INTERNATIONAL DEVELOPMENT AND VALIDATION OF A DISTRIBUTED SIMULATION FOR NAVAL SHIP REPLENISHMENT AT SEA

(DOI No: 10.3940/rina.ijme.2019.a1.514)

K McTaggart, Defence Research and Development Canada, Canada, **D Tozzi**, CETENA, Italy, **G Henry**, Systems Engineering & Assessment Ltd, UK, **F Valdenazzi**, CETENA, Italy, and **N Stuntz**, Bundeswehr Technical Center, Ministry of Defence, Germany

SUMMARY

Navies from Canada, France, Germany, Italy, and the United Kingdom collaborated to develop and validate a distributed simulation of ship replenishment at sea. The simulation models the seaway, ship motions including hydrodynamic interaction effects between ships, and the transfer of a solid payload between ships using replenishment gear. The simulation was developed using the High Level Architecture (HLA), which facilitates sharing of data and synchronization of simulation time among software components on networked computers. Simulation results were validated using experimental data. The project demonstrated successful application of distributed simulation to complex naval platform systems. Lessons learned are shared for several areas, including seaway modelling, ship hydrodynamic interaction, and planning of model tests and sea trials for simulation validation.

NOMENCLATURE

$[A]$	Added mass matrix
a	Wave amplitude (m)
B	Ship breadth (m)
B_{wl}	Ship beam at waterline (m)
$[b]$	Damping matrix
$[C]$	Hydrostatic stiffness matrix
C_B	Ship block coefficient
$[c]$	Hydrodynamic stiffness matrix
$\{F\}$	Force vector
H_s	Significant wave height (m)
HLA	High Level Architecture
$[K]$	Retardation function matrix
k_I	Wavenumber (/m)
L_{pp}	Ship length between perpendiculars (m)
L_{wl}	Ship length at waterline (m)
$[M]$	Mass matrix
N_I	Number of incident wave components
RAO	Response amplitude operator
RAS	Replenishment at sea
RTI	Run-time infrastructure
S	Spectral density (m^2/(rad/s) or m^2/(rad^2/s))
T_{mid}	Ship draft at midships (m)
T_p	Peak wave period (s)
U	Ship forward speed (m/s)
x^f, y^f	Earth-fixed horizontal coordinates (m)
$\Delta(\ldots)$	Increment of quantity in brackets
ε^I	Incident wave phase (rad)
ζ^I	Incident wave elevation (m)
$\{\eta\}$	Displacement vector (m and rad)
ν	Wave heading, from (deg)
τ	Delay time (s)
ω_I	Wave frequency (rad/s)

1. INTRODUCTION

A ship is a complex system of systems continuously interacting with an even more complex environment. Developing an experimental prototype is usually prohibitively expensive for a ship; thus, physics-based modelling and simulation are used extensively in the ship design process. Physics-based tools and methodologies for different design aspects are typically used by domain experts working largely in isolation. Ongoing efforts are enabling comprehensive simulation of complex ship systems. This paper describes a comprehensive simulation of ship replenishment at sea (RAS) developed under the International Replenishment At Sea (IRAS) project, which included navies from Canada, France, Germany, Italy, and the United Kingdom.

2. ASSESSMENT OF NAVAL OPERATIONS THROUGH SIMULATION

The purpose of a simulation is to reproduce the behaviour of a physical system. Simulation models are becoming more complex as they strive to model reality with high fidelity. To reliably simulate naval operations, many physical entities and interactions need to be modelled. Distributed simulation (Fujimoto, 2000) is often used for modelling complex systems. A typical distributed simulation involves multiple executable programs running on multiple computers, with data sharing and time synchronization occurring among executable programs via a network.

The benefits of distributed simulations are well known. Division of a problem into modules produces entities that are of manageable scope for software development and testing. Developed modules can often be reused in a number of different types of simulations. Distributed simulation also enables hiding of data that partners may not want to share, possibly for reasons of national security or commercial advantage.

The High Level Architecture (Kuhl et al., 1999) is a highly capable and widely used infrastructure for development and execution of distributed simulations. It was selected as the basis for the Virtual Ship framework for naval platform simulations. The Virtual Ship framework is intended to facilitate development of distributed simulations modelling multiple entities, including modelling of force interactions. Henry et al. (2008) and Henry et al. (2015) provide details regarding the Virtual Ship framework.

3. SIMULATION DESIGN AND DEVELOPMENT OF PROTOTYPE

The simulation was designed to model motions of supply and receiving ships and the transfer of a solid payload between the ships. The simulation models the following entities:

- Ocean environment, with emphasis on the seaway;
- Motions of the lead ship in waves;
- Helm control system for propeller(s) and rudder(s) of the lead ship;
- Motions of the following ship in waves;
- Helm control system for propeller(s) and rudder(s) of the following ship;
- Hydrodynamic interaction between the lead and following ships;
- Replenishment gear including solid payload.

