NAVAL OPERATIONS' ASSESSMENT THROUGH A MULTI-PURPOSE HLA SIMULATION FRAMEWORK

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ABSTRACT

Ship design is a complex process that needs a wide range of technologies and methodologies to be accomplished, from computational calculations to physic based analysis. The main lack of this process is that ship's performances and capabilities are difficult to be evaluated during early design phase. This is the reason why a simulation tool for the test and validation of naval operations procedures in different environmental conditions could fill this gap. Usually these operations involve more entities than the single ship, so it becomes important to arrange a synthetic environment in which different simulators and simulations are able to cooperate for demonstrating complex operations. Besides this, the "system of systems" approach finds its applicability in the naval field where a ship can be represented as the cooperation of several subsystems. HLA distributed simulations represent a good solution for creating and simulating complex scenarios, allowing several simulators and partners to work together just exchanging inputs and outputs, but keeping safe intellectual properties rights. CETENA's approach to deal with the evaluation of complex operations through the use of a multi-purpose HLA based simulation framework will be presented, with particular emphasis on the main simulation activities led by CETENA in the last years like Replenishment At Sea, Landing Craft maneuverability, Vertical Take Off and Landing, Small Craft Launch and Recovery.

1. INTRODUCTION

The ship is a very complex system of systems and interacts with an even more complex environment which influence and is influenced by the ship behavior.
Usually the ship is the only prototype of herself, this is the reasons why simulation, physic based analysis and computational calculations have been largely used since long time in ship design process.
These tools and methodologies are usually used separately, in different ways and by different experts, while the final user is rarely involved in the process.
These are some of key points that bring the design approach toward the use of Virtual Reality environment and High Level Architecture (HLA) based simulation in order to develop a distributed and interactive synthetic environment as much realistic as possible.
One of the most significant purposes is to provide building companies and Navies a tool to test the overall functionality of the ship by the interoperation of multiple simulators. Virtual Reality techniques are becoming commonplace in the field of industrial design since they can help reducing time and cost of building processes, as well as providing a higher quality of the final product [1].
CETENA's approach in the realization of a multipurpose HLA [2] (High Level Architecture – IEEE 1516) based simulation framework for ship's capabilities assessment is presented in this paper.

2. VIRTUAL PROTOTYPING IN SHIP DESIGN

A prototype is any preliminary working implementation of a product, component or system and often it is less detailed than the final version. Two main classes of prototypes are used in design processes: physical prototypes and virtual prototypes.
A physical prototype is a physical model of a product, component or system. Physical prototypes requires weeks-to-months fabrication time and their modification could require days-or-weeks.
A virtual prototype is a computer simulation model of a final product, component or system. A virtual prototype can be used in a design process specifically to explore design alternatives, demonstrate design concepts, test for requirements satisfaction and/or correctness.
In practice a virtual prototype is mainly composed by three elements and/or features:

- Visualization: virtual reality can be used for navigating inside the model. The user can walk

- through the complex project viewing exactly how the product will look like. Since the environment in which he is moving is all virtual and controlled by the computer, the user can easily query physical, topological and geometrical characteristics to any system or component.
- Simulation: a static 3D view or a flythrough can be insufficient to point out problems deriving from the movement of objects on deck or interaction between correlated components. Virtual reality can help in keeping together simulation results and real time photo-realistic visualization in synthetic environments.
- Interactivity: the capability to consider the human interaction with the object we are designing may represent a considerable step forward in the ergonomic field or in stressing operational efficiency during design time. The "man in the loop" represents an important design aspect rarely or difficulty taken into account in standard design processes.

Virtual prototyping is a good way to synthesis and visualize all design efforts both for the designer and for the client who can be more directly involved in strategic decisions from the very beginning since they can view and choose between different solutions.
A virtual prototype can be configured more quickly and cost-effectively than a physical one; it can be more abstract and can be invoked earlier in the design process. Moreover a single simulator can improve its capabilities and usefulness if included in a common environment where more simulators interoperate each other to reproduce the behavior of a more complex system.
Great effort is necessary to combine design expectation (simplicity, integration, etc.) with physical and mathematical modeling and simulation. Some interaction effects which are automatically accounted for in physical models need to be consciously accounted for in numerical modeling.
Validation, verification and accreditation of simulation will be the next important step for virtual prototyping credibility and interoperability.

