of their increasing performances and versatility thanks to recent progress of the technology. Today it is possible replace humans with such vehicles in many actions which makes them faster and more secure and their use is becoming popular in a large quantity of sectors from defense to civil protection, oil and gas, etc.

Figure 1 – EMF and corresponding Autonomous System Examples

In the external environments the autonomous systems deals with all the different domains including air (UAVm Unmanned Aerial Vehicles), sea surface (USV, Unmanned Surface Vehicles), land (UGV, Unmanned Ground Vehicles), underwater (AUV, Autonomous Underwater Vehicles,), etc. In particular the underwater environment emphasizes the importance of autonomy due to the heavy limitations in underwater communications affecting remote control and coordination capabilities over multiple domains (Tether 2009; DARPA 2012; Shkurti et al. 2012); among the others autonomous systems, the AUVs introduce additional challenges being a crucial element into the Extended Maritime Framework (EMF, sea surface, underwater, air, coast, space and cyberspace) (Shkurti et al. 2009) so it is evident the necessity to rely on Modeling and Simulation (M&S) to investigate the different possible solutions in such innovative sector and to test them integrated within real systems; indeed this context is pretty interesting for many strategic sectors such as Defense, Security, Port Activities and Oil & Gas (Bruzzone et al.2010; Bruzzone et al. 2011b; Bruzzone et al. 2014a).

Obviously a similar approach could be easily extended to be applied to other sectors, therefore the complexity of the marine environment (especially underwater) makes this solution pretty unique within this framework.

2. AUTONOMOUS SYSTEMS WITHIN EMF & JOINT SIMULATION ENVIRONMENT

In general, the autonomous systems development requires continuous test so a time-effective approach might result very useful. In this context, simulation fosters a better understanding of the behavior of Unmanned Vehicles and avoid useless experimentations and costs by allowing to identify and solve the problems in advance by virtual world experimentation (Stilwell et al. 2004).

Indeed the engineering processes gain from the simulation a strategic advantage for instance the creation of an interoperable synthetic environment for EMF allows to study the most effective and efficient behaviors for joint operations among multiple autonomous systems interacting with traditional assets; by this approach it becomes possible to optimize them and thus find critical points of the systems and to engineer their design. This paper presents the creation of a virtual environment with the aim to simulate and understand a Joint Naval Scenario over the EMF.

The scalability is a very crucial element considering that this EMF should be able to address from Hardware and Software in the loop issues up to operational procedures and policies.

This study especially focuses on the integration of Autonomous Systems with traditional assets; the proposed simulation deals with collaborative operation involving different types of Autonomous Underwater Vehicles (AUV), Unmanned Surface Vehicles (USV) and UAV (Unmanned Aerial Vehicle) with surface and underwater vessels as well as with sensor networks.

The authors designed an interoperable virtual simulation devoted to integrate different systems within one environment able to simulate and represent the overall situation. The simulators are combining discrete event stochastic simulator with continuous simulators (Bruzzone et al. 2007; Longo F. 2012, Longo et al., 2013); intelligent agents are used to create a distributed control of the autonomous systems (Bruzzone et al. 2011b; Ören et al. 2009; Feddema et al. 2002). The proposed system, designed MAMA (Multiple Advanced Maritime Architecture) is able to guarantee the simulation of the different systems as well as their supervision, but considering the different capabilities of sensors, communications systems and platforms (Bruzzone et al. 2011d); this simulation enables to address complex Measure of Merits including mission effectiveness as dynamic results dependent of the different variables and behaviors affecting the complex heterogeneous network of available assets.

The researchers aim to define also guidelines and standards to develop this flexible virtual simulation solution; in this case it was decided to create an HLA federation as crucial element to address the complexity of the EMF and to integrate them with IA-CGF (Intelligent Agent Computer Generated Forces) developed by Simulation Team (Kuhl et al.1999; Bruzzone & Massei 2007; Bruzzone 2008; Bruzzone et al. 2011e). In general use of Intelligent Agents enable the possibility to create complex behavior to investigate best policies and criteria for finalizing decision related to effective and reliable Course of Actions (Bruzzone et al. 2011a).