The lead ship is typically the bigger of the two ships, and can be either the supply ship or receiving ship. For example, a supply ship is normally the lead ship when supplying a smaller frigate. The simulated motions of the lead ship and following ship can include hydrodynamic interactions between the vessels, which can be important due to close proximity during replenishment at sea. Model tests and numerical predictions by McTaggart et al. (2003) indicated that hydrodynamic interactions in head seas can induce roll large motions on the smaller vessel, which was also demonstrated in recent model tests by Mathew et al. (2018).

Based on the requirement to model the above entities, the simulation design of Figure 1 was formulated. Each of the entities in Figure 1 is an executable program, with RTI denoting the run-time infrastructure, and the remaining simulation entities being referred to as federates. The composite simulation of federates is referred to as a federation. The federation has been designed in a modular manner such that individual federates can likely be reused in other future simulations. Hydrodynamic interactions are evaluated by a separate "Interactions" federate in Figure 1 that determines incremental forces arising on the ships due to hydrodynamic interaction effects. The execution manager assists with startup, data sharing, and time synchronization of the other federates. The data logger and visualizer passively monitor results from the other federates that generate data.

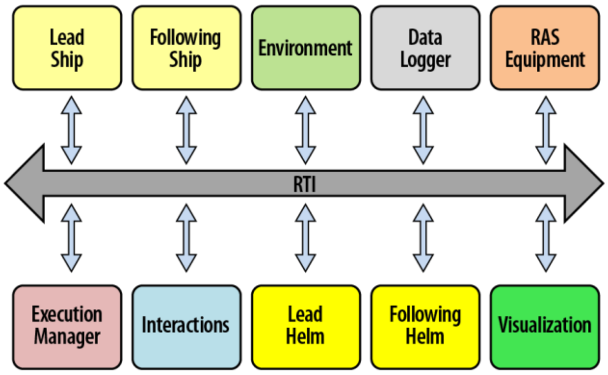

Figure 1: Replenishment at sea simulation federates and run-time infrastructure

An initial prototype federation was developed to test and refine the simulation design. The prototype federation included a fully functioning execution manager. Other prototype federates performed data sharing and time synchronization as planned, but produced data were merely nominal values. A common federate template assisted in the development of federates.

4. SIMULATION IMPLEMENTATION AND INTEGRATION

Fully functioning federates were implemented after successful completion of the prototype federation. This section describes the federates that were developed during the implementation phase and their integration.

4.1 ENVIRONMENT FEDERATE

Within the IRAS simulation, the primary purpose of the environment federate is to model the seaway. Realistic random seaways are modelled using superposition of sinusoidal wave components as follows:

$$\zeta_I(x^f, y^f, t) = \sum_{i=1}^{N_I} a_i \cos\left[k_{I-i}(y^f \sin \upsilon_i - x^f \cos \upsilon_i) - \omega_{I-i} t - \epsilon_{I-i}^f\right] \quad (1)$$

where ζ_I is wave elevation, x^f and y^f are earth-fixed coordinates in the horizontal plane, N_I is the number of incident wave components, a_i is wave component amplitude, k_{I-i} is incident wavenumber, υ_i is heading (from), and is ϵ_{I-i}^f wave phase. A random seaway is typically represented by using randomly generated wave phases ϵ_{I-i}^f. For modelling of a unidirectonal seaway (long-crested waves) with given energy density spectrum $S_{\omega_I}(\omega_{I-i})$, wave amplitude components are given by:

$$a_i = \sqrt{2 S_{\omega_I}(\omega_{I-i}) \Delta(\omega_{I-i})} \quad (2)$$

where $\Delta(\omega_{I-i})$ is the wave frequency range for component i. For modelling of a short-crested seaway with given directional energy density spectrum $S_{\omega_I,\nu}(\omega_I,\nu)$, wave amplitude components are given by:

$$a_i = \sqrt{2S_{\omega_I,\nu}(\omega_{I-i},\nu_i)\ \Delta(\omega_{I-i})\ \Delta(\nu_i)} \qquad (3)$$

where $\Delta(\nu_i)$ is the heading range for component i.

A regular seaway, such as might be used during model tests for validation, can be easily modelled using a single wave component.

There was much deliberation regarding the amount of data that should be transferred between federates over the network. For example, visualization of the seaway using wave elevations computed by the environment federate would require large amounts of data to be transferred from the environment federate to the visualizer federate at each time step. Alternatively, seaway component parameters (amplitude, wave frequency, wave number, direction, and phase) could be transferred to the visualizer federate at the beginning of each simulation, with the visualizer federate computing wave elevations on its own computer as required. This latter approach with minimal transfer of data across the network was adopted, and was found to work very well.

4.2 SHIP MOTION FEDERATES

Implementations of ship motion federates were developed by Canada, Italy, and the United Kingdom. All three implementations use potential flow boundary element methods for evaluation of hydrodynamic forces on the ship hull. Viscous forces and appendage lift forces are evaluated using coefficient-based methods. The ship motion federates evaluate hydrodynamic forces associated with a single ship in water. Additional forces from hydrodynamic interaction effects and replenishment gear are obtained from the hydrodynamic interaction and RAS equipment federates.