1.1 A laboratory for Virtual Prototyping

During the years, CETENA has developed a set of tools and software in Virtual Prototyping for Ship design. CETENA's Virtual Integrated Ship Laboratory (VISLab) is a place where experts from different ship design fields, along with IT experts, created an architecture devoted to incorporate and reuse all available software tools (COTS or in-house developed) normally used for different purposes with the objective of building a common environment for studying, using and operating virtual prototypes of existing and under design ships [3].

The underlying approach is HLA (High Level Architecture – IEE1516) which let the development of complex distributed simulations.

Being the ship an intrinsic system of systems, the HLA approach results well suited for modeling and building federations which are able to have different levels of details in the implementations of complex behaviors.
In particular this approach let us create simulation systems which can easily updated by the insertion of both new and more detailed physic effects and new interacting entities in the synthetic environment.

2.2 SAND: CETENA's Ship Simulator

The core of the VISLab consists in the CETENA's interactive ship simulator system called SAND.
SAND is a software for maneuvering simulation and training. It is compliant with the HLA 1516 architecture and it includes a ship console and high quality visualization system (Figure 1). A dedicated computing station is used to set the simulation conditions, in terms of scenario, environmental conditions, ship characteristics; the controls on the console can be easily set up through reconfigurable LCD touch panels in order to reproduce those of the simulated ship. During each simulation, all relevant data are stored for subsequent debriefing sessions.

Figure 1: SAND and 3D visualization system

In the tack of reusing all existing tools and competences and thanks to more than twenty years of R&D in ship design and consultancy for harbor designers and Port Authorities, SAND has rapidly reached a very high level of confidence in the representation of the ship behavior.
The CETENA's ship mathematical model included in SAND is based on a Maneuverability and Seakeeping model integration, that allows to calculate the six degrees of freedom (Surge, Sway, Heave, Roll, Pitch, Yaw) and has been validated during the years either from the use and sensitiveness of the Port pilots who used it during the port assessment activities and,

moreover, from the huge real data coming from the experiment activities CETENA performs onboard ships.
The simulation model is designed to be "open" and configurable for all type of ship (cruise, bulk carrier, petrol, LNG, container ship) and for all environmental scenarios (map, sea state, wind, sea current, time of day).
Different type of vessels can be easily configured using wide range of characteristics like:

- hull data
- engine type (diesel, diesel-electrical, turbine, or every combination of them)
- propulsion (azimuth, fixed/controllable pitch propeller, POD, water-jet)
- thruster
- rudder (simple type, compound butt, under hung deep horn, shallow horn, spade)

The physical model is completely modular allowing the implementation of add-ons to take into accounts new or more detailed environmental and interaction effects.
The user can choose the environmental condition through a set of sea state, wind intensity and sea current and the software compute the interactive ship behavior for very accurate and realistic vessel simulation taking into account several aspects like:

- shallow water effects
- navigation in narrow channel
- collisions
- anchors and chains

SAND can be used either as a stand-alone system or as a federate, therefore as part of a more complex HLA federation. This can be useful when other simulation entities has to be considered as actors in the same simulation environment. For this reason a basic standard HLA federation (Figure 2) was designed and developed within the VISLab and it is structured as follows:

- *Execution Manager federate* is used to set up the whole federation and to specify all the initial parameters.
- *Data Logger* records all the data send through the RTI, in order to be able to replay the federation in offline mode.
- *3D Visualization federate* visualize the simulation scenario in a 3D environment.
- *Environment federate* sets all the parameters concerning the marine and atmosphere conditions, as sea state, current, wind.

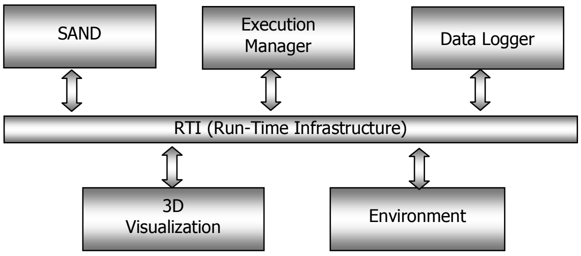


Figure 2: CETENA's basic standard HLA Federation.