The general architecture is proposed by figure 2; indeed the author decided to use HLA as already successful done in flexible marine simulation environments such as ST_VP (Bruzzone et al. 2011c); indeed HLA was also successfully used in marine ports applications for training purposes (Longo et al. 2013). In this case it was decided to implement multiple RTIs including Pitch, Mäk and Portico for being available for a wide spectrum of integration possibilities; the federation was extensively tested by integrating different federates such as virtual simulator JEANS (Join Environment for Advanced Naval Simulation, using Unity 3D Graphic Engine), constructive simulation MCWS (Marine Cyber Warfare Simulation), physical model MSTPA (Multi-static Tactical Planning Aid acoustic engine), SPARUS-ROS (AUV Real Control System based on Robot Operating System) and open to other models (Bruzzone et al. 2013b). Different kind of FOM was investigated and tested this architecture respect its capabilities including MCWS-MSTPA, RPR (Real-time Platform-level Reference for integrating DIS legacy systems) and preliminary STANAG 4684 (Virtual Ship).

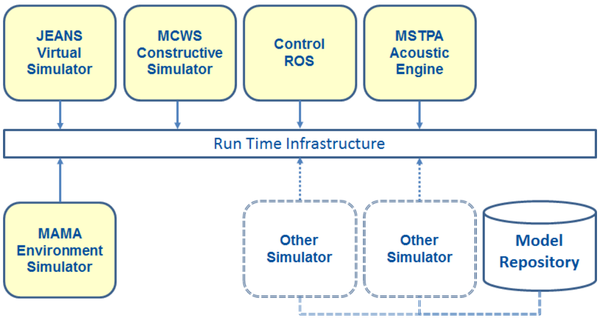

Figure 2 - Architecture Interoperable Simulation for EMF

Indeed this new generation of marine interoperable simulation represents an important strategic advantage being able to introduce new assets within the scenario as well as models characterized by different level of fidelity based on the simulation objectives; this allow to use it as a flexible approach for experimentation and investigating over a wide spectrum of problems related to the operational use of autonomous systems and to find new ways to use them respect different scenarios.

The paper proposes different scenarios: one related to military operations and another one on coastal and littoral protection where the virtual simulation proposes the overall situation and allows to experiment the different solutions into the virtual world considering the complex physics affecting movement, perception, interactions and communications (Bruzzone et al. 2012; Bruzzone 2013a).

By this approach it becomes evident the capability to identify, by experimental analysis within the virtual world, the new solutions in terms of engineering and technological configuration of the different systems and vehicles as well as new operational models and tactics to address the specific mission environment.

The proposed case study is about a maritime scenario with a representation of heterogeneous network frameworks that involve multiple vehicles both naval and aerial including AUVs, USVs, UAVs, gliders, helicopters, ships, submarines, satellites, buoys and sensors (Bruzzone et al. 2013c).

The simulator is developed according to High Level Architecture (HLA) Standard (IEEE 1516 evolved) to ensure interoperability and allow its extensibility for other case studies (Bruzzone et. al.2007c; Joshi et al.2006).

In some way this approach adopt the MS2G (Modeling, interoperable Simulation and Serious Game) paradigm combining M&S and Serious Game (SG) by framing integrating by HLA also a virtual world easily deployable on multiple distributed solutions (Bruzzone et al. 2014a). Involvement of Subject Matter Experts (SME) as users during the development process is fundamental to take advantage of their Know-How along the validation process in such sense the synergy with CMRE resulted very useful.

The creation of a versatile simulation engine is thus effective to achieve the highest knowledge collecting capability to allow expert to face the widest range of possible situations.