The Canadian federate evaluates accelerations $\ddot{\eta}(t)$ of a ship along its nominal heading at each time step using the following equation adapted from McTaggart (2015):

$$([M] + [A(U,\infty)])\{\ddot{\eta}(t)\} + [b(U)]\{\dot{\eta}(t)\} + \int_0^{\tau_{max}}[K(U,\tau)]\{\dot{\eta}(t-\tau)\}\,d\tau + ([C] + [c(U)])\{\eta(t)\} = \{F^I(t) + F^D(t)\} + \{F^{resist}(t)\} + \{F^{prop}(t)\} + \{F^{rudder}(t)\} + \{F^{interaction}(t)\} + \{F^{RAS}(t)\} \qquad (4)$$

where $[M]$ is ship mass, $[A(U,\infty)]$ is added mass at speed U for oscillations at infinite frequency, $[b(U)]$ is damping, $[K(U,\tau)]$ is retardation for delay time τ, $[C]$ is hydrostatic stiffness, $[c(U)]$ is speed-dependent hydrodynamic stiffness, $\{F^I\}$ is incident wave excitation, $\{F^D\}$ is diffracted wave excitation, $\{F^{resist}\}$ is resistance due to steady ship speed, $\{F^{prop}\}$ is propulsion force, $\{F^{rudder}\}$ is rudder force, $\{F^{interaction}\}$ is incremental interaction force due to another vessel in close proximity, and $\{F^{RAS}\}$ is replenishment gear force. Note that all hydrodynamic force terms other than $\{F^{interaction}\}$ are based on the ship being alone. The term τ_{max} is the maximum delay time for evaluating retardation functions in $[K(U,\tau)]$, with a value of approximately 20 s being sufficient for most ship motion computations. The federate from the United Kingdom uses a similar approach for evaluation of forces and resulting motions. The Italian federate (Tozzi et al., 2014) uses a modified approach that superimposes oscillatory wave-induced motions from response amplitude operators (RAOs) over motions based on maneuvering predictions in calm water.

Implementations of ship motion federates from Canada and the United Kingdom compute radiation and diffraction force terms in the frequency domain, which are then used to evaluate corresponding terms in the time domain. The Canadian federate uses the zero speed Green function in the frequency domain for evaluation of radiation and diffraction forces, as describe by McTaggart (2015). This approach assumes zero ship speed when modelling the free surface boundary condition, and gives good results for a single ship with forward speed Froude numbers up to 0.4. The federate from the United Kingdom uses a Rankine panel method, with panels on both the ship hull and free surface. This approach can model the influence of ship speed on the free surface boundary condition.

A time step of 0.1 s is sufficiently small for giving reliable ship motion simulations in most cases relevant to replenishment at sea. The three ship motion implementations typically give computational performance significantly faster than real time.

4.3 HELM FEDERATES

The helm federates obtain ship positional data (location, velocities, and accelerations) from the ship motion federates and provide input command values for propeller RPM and rudder deflection back to the ship motion federates. For the lead ship, the helm provides a constant propeller RPM value and rudder deflection commands to maintain constant heading. For the following ship, the helm continuously adjusts command propeller and rudder deflection values such that the following ship will attempt to maintain constant longitudinal and lateral positional values relative to the lead ship.

4.4 HYDRODYNAMIC INTERACTION FEDERATE

The hydrodynamic interaction federate obtains positional data from the ship motion federates, computes incremental forces arising from hydrodynamic interaction effects, and shares the interaction forces with the ship motion federates via the network. Canada and the United Kingdom both implemented hydrodynamic interaction federates through extension of their radiation and diffraction methods to the two ship case. McTaggart (2017) describes the Canadian implementation for computing hydrodynamic interaction forces.

The evaluation of hydrodynamic interaction forces for the simulation requires that ship positional data be extrapolated one time step due to the forces being dependent on results from three different federates. For example, added mass interaction forces computed by the hydrodynamic interaction federate for time t are dependent on accelerations of both ships at time t. Such positional extrapolation is commonly performed in distributed simulations and is referred to as dead reckoning (Fujimoto, 2000). The following approximations yield reliable results for evaluation of hydrodynamic interactions with adequately small time steps:

$$\{\eta(t+\Delta t)\} \approx \{\eta(t)\} + \Delta t\,\{\dot{\eta}(t)\} + \frac{1}{2}(\Delta t)^2\,\{\ddot{\eta}(t)\} \quad (5)$$

$$\{\dot{\eta}(t+\Delta t)\} \approx \{\dot{\eta}(t)\} + \Delta t\,\{\ddot{\eta}(t)\} \quad (6)$$

$$\{\ddot{\eta}(t+\Delta t)\} \approx \{\ddot{\eta}(t)\} \quad (7)$$

where Δt is time step size.