In order to be compliant with HLA distributed simulations standards, the above mentioned federation was developed using the VS-FOM (Virtual Ship – Federation Object Model) [4], deriving from the RPR-FOM (Real-Time Platform Reference – FOM).
Multiple entities of SAND can be run in a federation allowing different ships interact in the same synthetic environment.
A portable version of the SAND simulator (see Figure 3) was recently developed in order to easily transport the simulation system into possible partners' facilities and to participate to any other HLA based federation.

Figure 3: Portable SAND

3. APPLICATIONS IN EVALUATING NAVAL OPERATIONS

As previously stated, the driving idea in the VISLab activity is that interactive real-time simulation can be used to investigate complex ship operations for verifying performances and receiving feedback for the design phase.
The implemented architecture and the open structure of the SAND "federate" are the basic ingredients for implementing complex distributed federation simulating operations involving multiple ships or multiple other entities.
In all the following presented experiences the least common denominator is the use of the previously described framework for multidisciplinary topics, with the aim of verifying contractual requisites and also extreme conditions scenarios which may be dangerous to verify in reality.

3.1 Replenishment at Sea (RAS) Operation

Replenishment At Sea is one of the more complex operations performed by modern navies. The operation is executed in three main phases:

- The vessels approach each other and sail alongside.
- The transfer system is established between the vessels using a cable system and the fuel is transferred.

- The transfer system is removed and the ships depart (breakaway).

In all these phases there is a risk of ship collision, especially in high sea states, and when small receiving vessels are involved. A simulation of the RAS operation will allow safe operating conditions to be determined and may influence the design of the supply ship, receiving ship and transfer rigs.

Primary goals of the simulation scenario are:
- to simulate Replenishment operations in open seas with different meteorological conditions;
- to verify operation constraints (ship speed, distance, etc.);
- to analyse different RAS devices in term of position, operative behaviour and efficiency;
- to study refuelling operation (no solid objects transfer).

Basically the operation is focused on the capability of the two ships to navigate parallel for a enough long period of time avoiding collisions and early breakaway. Studies of port manoeuvrability or approaching operations also in open seas are similar to RAS operations and the implemented federation reused all these experience improving the mathematical model of interactions between the two ships.

The two ships are interactively manoeuvrable and the systems reacts in real-time to any change in speed and direction of each ship. In particular the federation can take into account problems deriving from a malfunction in the manoeuvring devices (rudder, propeller…) of one of the two ships in order to accordingly evaluate the capability of the other ship to avoid collision and to continue in the parallel course. This may be very interesting in the design assessment of either the supply and the receiving ships.

From the implementation point of view, two SAND federates were involved in the federation in order to simulate both the supply and the receiving ships. In addition to the standard CETENA's federation two federates were developed and inserted in the federation: a *RAS equipment federate* and an *Interaction federate*.

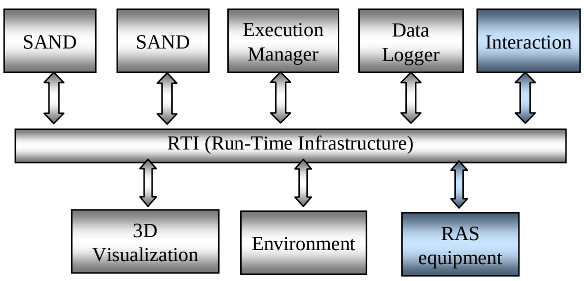


Figure 4: RAS federation

RAS equipment federate was design for the calculation of the forces applied to the cables used for the fuel transferring operation. In case the RAS cables were subjected to a tension exceeding the maximum allowed, federate is able to give a warning representing the unsuccessfully result of the operation.

Interaction federate was designed in order to simulate the forces due to the side by side shipping; it was developed using mathematical models deriving from towing tank tests and it can be configured to simulate this specific behaviour for different kind of ships.

Figure 5: Screenshot of the RAS simulation

The implemented simulation system is completely configurable and parameterized so that it can be used to simulate ship-to-ship transfer of liquids for:
- Any pair of ships
- Any sea state
- Any type of transfer rig
- Any type of liquid
- Any flow rate of liquids transfer.