In MAMA areas are defined where weather condition are defined including sea current, wind, waves, surface temperature, fog, rain, salinity and thermal layers, etc (Lundquist 2013). For instance the sea current is introduced as additional velocity component for all objects operating within the water, under the assumption that it provokes a body shifting as if bodies are moving respect to a steady drifting inertial coordinate system.

MAMA framework support integration with real systems this allows to federate also hardware and software in the loop as well as man in the loop controls.

3. MODELS OF PLATFORMS & SYSTEMS

To simulate the different assets operating within EMF it is necessary to adopt real-time models able to deal with a large number and variety of platforms. Several alternative models has been tested, therefore, as expected, the main issue in this phase is to properly scale fidelity with computational workload. The guideline is obviously defined by the specific requirements and objectives of the simulation; indeed the authors by MAMA allowed to use different models with different resolution levels and fidelity; for instance the acoustic models for the passive sonar have been developed ad hoc for this project, while active acoustic could be based on simplified meta-models or by federating a specific acoustic engine.

In the deep sea scenario models of AUV and Gliders have been developed including physics, control, communications and sensors; the different models of each new asset or system is defined within a repository that allow to use it for different scenarios based on the specific needs (Maravall et al. 2013).

Indeed the simulation instantiates all the n-copies of library objects and assigns their control to the IA (Intelligent Agent) related to the specific system or platform. In most case it was decided to use simplified meta-models (e.g. sea keeping, underwater communications) that consider just main elements in order to guarantee the possibility to conduct experimentations also with an high number of objects to be simulated.

For instance it was implemented a model for the gliders that are autonomous underwater vehicles without propeller with long autonomy able to operate and move just by changing buoyancy in order to glide underwater up and down (Bhatta et al. 2005); for these platform a special pitch control was activated allowing them to sail underwater by triggered based on vehicle depth and sea bed configuration; in this way the vehicle glides avoiding impact on the bottom and move towards. Those depths are computed as a function of the advance speed and the trim angle of the vehicle considering a circular trajectory (conservative) and then adjusted through safety factors.

The glider stops pitching (angles positive clockwise) when the limit on the trim angle is reached. Second derivative of trim angle over the time (angular acceleration) is given as a descriptive parameter of the system to be modeled.

As a matter of example is reported the portion of the code responsible for the computation of the safe distance where to pitch 'rkm3':

$$R_{cr} = S / As_2$$

$$Hs = k_1 R_{cr} \ (1 - \cos(|a_2|)) + k_2;$$

R_{cr}	curvature radius,
S	advancing speed of the vehicle along his longitudinal axis
As_2	Angular velocity respect pitch
a_2	Pitch
k_1 ,k_2	safety factors (e.g. $k_1 = 1.2$, $k_2 = 1$)
Hs	safe distance to change the pitch for gliding

Indeed the advance speed that is one of the governing parameter for the current control; the model considers that this speed is influenced by the oscillation on lift direction, resulting in reducing velocity when the glider surge direction is close to be horizontal.

Indeed the control allows for heading on targets and waypoints

Course angles in the horizontal plane (angles positive clockwise) are:

a_1	the course as angle between North and platform advance
drd	direction between north and the vector pointing at the target/waypoint
drd_0	the difference of the two and indicates the yaw

angle to be covered to head on the target.

If drd_0 module is higher than 180 degrees than his complementary is chosen, meaning the vehicle yaws on the opposite direction.

Once determined drd_0 as the most convenient angle to head on the target, the vehicle experiences an angular acceleration representing the lift force generated by the rudder blade.

To allow the vehicle to keep the course heading on the target, the angle A_{IRB} when to invert the rudder blade (when an opposite angular acceleration start to be experienced on the center of gravity) is computed as

$$A_{IRB} = k_3 \left|Sa_1^2 / Aa_1\right|$$

Sa_1	angular yaw velocity
Aa_1	acceleration on yaw
k_3	safety factor (e.g. k_3=0.9)

Target is considered reached when the vehicle gets to a certain distance in the horizontal plane; normally to speed up simulation this distance is proportional to platform speed based on a parameter specific for the platform that affects the precision of the targeting; the gliders and AUV could be assigned to path based on waypoint or on patrolling an area autonomously based on different scheme such as creeping line and random multi-agent search.