4.5 REPLENISHMENT GEAR FEDERATE

The replenishment gear federate simulates transfer of a solid payload from the supply ship to the receiving ship. The replenishment gear federate obtains ship positional data from the lead ship and following ship federates. In addition to evaluating the position of the solid payload, the replenishment gear federate evaluates the loads acting on each ship and shares these loads over the network with the ship motion federates. Dead reckoning is required when modelling physical interactions between the ship motion and replenishment gear federates.

Both Canada and the United Kingdom developed replenishment gear federates. The Canadian federate models a system that uses a hydraulic ram to regulate tension in the high line, with McTaggart and Langlois (2009) describing the simulation model illustrated in Figure 2. The federate from the United Kingdom models a system that uses electrical control of motors to regulate the tension in the high line.

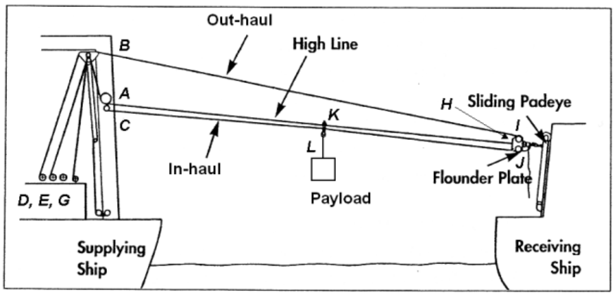

Figure 2: Schematic of hydraulic replenishment gear

4.6 VISUALIZER FEDERATE

The visualizer federate provides a three-dimensional visualisation of the executing federation. By default, it attempts to render the visuals at real-time rates. Optionally, it may allow the user to speed up or slow down the rendering, or pause the rendering (and also the federation execution). The visualization federate is based on OpenGL (Shreiner et al., 2013). Although emphasis has been placed on visualization for engineering assessment, incorporation of ongoing improvements to OpenGL is providing strong visual realism with only moderate programming effort. Figure 3 shows visualization of a supply ship transferring a solid payload to a destroyer.

Figure 3: Visualization of replenishment simulation with transfer of solid payload from supply ship to destroyer

4.7 INTEGRATION OF SIMULATION FEDERATES

Integration of the implemented federates was a critical phase of the simulation development. An integration plan was developed to ensure proper management of the whole federation. The integration was approached in a phased manner, progressing as follows:

- Verification of successful execution of each federate;
- Verification of compliance of each federate with the specified data formats;
- Verification of data communication and synchronization among federates;
- Verification of execution of entire federation.

The majority of the integration was performed by personnel who were not involved with the development of the individual federates. This approach was very successful in identifying deficiencies in submitted federates and their documentation, and also for providing objective feedback regarding improvements to federates. Constructive communications between federate developers and integrators yielded improvements to federates and the overall simulation design.

5. VERIFICATION AND VALIDATION

After initial integration of simulation federates, verification was performed to ensure that federates were correctly implemented. Validation was then performed using data from model tests and a full-scale sea trial. Simulation federates were modified during both verification and validation, thus resulting in iterative improvements to simulation fidelity.

5.1 VERIFICATION

Most simulation federates are based on software that was originally developed for stand-alone simulations (i.e. were not part of a distributed simulation) and had been extensively verified. Consequently, the majority of verification effort was devoted to ensuring that federates had been implemented correctly and produced results that were consistent with previously developed stand-alone software.

As mentioned previously, several of the federates incorporated ocean wave models that obtained wave component data from the environment federate at the beginning of the simulation. This approach required that federates be verified to ensure consistent modelling of ocean waves among the federates. The required verification effort was modest, and ensured successful execution of this approach for greatly reducing the amount of data that needed to be transferred across the network during simulation execution.

5.2 MODEL TESTS CONDUCTED IN CANADA FOR A SEMI-RESTRAINED SUPPLY SHIP AND SEMI-RESTRAINED FRIGATE

Early validation efforts focussed on motions of ships in waves including hydrodynamic interaction effects. New software was developed by both Canada (McTaggart et al. 2017) and the United Kingdom (Henry et al. 2015) for predicting ship forces and motions in the time domain prior to integration of this software into federates. Existing model test data from McTaggart et al. (2003) were used to validate this software. Table 1 gives principal dimensions for the ship (full-scale values are provided in this article), and Figure 4 shows the smaller frigate alongside the larger supply ship. The modelled conditions included the ships travelling in head seas at 12 knots, with a lateral gap distance of 30 m between the vessels. The frigate was aligned longitudinally with the supply ship for some tests, and was 45 m ahead of the supply ship for other tests. Regular seas with steepness of 1/40 were modelled.