3.2 Load Transfer operation

The load transfer between two ships in navigation is part of the NOSE (Naval Operations Simulation Environment), a project led by the Italian Navy and implemented by CETENA.
This operation is similar to the RAS operation but in this case a new simulator has been design in order to analyse the behaviour of the heavy load during its transfer from a ship to the other one. The above mentioned scenarios were developed with the same architecture actually in force at the CETENA' VISLAB facilities, the HLA (High Level Architecture), so that different software modules can be shared among different projects and also among different partners.
In this case the simulation framework previously described has been revisited in order to be compliant with the latest STANAG on Virtual Ship.

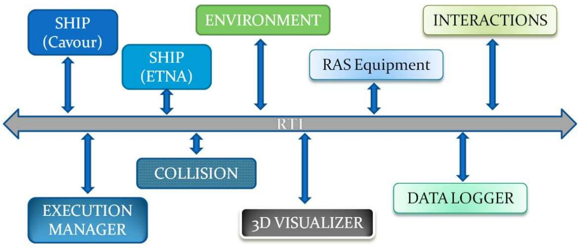


Figure 6: RAS federation

RAS equipment federate has been adapted in order to calculate the forces applied to the cables used for the load transfer operation. The Early Prototype version of the RAS federate can simulate the motion of the load while it is transferred along the cable from a ship to the other. To do that a dynamics simulator based on open-source physical libraries was developed in order to reproduce the behaviour of an object moving on a cable through the use of a system composed by two spherical joints. In the Early Prototype federation the cable among the two ships has been supposed to be linear.

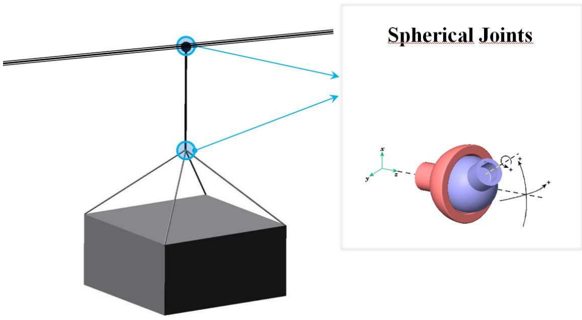


Figure 7 – Heavy Load for RAS simulation

Interaction federate has been reused from the previously described experience, since the aim is still to simulate the forces due to the side by side shipping.

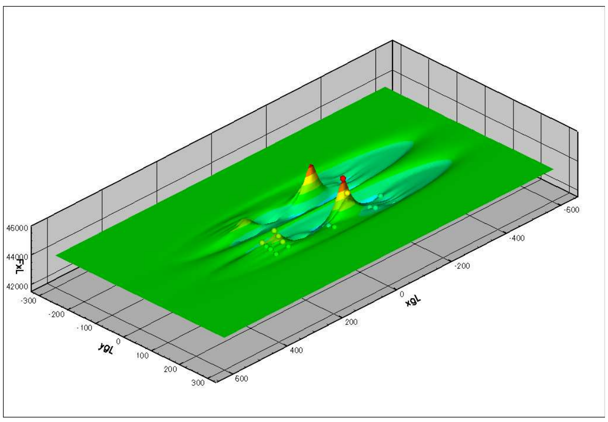


Figure 8: Graphical representation of the Interaction module's results

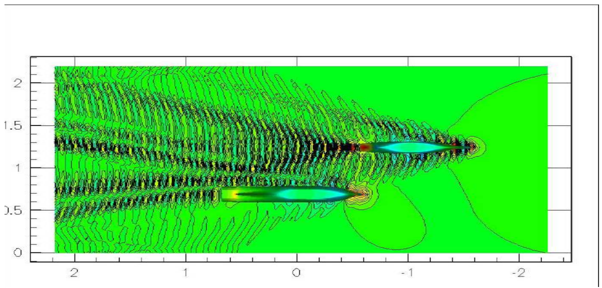


Figure 9 - Graphical representation of the Interaction module's results

Figure 10 – Tank test for interaction forces

The adopted architecture allows the reuse of each federate in other federations and the improvement of the mathematical model for any of the effects to be taken into account. This improvable approach will allow CETENA to easily maintain and upgrade the developed software for future purposes. Some of the federates have been recently used in an international project and simulation results have been validated with sea trials data and towing tanks tests results.