A different and integrated control is defined for course and pitch respect the presence of other vessels in order to avoid collisions.

Indeed obstacle avoidance is currently under development to combine the vertical management of this issues with course adjustment when the longitudinal projection of body cross section intercept a physical object and there is not enough depth into the area to glide down.

These controls are integrated within an intelligent agent that drives each of the glides within the scenario and take care of activating SATCOM when surfacing for data transfer.

The IA uses collisions in order to generate HLA interactions based on box colliders able manage the phenomena.

4. MS2G & MAN-ON-THE-LOOP

MS2G is a powerful paradigm able to guarantee the engagement of SMEs in many different areas; in MAMA case this allow to get a comprehensive representation of the EMF within the virtual reality; obviously this support the man-on-the-loop concept (Magrassi 2013).

This means that decision makers could observe in the virtual environment a 3D representation of assets and their capabilities (e.g. discovering spheres, autonomy ranges, communication ranges) and assign high level task to the IA controlling each autonomous system without need to remotely control in details their activity directly or through waypoints (Cooke et al. 2006); this leads towards introduction of orders and collaborative behavior through combined task assignment to autonomous vehicles operating within an area (Bruzzone et al. 2013b; Ferrandez et al. 2013; Kalra et al. 2007; Shafer et al. 2007a; Vail et al. 2003); for instance it could become possible to assign a USV to recharging and fast data collection over a set of AUV within an area or a set of AUV to create a dynamic underwater dynamic cascade communication network over a zone; indeed in the future collaborative tasks are expected to become very important (Richards et al.2002; Ross et al. 2006; Tanner et al. 2007; Shafer et al. 2007b).

Obviously this approach supports improvements in distributed exercising providing a more clear understanding of the events and situation; in this case the users could be able to figure visually the different COAs (Courses of Actions) in the Extended Maritime Framework, while the interoperable stochastic simulator evaluates consequences of the different alternatives and estimates risks.

The expertise accumulated via MS2G constitutes a base knowledge for future projects.

The communications among the entities are defined through a dynamic evolving set of nodes and links connecting real and virtual assets; each of these links is defined in terms of type (e.g. Radio frequency, Satcom, Acoustic Modem, optic fiber, etc); capability, bandwidth, basic model, background standard traffic model, reliability, confidentiality, availability, integrity, mutual interference; the messages are managed as pockets moving along the heterogeneous networks and even visualized in terms of status and connection over the virtual representation of the EMF; each assets could define a connection point to visualize the communication by some kind of augmented reality; it is important to outline that underwater communications are usually strongly constrained in terms of range and speed going often down to 100 bauds. Based on the communication model adopted the availability of the communication is computed even considering the capability to use other nodes as bridges; in similar way a standard traffic model is used to considering the bandwidth utilization where to add the specific communication packages simulated, allowing to use simplify meta-models and networks; therefore MAMA structure allows to integrate specific communication models in case the need for an high fidelity simulation of detailed large communication architectures; in the past for instance the authors have developed federation integrating Opnet based simulators to deal with these aspects.

5. GRAPHICS

The authors evaluated different solutions for the graphic engine including among the others Vega Prime, VBS2 and 3, Unity 3D; also in this case the use of MAMA architecture keeps open the possibility to use different visualizers and currently the author are working on a distributed application integrating both Unity 3D and Vega Prima for AUV docking simulation using legacy simulators (Bruzzone et al. 2011e; Zini

2012).
However all the cases proposed here are using Unity3D as graphic engine and Suimono as graphic tool for water effect; indeed Suimono tool does not consider influence of external forces on ship hull, but hydrostatic pressure distribution given directly as buoyancy force as an input parameter. Therefore the authors are using their physical models to deal with these aspects and in particular to develop the dynamic description of buoyant or submerged body; indeed in this case is necessary to create an own model taking into account hydrostatics and hydrodynamic forces addressing at hull stability, motions of body in still water, sea keeping, maneuverability, ship propulsion and all what Naval Architecture concerns.