Table 1: Supply ship and tanker dimensions (full-scale) for model tests conducted in Canada

	Supply ship	Frigate
Length, L_{pp}	180.0 m	122.0 m
Beam, B_{wl}	31.096 m	14.805 m
Draft, T_{mid}	8.500 m	4.500 m
Block coefficient, C_B	0.578	0.489

Figure 4: Semi-restrained models of a supply ship and frigate for tests conducted in Canada

Figure 5 shows roll motions of the frigate in head seas at 12 knots when there is a 30 m lateral gap between the vessels and midships of the frigate is 45 m ahead of midships of the supply ship. Two interesting physical phenomena are evident when considering motions of two ships in close proximity. McTaggart (2017) notes that wave reflections between vessels cause radiated waves to decay much more slowly for the two ship case than for the single ship case. Furthermore, von Graefe et al. (2013) note that the influence of forward speed on the free surface boundary condition is more important for the two ship case than for the single ship case, likely contributing to differences between model test results and predictions in Figure 5.

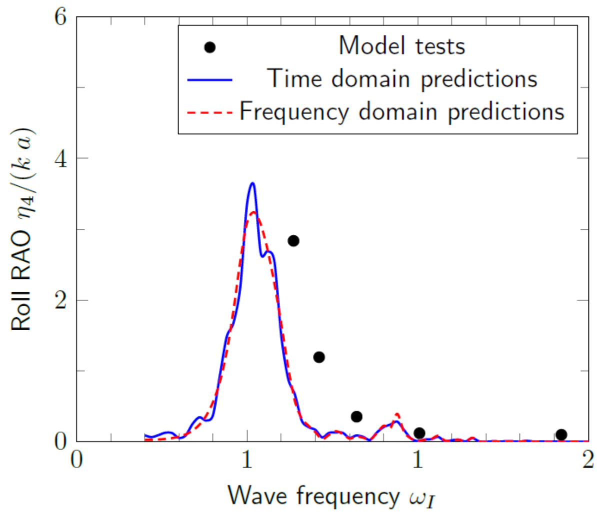

Figure 5: Roll motions for frigate 45 m ahead of supply ship in head seas at 12 knots

5.3 MODEL TESTS CONDUCTED IN ITALY FOR SEMI-RESTRAINED LANDING PLATFORM DOCK SHIP AND SEMI-RESTRAINED TANKER

Model tests were conducted in Italy for a semi-restrained landing platform dock (LPD) ship and a semi-restrained tanker, with main dimensions given in Table 2 and the models shown in Figure 6. The modelled conditions represented the ships travelling at 10 knots with lateral gaps between the ships of 22 m, 39 m, and 55 m. Random head seas were modelled using Bretschneider spectra for Sea States 3 and 4, with associated significant wave heights of 0.88 m and 1.88 m, and peak wave periods of 7.5 s and 8.8 s. Both ships were free in heave, roll, and pitch, but were restrained in surge, sway, and yaw.

Table 2: Landing platform dock ship and tanker dimensions (full-scale) for model tests conducted in Italy

	LPD ship	Tanker
Length, L_{pp}	170.0 m	138.0 m
Breadth, B	30.0 m	21.0 m
Draft, T_{mid}	6.525 m	7.325 m
Block coefficient, C_B	0.576	0.632

Figure 6: Semi-restrained models of an LPD ship and tanker for tests conducted in Italy

The replenishment at sea simulation was run using several different configurations, using ship motion federates from Canada, Italy, and the United Kingdom. Validation of the motions in waves for the model test conditions ultimately proved to be difficult due to the small magnitudes of the observed motions and also due to tank wall interference effects (Goodrich, 1969), affecting the observed ship motions in the lower frequency range. These tank wall interference effects could be modelled numerically in future validation efforts.

5.4 MODEL TESTS CONDUCTED IN FRANCE FOR SEMI-RESTRAINED TANKER AND FREELY MANEUVERING DESTROYER

Model tests were conducted in France for a tanker and destroyer with dimensions given in Table 3. McTaggart et al. (2018) provide a full description of the model tests and validation, with an overview presented here. The tanker model was restrained in sway, roll, and yaw, and was towed using a soft spring attached to a towing carriage. The destroyer model, which was based on the DTMB 5415 model widely used in the open literature, was freely maneuvering. Controllers for the propellers and rudders ensured that the destroyer model maintained its position relative to the tanker. Random head seas were modelled using Bretschneider spectra for Sea States 4, 5, and 6, with associated significant wave heights of 1.88m, 3.25 m, and 5.0 m, and peak wave periods of 8.8 s, 9.7 s, and 12.4 s. The model tests in random waves included two relative longitudinal locations and five relative lateral locations. Some of the model tests included a weight and pulley system to model the replenishment gear tension between the ships.