Figure 11: Screenshot of the RAS simulation

3.3 Landing Craft Unit approaching manoeuvre to an LPD ship

In this case an interactive simulation system was developed with the purpose of allowing the Italian Navy to define and verify the operational limits related to the manoeuvrability of a Landing Craft Unit (LCU) while it is approaching the stern of a LPD ship. This study is part of the NOSE project too.

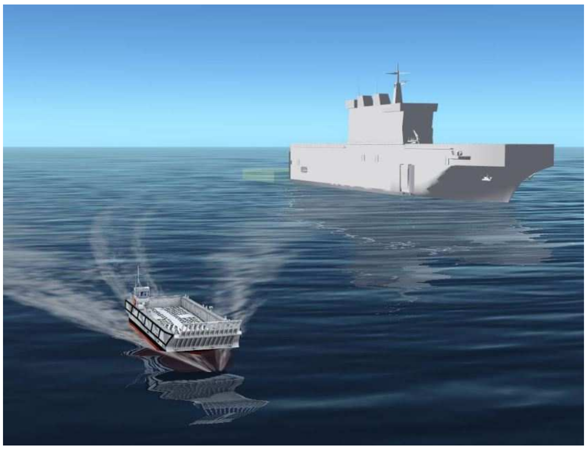


Figure 12 – Screenshot of LCU simulation

All the entities in the scenario are completely interactively manoeuvrable.
Again, the LPD ship is implemented using the SAND federate while the LCU manoeuvrability and seakeeping model is under development in order to take into account the effects caused by the particular type of hull and propulsion and by the stern wake effect generated by the mother ship.

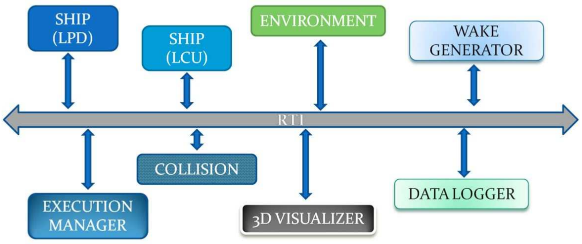
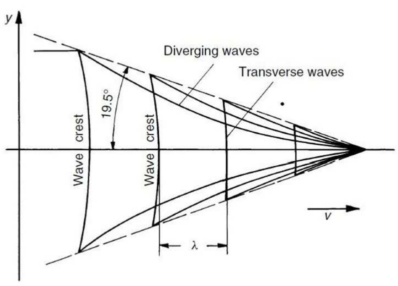


Figure 13: federation for LPD-LCU simulation

The focus of the complete federation will be to accurately simulate the behaviour of the LCU while it is located in the space behind the stern of the mother ship, where the influence of the stern wake is more significant.



For this reason a hydrodynamic study was conducted with the purpose of creating the bases and the knowhow to improve the LCU hydrodynamics model that will be implemented in the final stage of the project.
The manoeuvre can be divided in three phases:

1. The LCU is far from the LPD ship and it is not affected by the waves in the stern of the LPD ship.
2. The LCU is in a region where it is affected by the LPD stern wake but it is still far from the LPD stern door.
3. The LCU is close to stern door ans is about to enter the wet dock of the LPD.

The NOSE project focuses on the second phase of the above mention approaching manoeuvre. In this phase the LCU is moving in waves that are the result of the superposition of the sea waves and the LPD stern wave.

The hydrodynamic study has been performed for the case in which the LPD ship has a forward speed of 5 knots and travels in sea state 4 waves... In these conditions, the wave generated by the LPD can be modelled as a Kelvin wave and its effects can be superimposed to those of the sea waves.
The motions of both LPD and LCU have been computed using a BEM based seakeeping code which, in addition to providing the ship motions, ,allows to predict the interaction between the sea waves and the LPD and the shielding effect exerted by the LPD on the LCU for head seas, when the LCU is close to the entrance of the wet dock.
The comments that can be made as a result of this study are the following:

- The LCU motions are not affected by the waves generated by the mother ship (in the speed and sea state conditions considered in this study).
- The shield effect of the LPD ship on the LCU when the waves are coming from the bow is relevant for the last phase of the approaching manoeuvre.
- The LPD motions in sea state 4 are within the limits permitted for the performing of the manoeuvre.