The 3D representation of the scenario include visualization of assets and communications as well as capabilities; these are supported by a free camera management system implemented within the Graphic User Interface (GUI); this entitles the users to fly around and observe the whole EMF scenario and to move freely in the synthetic environment in order to investigate different phenomena by best perspective of the scene.

Moreover, each object has its own inertial camera; so the players are enabled to adopt the visual from that specific object and to observe what is going on the scene from that point of view. This should allow players to have a better involvement in the simulation and to understand the COA by a direct visual perception of what is happening in every moment.

In facts the simulator is supplied with features to improve perception of the scenario and to see beyond the limit of real awareness, providing visual representation for the limitation of aerial and underwater communications, underwater sight, etc.; in addition the whole water can be toggled removing it to see the whole assets over and under the surface, additional markers are used to identify the platforms and understand their operational status.

This approach was extensively used with SME for supporting VV&A (Verification, Validation and Accreditation) of the models and of their interactions; in addition the proposed graphic supports the training and after action review fur future applications (Massei & Tremori 2010; Kennedy 2010; Kracke et al. 2006)

6. SCENARIOS

Different scenarios have been simulated to validate MAMA approach. Deep water scenario includes difference cases and aims to simulate interactions between traditional assets in EMF (i.e. satellites, navy ships, submarines, NATO Research Vessels (NRVs) helicopters) with new generation unmanned assets (i.e. AUV, Gliders, UAV, USV) and the mutual advantage the subjects involved in the scenario can have. In other word, the increase in persistence, interoperability and efficacy.

The littoral scenario is mostly devoted to model the behavior of unmanned assets and traditional asset involving AUV, USV and vessels to control the coast and to patrol a harbor to find possible threats through a persistent surveillance. These cases aims to develop and test new solutions for autonomous vehicle release and docking as well as for patrolling; for instance it was studied an algorithm to lead patrolling toward an optimum, guaranteeing an high probability of success in the safest way reducing human involvement in the scenario for marine C-IED missions (Counter Improvised Explosive Device).

In all scenarios the authors are experimenting the different engineering solutions and integration technologies in order to guarantee interoperability among the different systems; in particular experimentation are ongoing by testing them within HIL and SIL simulations (Hardware and Software in the loop).

Deep Water Scenario - Glider Fleet Management Case

In this case a Destroyer and a oceanographic ship are sailing while a fleet with up to 200 underwater gliders are moving autonomously underwater to collect salinity and temperature data and using passive acoustic sensors; over them a Predator and a Global Hawk are available as sensor platform and communication nodes as well as a Satellite; on the sea bed in this scenario a sensor infrastructure is collecting passive data while sonobuoy are active for multi-static operations.

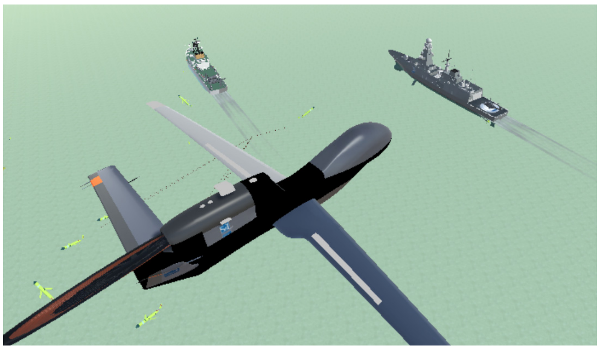

Figure 3 - Deep Water Scenario - Glider Fleet Management Case

Deep Water Scenario – Task Force Defense

This scenario involves a surface task force including 2 frigates, 2 destroyers, a medium size aircraft carrier; the task force and its aerial resources is supported also by a submarine, some AUV and an air patrol provided by UAV; the task force has to face up to over 30 supersonic missile threats launched behind the horizon by an hostile attack submarine that is receiving satellite information on task force; also in this case helicopters, sonobuoy and underwater sensor networks could be activated; the scenario allows to investigate different cooperative engagement policies as well as reliability of the processes (Calfee & Rowe 2004)

