A SIMULATION FRAMEWORK FOR SHIPS PILOTS TRAINING

Francesco Longo[(a)], Roberto Musmanno[(b)], Letizia Nicoletti[(c)], Alessandro Chiurco[(d)]
[(a)(b)(c)(d)]DIMEG, University of Calabria, Rende (CS), Italy

f.longo@unical.it[(a)], musmanno@unical.it[(b)], letizia.nicoletti@unical.it[(c)], a.chiurco@unical.it[(d)]

ABSTRACT
The paper proposes an advanced simulator of a commercial containership within a virtual environment reproducing the port of Salerno. The motion of the ship at sea is based on a 6 Degree Of Freedom (DOF) model that includes the MMG model for surge, sway and yaw and closed form expression for pitch, roll and heave. The simulator is part of an on-going research project (HABITAT, Harbour Traffic Optimization System) and is intended for ship pilots training for manoeuvring inside the port area (i.e. while entering and/or exiting from the port, mooring operations, etc.) therefore it seeks to recreate the experience of a real ship manoeuvring with accuracy.
To this end, the analytical model for the ship motion has been validated through a dedicated software tool that has been developed writing a C++ programming code. This tool allows testing the behaviour of the simulator according to the desired configuration of the ship.

Keywords: Ships Pilots Training, Modelling& Simulation, marine ports

1. INTRODUCTION

Steering a large ship inside a commercial port can be a complex and dangerous process for several reasons. Indeed, in standard traffic conditions it is possible to have a great number of vessels of different sizes (i.e. small motorboats, huge container carriers, cruise ships etc.). In addition, manoeuvring times (and reaction times) of vessels are very slow compared to other vehicles especially for large vessels. Due to their prominent size and mass, in case of mistake and accident, large vessels may cause enormous damages (consider the recent accident on May 7th, 2013 of the Italian container ship Jolly Nero in the port of Genoa).

In the Logistics area, Modeling & Simulation (M&S) has widely proved to be a powerful and profitable tool (Merkuryev and Bikovska, 2012; Narciso et al. 2010); as far as the ship manoeuvrings in the port area are concerned, M&S can be profitably used for ship pilots, training purposes, for procedures definition, evaluation and testing, for understanding vessels interactions within the port area, for evaluating the effects on ships maneuvering in the port area of adverse weather conditions (including wind, sea waves and marine currents). As a matter of facts M&S allows a greater standardization and effectiveness of training processes. The trainee can steer the virtual ship in any critical or dangerous condition; he can perform both standard and non-standard manoeuvres and therefore he is trained to handle those situations that cannot be recreated during traditional training sessions in a real ship.

There is a relevant reduction of direct costs. These costs reduction is related to the increase of productivity when workers (in this case ship pilots) are well trained to perform their job. There is also a reduction of the indirect costs caused by accidents during training and normal activities as well as the possibility of collecting a large amount of data about trainees' performance in a controlled simulated environment.

Moreover, simulation-based training is fruitful not only for beginners but also for expert pilots. For instance, it can be useful to have a first approach with a never used type of ship or to learn how to put in practice the procedures currently adopted in a specific port. Moreover the simulator can be used to understand how manoeuvring a ship in critical conditions (i.e. strong wind and/or marine currents), how to carry out complex manoeuvres with the help of tugboats, how performing mooring operations and control the ship when close to the assigned berth area, etc.

Indeed, the literature review confirms that there is quite a large amount of research works that show how simulation has already been successfully applied for training operators working within the port area, i.e. cranes, trucks, straddle carriers operators, etc. (Kim, 2005). Many simulators are intended to quay cranes operators' training (Wilson et al., 1998; Huang, 2003; Daqaq, 2003; Rouvinen et al., 2005) and specific research works have also investigated the training for supporting security procedures integration in the marine port operations (Longo et al., 2006, Longo, 2010 and Longo 2012). To this end, it is worth mentioning that a comprehensive survey of research projects dealing with advanced simulation systems for operators training in marine ports is the main deliverable of the OPTIMUS project (Operational Port Training Models Using Simulators, financed by the European Community). The OPTIMUS project provides a detailed description of many commercial simulators for marine port operators training. Such simulators include crane simulators mainly.