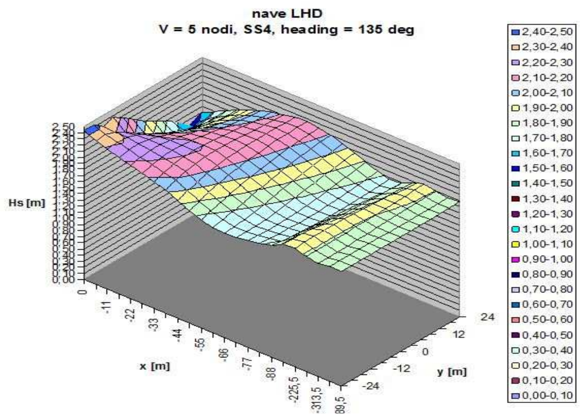


Figure 15 – Numerical results of LPD stern waves

The results of the hydrodynamics study will be used to improve the LCU seakeeping model that will be integrated in the corresponding federate.

All these developments will be included as supporting effects to the main SAND engine and will be reused in future federations.

3.4 Landing Craft Unit operations inside amphibious ship

Another example of complex operation involving multiple interactive but independent entities is the federation we designed an built for reproducing the manoeuvrability of a landing craft (LCU) inside the wet dock of an amphibious ship (LPD) and the transfer of a tank from the Landing Craft to the dock of ship.

Again, the ship is implemented using the SAND federate while the Landing Craft Unit is a completely new mathematical model due to the particular type of hull and propulsion and moreover due to the shallow water effect inside the dock.

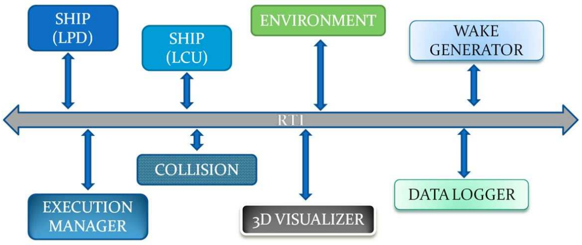


Figure 16: federation for LPD-LCU simulation

Four additional federates were developed in order to simulate the following entities:

- The Landing Craft maneuverability: this model was developed using Physx SDK, an open source physics simulator []. With Physx it is possible to simulate the dynamics of one or more objects with different geometries and characteristics. Moreover, Physx allows to interact with the simulated objects by applying to them some forces and moments.
- The Shallow Water effect: the hydrodynamic forces due to the shallow water inside the dock were applied to the Landing Craft. The Tank: when the Landing Craft approaches to the dock and it is stable, the tank can be moved from the landing craft itself to the LPD dock.
- The Collision Detection: when the Landing Craft is inside the LPD dock it is important to monitor the clearance among the craft and the dock. At the end of the simulation the federate can produce a report with the list of collisions detected during the running.

Particular attention has been put in the sloshing effect which is very complicate due to the fact that it is generated by the LPD Ship and is characterized by the volume of the water in the wet dock. Experimental test have been performed to tune the mathematical model.

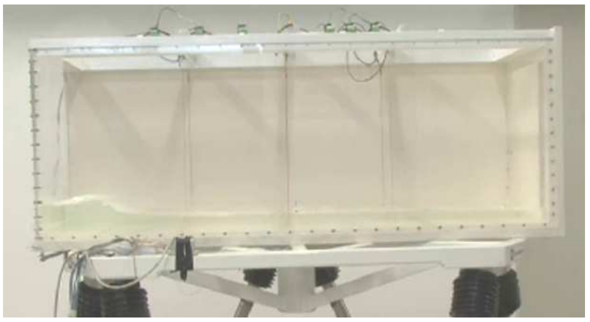


Figure 17: Sloshing experimental tests

The implemented federation has been used during the design of a possible LPD ship and one of the asked question was to determine which was the optimal trim for the internal wet deck in order to have enough ware to avoid collisions with the bottom of the LCU during movements inside and especially loading and unloading operation of the tank.