Table 3: Tanker and destroyer dimensions (full-scale) for model tests conducted in France

	Tanker	Destroyer
Length, L	188.7 m (L_{wl})	131.54 m (L_{pp})
Beam, B_{wl}	28.19 m	17.66 m
Draft, T_{mid}	7.967 m	5.7 m
Block coefficient, C_B	0.681	0.506

Figure 7 gives mean and RMS roll motions of the destroyer in Sea State 5 as functions of destroyer longitudinal position. The nominal relative separation between the ship centrelines is 58.9 m. The mean roll motions of the destroyer show excellent agreement between model tests and simulations, including prediction of the roll induced when the replenishment gear is present. The RMS roll motions of the destroyer show excellent agreement between model tests and simulations, with the exception of when the destroyer is in the foremost location relative to the tanker. It is postulated that the variation of agreement with longitudinal position could be due to the hydrodynamic force predictions not including the influence of forward speed on the free surface boundary condition. In reality, the influence of forward speed causes radiated waves to be swept downstream relative to each ship.

5.5 MODEL TESTS CONDUCTED IN THE UNITED KINGDOM FOR AN AIRCRAFT CARRIER AND TANKER

Henry et al. (2015) present comparisons from the United Kingdom of hydrodynamic force predictions with model tests for an aircraft carrier and tanker in close proximity. In contrast to the Canadian and Italian hydrodynamic force prediction methods, the method from the United Kingdom includes modelling of flow separation when evaluating steady hydrodynamic forces in calm water. This approach gives excellent predictions of steady lateral forces induced by hydrodynamic interaction during replenishment at sea.

5.6 SEA TRIALS CONDUCTED BY GERMANY FOR A SUPPLY SHIP AND FRIGATE

Germany conducted sea trials in the North Sea for a supply ship and frigate performing replenishment at sea operations. Detailed measurements were taken for motions of each ship. A dedicated load sensor was installed during the sea trials for monitoring of tension on the replenishment gear. Wave conditions at the trial locations were estimated using existing fixed wave buoys operated by the Federal Maritime and Hydrographic Agency of Germany, and also using numerical wave hindcast models based on recorded meteorological data. These approaches provided estimates of significant wave height, peak wave period, and mean directions for sea and swell. It was determined during the validation process that uncertainty regarding directional wave spreading posed a major challenge for rigorous validation of the numerical ship motion predictions. Further uncertainties regarding roll inertia and metacentric height for both ships also contributed to challenges with validation.

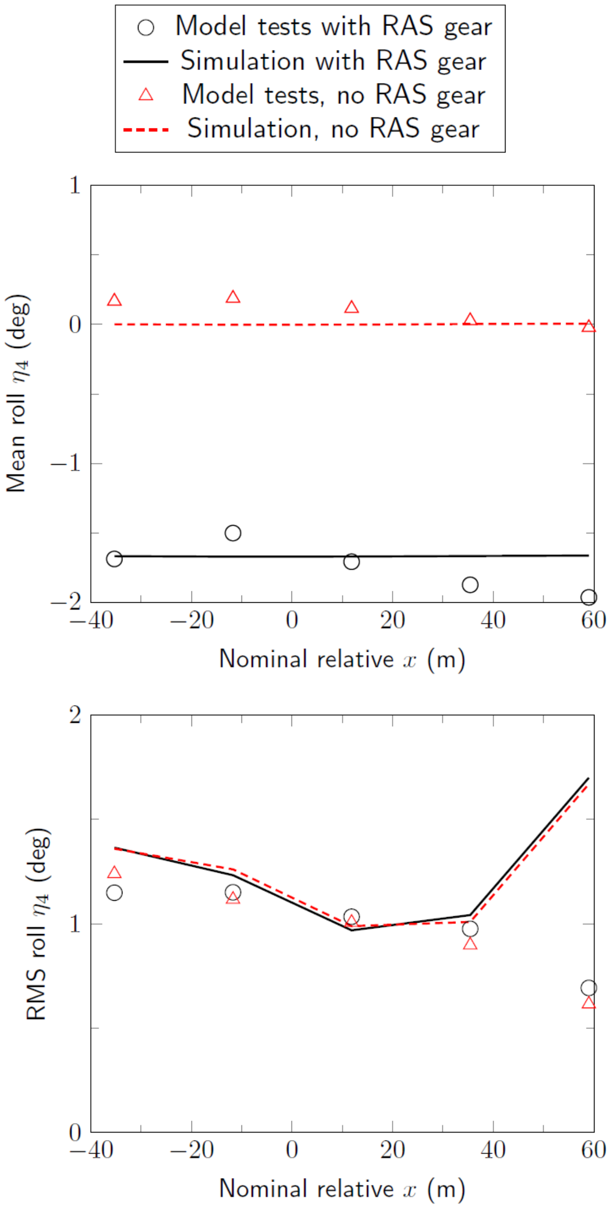

Figure 7: Destroyer mean and RMS roll when operating near tanker at 15 knots in Sea State 5

6. DISCUSSION

The work described above provides insight into a variety of areas. This section gives an overview of final results from the collaborative project.