In addition, innovative approaches based on interoperable simulation have been proposed. Specific examples regards the training of marine ports operators, i.e. Bruzzone et al. (2011-a), Bruzzone et al. (2011-b) developed interoperable simulators based on the High Level Architecture (HLA) integration standard for different container handling equipment (gantry cranes, transtainers, reach stackers, trucks, etc.) offering advanced solutions in terms of external hardware i.e. motion platform, different types of external controllers from joystick to wheels and pedals, etc.) and even containerized solutions.

As for ship simulators, interesting applications can be found in Ueng et al. 2008, Sandaruwan et al. (2009), Sandaruwan et al. (2010) and Yeo et al. (2012). Although in such works an immersive visualization system and the dynamic behaviour of the ship have been implemented, there is still substantial room for improvement above all in terms of ship motions predictions and validation. Moreover, in these works no attention has been paid on the last/second last mile of navigation (including manoeuvring and mooring operations in the port area) that, as explained before, it is as important as offshore navigation. A review of the state of the art related to traffic controllers and ships pilots training in marine ports can be found in Bruzzone et al. (2012).

Indeed, the main goal of this paper is to present a six degree of freedom ship simulator intended for the pilots involved in the last mile of navigation. The proposed tool can be used for training of both inexperienced pilots and experienced pilots steering a new kind of ship. Besides the proposed simulator can be also used to train ship pilots on specific port procedures regulating entering/exiting manoeuvres; as a matter of facts such procedures are established by port authorities based on port characteristics and therefore may be different from port to port.

The simulator has been developed within the framework of an on-going research project: HABITAT. This project is co-founded by the Italian Ministry of Education, University and Research as part of the PON Research Program.

Before going into details, the paper is organized as follows: section 2 summarizes the main features of the simulated scenario (that recreates the port of Salerno, Italy). Then, the commercial containership, which the simulator refers to, is introduced. Section 3 illustrates the mathematical model that has been adopted to recreate the ship motion at sea; section 4 describes the software tool that has been implemented for Verification, Validation and Accreditation (VV&A) of the ship motion models. Section 5provides an overview about the development phases and the requirements of proposed ship simulator providing also an overview of the 3D virtual environment. Lastly, section 6 summarizes the scientific contribution of the paper and future developments.

2. THE TRAINING SCENARIO

The training scenario considered in this research work is the Port of Salerno (see Figure 1) while the ship being simulated is a commercial container carrier.

The port of Salerno, thanks to its central position in the Mediterranean Sea, has a crucial role in the national and international maritime trade. The port area includes the following quays:

- Quay of Ponente , length 563m, dockings n. 22-24;
- Rosso quay, length 226m, dockings n. 20-21;
- Trapezio quay, length 890m, dockings n. 13-19;
- Ligea quay, length 250m, dockings n. 11-12;
- 3 Gennaio quay, length 446m, dockings n. 7-10;

Outside the commercial area, on the east side of the port is located the Manfredi quay (length 380m, dockings n. 1-3) where a Marine Station devoted to cruise ships is being built. An entrance channel (280m large and 13m deep) with a 550 m diameter and 12 m deep evolution area characterizes the port. Moreover the port is served by 4 tugboats (working 24/24 h), 5 expert pilots with 2 equipped pilot-boats and 10 mooring operators with 2 equipped motorboats.

Vessels can pass across the entrance channel only one-by-one; according to this restriction if a boat is entering the port and another one is exiting, the incoming boat has to wait until the other has safely completed its manoeuvres. In addition, owing to Port Authority restrictions on side thrusters' use and to strong winds (that can reach 40kn) most of the large ships are supported by at least one tugboat during their manoeuvres.

Figure 1- Panoramic view of Salerno port

As mentioned before, the ship that has been modelled by the simulator is a commercial containership based on the Kriso containership model, whose main particulars are summarized in the following:

- Hull
  - Length between perpendiculars 230.0 m
  - Length water line 232.5 m
  - Breath 32.2 m
  - Depth 19.0 m
  - Displacement 52030 m^3
  - Coefficient block 0.651
- Rudder
  - Type semi-balanced horn rudder
  - Surface of rudder 115 m^2
  - Lateral area 54.45 m^2

- Turn rate 2.32 deg/s
- Propeller
  - Number of blades 5
  - Diameter 7.9 m
  - Pitch ratio, P/D (0.7R) 0.997
  - Rotation Right hand

3. THE SHIP MOTION EQUATIONS

A 6DOF mathematical model is used to reproduce the ship motion at sea. In particular, for surge, sway and heading the Manoeuvring Mathematical Modelling Group model (MMG) has been followed. Such model takes the name from the Japanese research group that implemented it for the first time between 1976 and 1980). Hence, the MMG group (1985) defined for the first time a prediction method for ship manoeuvrability.