During the development also the external approach phase of the LCU has been simulated with a very simplified but effective mathematical model. Even if the main purpose is for inside operations, also external behavior of the ship and the LCU are simulated

Figure 18: Screenshot of the Landing Craft simulation

Now the work is going on and the federation will be updated with a more sophisticated physic model of the behavior of the LCU behind the Ship. The LCU travels in a wave field that is the superposition of the LPD's stern wave and the sea waves modified by the presence of the LPD.

Hydrodynamic motion and forces due to the wave actions are now accurately predicted in frequency domain and time domain module accounting for complete wave actions is under development.

All these development will be included as supporting effect to the main SAND engine and will be reused in future federations requiring them.

3.5 Vertical Take Off and Landing (VTOL)

Take-off and landing operations involves different issues related to the interaction between the ship and the air vehicle.
One of the problems is related to the forces during touch down: the ship moves and air vehicle approaches her choosing the best moment for touching the deck. The forces involved are the ones coming from the ship motions and the ones coming from the drop of the vehicle. Especially in heavy sea state the sum of the forces can be very high and can damage the air vehicle landing devices [3].
This effect has been studied in one of the first federation developed inside an international group studying the best landing period for an helicopter to land on a frigate [4].
Besides this impact effect, another important aspect to take care of is the turbulence generated by superstructure in the surrounding of the landing spots. This aspect involves an heavy interaction between fluid dynamic calculations (CFD) for simulating the flows around the structures (Air Wake) and the relative position of the two moving entities: the helicopter and the ship. As in other experiences, these two separated effects were already studied in CETENA and we have the competences and codes for simulation the two effects separately.

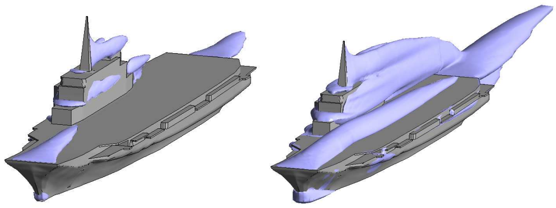


Figure 19: CFD results for VTOL simulation

Again, reusing these knowledge and making the relative tools interoperable, has brought to the design and implementation of a federation simulate the interactive scenario of an helicopter landing on a ship dynamically taking into account in real-time of the air-wake effect and the relative movements and forces between the two moving entities.
The developed system was composed by the standard basic federation for the ship with the addition of some new federates: the helicopter and the airwake.

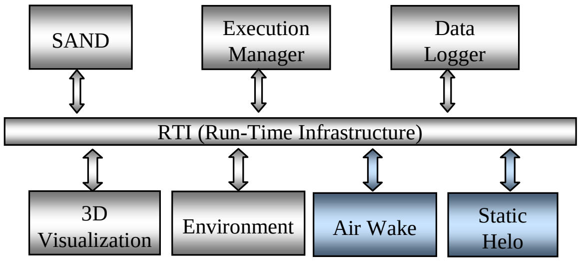


Figure 20: VTOL federation

The helicopter federate is in reality a ultra simplified federate which simulate a point in the space and collect information from the flows deriving from the airwake and the distance from the ship.

The airwake federate is basically a sophisticated interpolator of pre calculated values coming from offline CFD processing. Depending on the relative position from the ship, the speed, the wind direction and other physical parameters, the federate determine the flow pressure and speed in a certain point.

Figure 21: Screenshot of the VTOL simulation

As a matter of fact, since the federation was developed in compliance with both the VS-FOM and the RPR-FOM, a whatever Helicopter federate compliant with the above mentioned FOMs can be easily integrated

3.6 Small Craft Launch and Recovery

CETENA, as a member of CRS (Cooperative Research Ships) group, participated to a Simulation Group focused on the design and implementation of a HLA federation to be used to simulate Small Craft Launch and Recovery (SCLaR) operations.

Also in this context many of the expertises and algorithms developed in previous studies has been reused and integrated in the complete federation.

In particular, in the international project, CETENA provided its VISLab laboratory to integrate the whole federation structured as described in Figure where the "blue" federates were developed by CETENA and the "yellow" ones were developed by other partners.