6.1 DEVELOPMENT OF VIRTUAL SHIPS SIMULATIONS USING THE HIGH LEVEL ARCHITECTURE

The decision to use the High Level Architecture (HLA) was based in part on a high level of enthusiasm for it among the international defence simulation community commencing in the late 1990s. HLA is one of several architectures available for distributed simulation. During development of virtual ships simulations, it became evident that HLA is very capable but also very complex. Simulation architects and software developers require significant training and experience to become proficient. Much virtual ships software is written in C++, which itself is a challenging programming language. Furthermore, software developers must be proficient in mixed language approaches because many of the underlying virtual ships models are written in other languages, such as C#.

Virtual ships simulations typically use only a small subset of HLA capabilities; thus, architects and developers can narrow their focus to these core components. Training and software development were aided by the availability of the open source CERTI run-time infrastructure (RTI) (Noulard et al., 2009). The availability of an open source RTI removed barriers to training and software development that can arise with commercial software.

6.2 SEAWAY MODELLING

Modelling of seaways using one or multiple sinusoidal wave components was considered appropriate for simulation of replenishment at sea, which occurs in moderate wave conditions. For simulation of operations in severe wave conditions, more complex seaway models could be considered. The relative simplicity of the seaway modelling facilitated development of local implementations for each federate as required, eliminating the need to transfer large amounts of flow condition data across the network. For example, the visualizer computed wave elevations for rendering using computations on its own local computer.

Although the implementation of local seaway models within federates contributed to simulation efficiency, this approach implies that care must be taken if federates are to be re-used in the future. Any changes to the seaway model will need to be implemented in all federates with a local seaway model.

6.3 SHIP HYDRODYNAMIC MODELLING

Potential flow modelling of flow around ships enabled fast and robust evaluation of forces acting on ships and resulting motions. In comparison to simulation of motions for a single ship, the influence of ship speed on the free surface boundary condition is more important when two or more ships are in close proximity (von Graefe et al., 2013). Future validation work could provide greater understanding of the impact of this phenomenon on simulation of replenishment at sea.

Work by the United Kingdom (Henry et al., 2015) indicates that models based on potential flow with the addition of flow separation effects can give very good results for maneuvering forces during replenishment at sea, including interaction effects. This result is very encouraging given that the alternatives of model experiments and Reynolds-averaged Navier-Stokes computational fluid dynamics require much greater effort.

6.4 REPLENISHMENT GEAR MODELLING

The replenishment gear federates developed by Canada and the United Kingdom have not been subjected to extensive validation. Ideally, these models would be thoroughly validated using replenishment gear with land-based testing systems and full-scale sea trials. For simulations focussing on ship motions during replenishment at sea, the existing replenishment gear models are considered adequate because they can model the relatively constant tension forces that are applied to ships during routine replenishment operations.

6.5 VERIFICATION

Many software components in the distributed simulation had been previously verified and validated as stand-alone modules outside of the distributed simulation; thus, much of the verification of distributed simulation could focus on ensuring that software components had been correctly implemented within the distributed simulation. For example, ship motion simulations within the distributed simulation should give results that are equal to stand-alone simulation results for applicable cases.

For virtual ships simulations, it was found that special attention should be given to ensure correct implementation of coordinate systems. Software components integrated into federates often use coordinate systems for internal computation that differ from virtual ships simulations; thus, verification should ensure that coordinate system transfers are being performed correctly.

6.6 VALIDATION WITH MODEL TESTS

Validation with model tests in wave tanks and basins can be invaluable due to precise control over experimental conditions and also due to relative ease of measuring data. Model tests in regular waves can be very useful due to experimental conditions that are well known and understood. In comparison to model tests for a single ship, it is recommended that model tests for two ships in waves use a finer wave frequency increment due to the greater sensitivity of ship motions to wave frequency when two ships are present.

Care must be taken to minimize wall interference effects during model tests. The presence of two models during towing tank experiments leads to greater interference from tank walls relative to single ship cases due to the greater total width required by two separated ship models. If experimental data are found to be affected by tank wall interference, consideration can be given to numerical modelling of tank wall effects during validation.

6.7 VALIDATION WITH FULL SCALE TRIALS

Sea trials of replenishment at sea highlighted the requirement for directional wave spectral data for validation of the simulation. Challenges with full scale validation are further compounded by the transient nature of replenishment at sea operations. Ideally, acquisition of validation data would include multiple repetitions (e.g., 10 or more) of payload transfers for each combination of seaway spectrum, ship speed, and ship heading. These multiple repetitions would facilitate required statistical analysis for validation.

6.8 APPLICATION TO NAVAL SHIP DESIGN AND OPERATION

The developed simulation has potential for application to various aspects of naval ship design and operation. Note that application to design and operation requires that the simulation first be determined to be fit for purpose.

It is essential that ships maintain controllability during replenishment at sea. The simulation could be used to assess that the ships are able to maintain controllability even while subject to forces from hydrodynamic interactions and replenishment gear. Ship headings, separation distance, and relative longitudinal separation are key indicators of controllability.

Replenishment gear must be able to cope with changes of relative ship locations. The simulation could be used to assess expected variations in ship relative locations, providing valuable input for design of replenishment gear.