Afterwards, Kijima (1999) taking into account the effects of the stern, proposed the approximate formulas for evaluating the hydrodynamic forces acting during manoeuvring motions. As for the hydrodynamic coefficients within the ship manoeuvring, empirical formulas are given in Rhee and Kim (1999) and Lee et al. (2003). Moreover, Yoshimura (1986) and Perez et al. (2006) describe how some parameters and dimensions influence manoeuvrability characteristics while Hasegawa et al. (2006) have discussed the course-keeping in windy condition. These findings have been integrated within the MMG model that includes three equations of motion (1, 2, 3) for surge, sway and yaw respectively based on the Newton's second law.

$$(m + m_x)\dot{u} - mvr = X \tag{1}$$

$$\left(m + m_y\right)\dot{v} + mur = Y \tag{2}$$

$$(I_{zz} + i_{zz})\dot{r} = N - x_G Y \tag{3}$$

In equations 1, 2 and 3:

- *m* is the mass of the ship;
- m_x and m_y are the added mass in x and y direction respectively;
- I_{zz} is the moment of inertia;
- i_{zz} is the added moment of inertia around z;
- *u* is the surge speed;
- *v* is the sway speed;
- *r* is the rate of turn;
- x_G is the distance from amidship to the centre of gravity of the ship
- *X* and *Y* are respectively the total external surge and sway forces;
- *N* is the yaw moment;

Added masses and added moment of inertia can be found using the equations proposed by Hooft and Pieffer (1988). In some equations non-dimensional variables are used, they are marked with the prime symbol. The external forces are those produced by the hull, the propeller and the rudder; they are marked with the subscripts H, P and R respectively, therefore surge sway and yaw can be also expressed as shown in equations 4, 5 and 6.

$$X = X_H + X_P + X_R \tag{4}$$

$$Y = Y_H + Y_R \tag{5}$$

$$N = N_H + N_R \tag{6}$$

Since the hull of the ship has a complex shape it is quite difficult to calculate hull forces. To this end, the equations 7, 8 and 9 (proposed in the Proceedings of the 23rd ITTC 2002) have been used.

$$X'_H = -(X'_0 + \left(X'_{vr} - m'_y\right)v'r') \tag{7}$$

$$Y'_H = Y'_v v' + \left(Y'_r + m'_x\right)r' + Y'_{vvv}v'^3 + Y'_{vvr}v'^2 r' + Y'_{vrr}v' r'^2 + Y'_{rrr}r'^3 \tag{8}$$

$$N'_H = N'_v v' + \left(N'_r + m'_x\right)r' + N'_{vvv}v'^3 + N'_{vvr}v'^2 r' + N'_{vrr}v' r'^2 + N'_{rrr}r'^3 \tag{9}$$

It is worth noticing that the higher order terms have been omitted in the surge force equation because their influence is negligible and an appropriate formula to calculate the coefficients is not available yet.

The equations 7, 8 and 9 define a relation between velocities and hull forces with hydrodynamic non-dimensional coefficients. Such coefficients are normally obtained through tests but a set of semi-empirical equation can be found in Lee et al. (2003). Therefore, the total non-dimensional resistance, X'_0, has been calculated as shown in equation 10 where C_T is the total resistance coefficient (obtained from model resistance tests), *S* is the wetted surface, *L* is the length between the perpendiculars, and *d* is the draft.

$$X'_0 = \frac{C_T S}{Ld} \tag{10}$$

On the other hand, the equations for non-dimensional variables are given in 11, 12, 13, 14, 15 according to Kijima (1993).

$$m', m'_x, m'_y = m, m_x, m_y / 0.5\rho L^2 d \tag{11}$$

$$X', Y' = X, Y / 0.5\rho L d U^2 \tag{12}$$

$$N' = N / 0.5\rho L^2 d U^2 \tag{13}$$

$$r' = \frac{rL}{U} \tag{14}$$

$$v' = \frac{v}{U} \tag{15}$$

In equations 11, 12, 13, 14 and 15, ρ is water density and U is the ship speed that can be calculated according to 16.

$$U = \sqrt{u^2 + v^2} \tag{16}$$

The force generated by the propeller is obtained using the equation 17 from Kijima(1993) where n is the propeller rate expressed in RPM, t is the suction coefficient, D_p is the propeller diameter and K_T is the propeller thrust coefficient.

$$X_P = (1 - t)\rho n^2 {D_p}^4 K_T \tag{17}$$

It is possible to express K_T as a function of the propeller advance coefficient J, as shown in equations 18 and 19.

$$J = (1 - w_P)u/(nD_P) \tag{18}$$

$$K_T = C1 + C2 + C3J^2 \tag{19}$$

In equation 18, w_p is the wake fraction while to identify $C1$,$C2$ and $C3$in equation 19 it is necessary to use the least squares method on Wageningen B systematic series for the appropriate propeller.