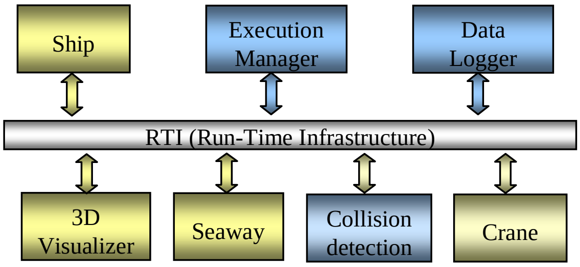


Figure 22: SCLaR Federation

The federation was run in our VISLab and a screenshot is visible in figure Figure .

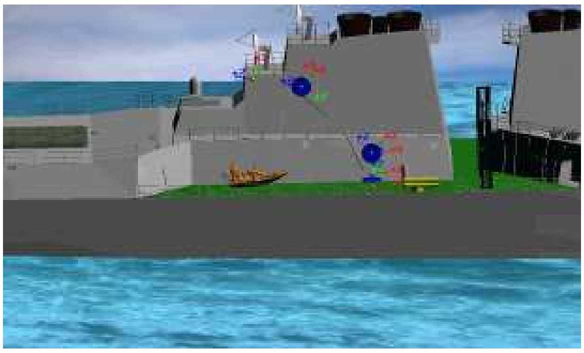


Figure 23: SCLaR screenshot of the small craft launching phase

Primary scopes of this application were the following:

- To share with CRS-SIM group members the knowledge in the development of distributed simulations.
- To set up a common framework able to be improved with detailed simulation models, for the following purposes:
  - To test the winch system in different weather conditions
  - To monitor the waves contact on the small craft during the launching phase
  - To measure the time spent to perform the whole Launch/Recovery operation.

Many of the software and solutions identified in the development of the project have been reused in other applications during the years.

4. INTERNATIONAL COOPERATION

The use of a distributed simulation system utilising the High Level Architecture (HLA) allows the reproduction of a complex scenario in a synthetic environment, permitting several simulators and partners to work together through the simple exchange of inputs and outputs, whilst protecting confidential information. International Replenishment At Sea (IRAS) Project conducted through a 5-nation Project Arrangement under the Virtual Ships Memorandum of Understanding is an example of an international cooperation in which Italian Navy and CETENA, as technical supporter, is currently involved. The IRAS Project Arrangement encompasses the design, development and validation of a distributed simulation of Replenishment at Sea (RAS) using HLA. The simulation architecture has been developed with the intention also of exercising the draft Virtual Ships (VS) Standardisation Agreement (STANAG) and corresponding Allied Naval Engineering Publication (ANEP) [8]. Relevant pre-existing HLA compliant simulations developed by the Project partners have been collected and revised as necessary to enable them to take part in the federated simulation system for comparison and validation purposes. The verification and validation process has been carried out using both sea trials and tank test data. The final aim of this project is both to create and share a reliable, reusable simulation framework which can be adopted by the partners' Navies and design contractors during the first design phase of future vessels, and to permit the practicalities of international RAS operations to be assessed. The significant results obtained in this project demonstrate that the same approach could be adopted for a wide range of different naval operations.

5. CONCLUSIONS AND FUTURE DEVELOPMENTS

New technologies, higher computational resources and a new cultural way in the relationship with the computer (especially derived by video games) have foster the idea that something new could be done to face the above mentioned distortions.

Tools, systems and standards are growing. Now it is our turn to put all these staff together and build the Virtual Ship. Two major obstacles on the horizon: costs and culture.

The first one is mainly evident when simulation is seen only as a tool for design purposes and no "reuse" is foreseen. In this case, yes, simulation is a cost and the return of the investment is very small. Making simulations and simulator reusable for other purposes and for other project is a solution to overcome the problem. In this perspective if most of the models and algorithms developed in the design phase can be reused for instance in a training environment, the ROI is shifted in this second phase which can start before the ship is built and can be a benefit for the customer who can train the crew in advance but also for the shipbuilder who has the chance to expand its business also in the post sale area of the ship and can build an even more strong relationship with the ship-owner.

Italian Navy, with the technical support of CETENA, is now working on the definition of another Project Arrangement to be established with other nations entitled "International Launch And Recovery" project, concerning cooperation in simulation-based design and virtual prototyping for naval ships. This Project Arrangement concerns the design, development and validation of a distributed simulation framework of launch and recovery of small boat using the High Level Architecture (HLA). Two kind of launch and recovery approaches shall be considered, both the stern and the side one.

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