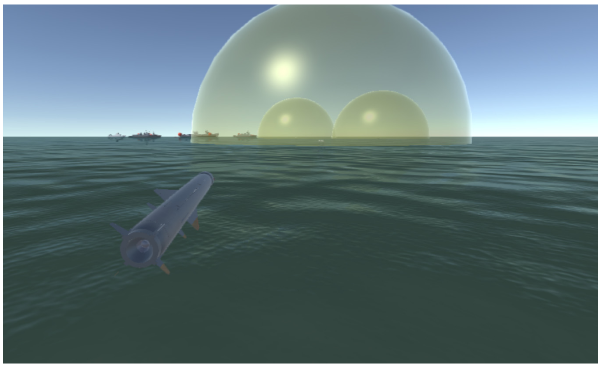

Figure 4 - Deep Water Scenario – Task Force Defense

Littoral Scenario – Patrolling, Deploying and Recovery

This scenario includes an oil platform, a frigate and a set of AUV; the AUV patrol the area by different logic and could dock or board the frigate autonomously avoiding collision and properly board by approaching the vessel' stern gate usually used for its larger RHIB (Rigid Hull Inflatable Boat).

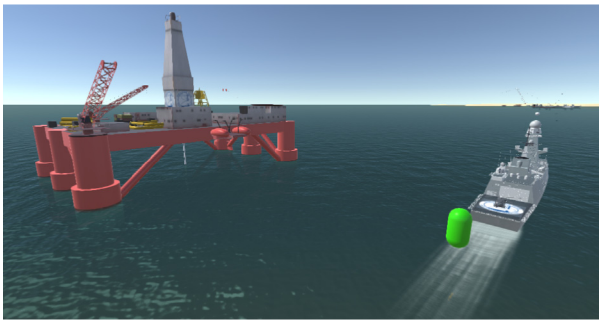

Figure 5 - Littoral Scenario – Patrolling, Deploying and Recovery

Littoral Scenario – Port Protection

In this case a USV is acting as gateway for a UAV patrolling the docks and ships into a port for marine C-IED; a UGV on the ground is used to patrol the piers from land and they are connected through an UAV flying over the area and guaranteeing a bridge with ships sailing over the horizon and for inland targeting (Martins et al. 2011; Michael 2007; Dogan and Zengin 2006; Grocholsky et al. 2006).

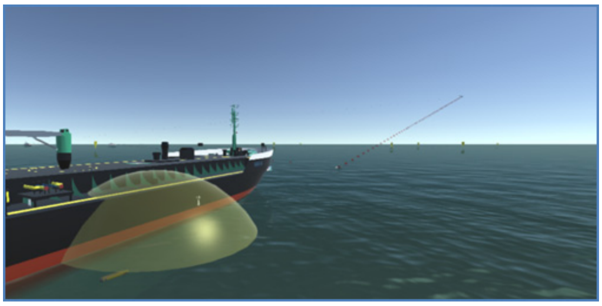

Figure 6 - Littoral Scenario – Port Protection

7. CONCLUSIONS

The proposed environment was completed and experimented confirming the validity of the proposed approach; the scenario developed include pretty advanced scenarios interoperating over a wide spectrum of simulators and systems as confirmation of the flexibility achieved. The key of success was based on availability of previous researches used for creating the new MAMA environment and the approach based on multi resolution meta-models to be integrated based on specific simulation need.

Currently the authors are proceedings in further developing the proposed models as well as in integrating new systems and new aspects.

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