The simulation could be used for operational planning, including selection of optimal speed, heading, lateral separation, and relative longitudinal position. The simulation enables safe and economical evaluation of many different operational scenarios. Experience with the simulation indicates that variation of operational parameters often leads to counter-intuitive results due to the complex nature of the underlying physics, such as hydrodynamic interactions.

7. CONCLUSIONS

A distributed simulation of replenishment at sea was developed using the High Level Architecture. The simulation components can be adapted for other naval scenarios, such as launch and recovery of water craft. Implementation using HLA was facilitated by focussing on a limited required subset of HLA. The open source CERTI HLA run-time infrastructure was highly useful for acquiring HLA skills and implementing the simulation.

Modelling of seaways using single or multiple sinusoidal wave components was suitable for simulating naval operations in realistic wave conditions and enabled implementation of non-networked seaway models that could be quickly accessed by simulation components. Ship motion computations were based on potential flow models, which provided performance that was much faster than real-time.

Ship motions for interaction cases can be very sensitive to wave frequency; thus, fine wave frequency increments are recommended when performing model tests in regular waves for validation purposes. Tank wall interference can affect the results of model tests in irregular waves in the lower frequency range and need to be taken into account in the validation. Validation sea trials should include detailed measurements of directional wave spectra.

Validation has indicated that the influence of ship forward speed on the free surface boundary condition is more pronounced for ship interaction cases than for single ship cases. In-depth validation of replenishment gear simulation components is a recommended area for future work.

8. ACKNOWLEDGEMENT

The authors would like to acknowledge Dr. John Duncan of the Ministry of Defence for his leadership of UK contributions to this work and Captain Sergio Simone of the Italian Navy for his support and coordination of the Italian contributions.

9. REFERENCES

1. FUJIMOTO, R.M. (2000) *Parallel and Distributed Simulation Systems*. John Wiley & Sons, New York.
2. GOODRICH, G.J. (1969) *Proposed standards of seakeeping experiments in head and following seas*. 12th International Towing Tank Conference, Rome.
3. HENRY, G., MCTAGGART, K., DE KRAKER, K.-J., and DUNCAN, J. (2008) *NATO virtual ships standards*. SimTecT 2008, Melbourne, Australia.
4. HENRY, G.K., FIDDES, S.P., BURKETT, C.W., DUNCAN, J., MCTAGGART, K.A., STUNTZ N. AND TOZZI, D. (2015) *International simulation of replenishment at sea using the virtual ship standard*. International Conference on Computer Applications in Shipbuilding, Bremen, Germany.
5. KUHL, F., WEATHERLY, R. and DAHMANN, J. (1999) *Creating Computer Simulation Systems – An Introduction to the High Level Architecture*. Prentice Hall PTR, Upper Saddle River, New Jersey.
6. MATHEW, J., SGARIOTO, D., DUFFY, J., MACFARLANE, G., DENEHY, S., NORMAN, J., CAMERON, A., EUTICK, N., and VAN WALREE, F. (2018) *An experimental study of ship motions during replenishment at sea operations between a supply vessel and a landing helicopter dock*. Transactions RINA, Vol. 160, Part A2, International Journal Maritime Engineering, Apr-Jun 2018.
7. MCTAGGART, K. (2015) *Ship radiation and diffraction forces at moderate forward speed*. World Maritime Technology Conference, Providence, Rhode Island.
8. MCTAGGART, K. (2017) *Radiation and diffraction forces and motions for two ships at moderate forward speed*. Society of Naval Architects and Marine Engineers Maritime Conference, Houston.
9. MCTAGGART, K, CUMMING, D., HSIUNG C.C. and LI, L. (2003) *Seakeeping of two ships in close proximity*. Ocean Engineering, Vol. 30, No. 8, pp. 1051-1063.
10. MCTAGGART, K, ROUX DE REILHAC, P., BOUDET, L. and OAKEY, S. (2018) *Validation of a distributed simulation of ship replenishment at sea with model tests*. Accepted for publication.
11. NOULARD, E., ROUSSELOT, J.-Y. and SIRON P. (2009) *CERTI, an open source RTI, why and how*. Fall Simulation Interoperability Workshop, Orlando, Florida.
12. SHREINER, D., SELLERS, G., KESSENICH, J., and LICEA-KANE, B. (2013) *Programming Guide, Eighth Edition: The Official Guide to Learning OpenGL, Version 4.3*, Addison-Wesley, Upper Saddle River, New Jersey.
13. TOZZI D., VALDENAZZI, F., and ZINI, A. (2014) *Use of HLA federation for the evaluation of naval operations in ship design*. International Workshop on Modelling and Simulation for Autonomous Systems, Rome.
14. VON GRAEFE, A., SHIGUNOV, V., and EL MOCTAR, O. (2013) *Rankine source method for ship-ship interaction problems*, 32nd International Conference on Offshore Mechanics and Arctic Engineering, Nantes, France.