Lastly, the equations used to calculate rudder forces are 20, 21 and 22 taken from Kijima (1993). In these equations:

- t_R is the rudder drag coefficient;
- F'_N is the normal force applied on the rudder;
- a_h is a coefficient that expresses the interaction between rudder and hull forces;
- x'_R is the non-dimensional coordinate of the centre of lateral force along the x-axes;
- x'_H is the non-dimensional coordinate of the centre of additional lateral force along the x-axis (such values can be evaluated by using the equations given in Kijima et al., 1993);
- δ is the rudder angle.

$$X'_R = -(1 - t_R)F'_N sin\delta \tag{20}$$

$$Y'_R = -(1 - a_H)F'_N cos\delta \tag{21}$$

$$N'_R = -(x'_R - a_H x'_H)F'_N cos\delta \tag{22}$$

On the other hand, heave pitch and roll have been modelled according to Jensen, (2001) and Jensen et al (2004). The proposed model is based on simplified equations, one for each DOF, devoted to work out ship motions in regular waves. Basically, in these equations, the coupling terms are neglected and the sectional added mass is equal to the displaced water.

$$2\frac{\mathrm{kT}}{\omega^2}\ddot{\omega} + \frac{\mathrm{A}^2}{\mathrm{kB}\alpha^3\omega}\dot{\omega} + \omega = \mathrm{aFcos}(\overline{\omega}\mathrm{t}) \tag{23}$$

$$2\frac{\mathrm{kT}}{\omega^2}\ddot{\theta} + \frac{\mathrm{A}^2}{\mathrm{kB}\alpha^3\omega}\dot{\theta} + \theta = \mathrm{aGsin}(\overline{\omega}\mathrm{t}) \tag{24}$$

$$\left(\frac{\mathrm{T_N}}{2\pi}\right)^2 \mathrm{C_{44}}\ddot{\varphi} + \mathrm{B_{44}}\dot{\varphi} + \mathrm{C_{44}}\varphi = \mathrm{Macos}(\overline{\omega}\mathrm{t}) \tag{25}$$

The equations 23 and 24 are related to heave and pitch respectively while equation 24 refers to roll motions. Here, derivation with respect to time is denoted by a dot, k is the wave number, ω is the wave frequency, B is the ship breadth, T is the ship draught, $\overline{\omega}$ is the frequency of encounter, a is the wave amplitude and A is the sectional hydrodynamic damping that can be evaluated according to Yamamoto et al. (1986). F and G are the forcing functions whose values can be worked out according to Jensen et al. (2004).

As for roll, φ is the roll angle, T_N is the natural period for roll, B_{44} is the ship hydrodynamic damping, C_{44} is the restoring moment coefficient and M is the roll excitation moment.

The hydrodynamic damping coefficient B_{44} can be found by applying the method described in Jensen et al. (2004). The roll excitation moment M can be derived from the Haskind relation, while the restoring moment coefficient C_{44} can be expressed as a linear function of the displacement Δ, the transverse metacentric height GM_T and the acceleration of gravity g (see equation 26).

$$\mathrm{C_{44}} = \mathrm{gGM_T}\Delta \tag{26}$$

It is worth noticing that this research work proposes a new application of the Jensen's et al. (2004) model. As a matter of facts, ship responses are calculated in in the time domain instead of in the frequency domain as it was in the original formulation. Thus, this model has been used to provide the simulation and visualization system with real-time data about heave, pitch and roll motions.

4. THE SHIP MOTION TEST

The above-discussed mathematical models have been extensively validated before being implemented within the simulator. To this end, a dedicated tool has been developed by Visual Studio 2008 with the C++ programming language.

This tool allows setting the most important parameters such as the number of iterations to be executed, the time between two iterations, the propeller rate, the initial speed and the rudder angle. In this way, it is possible to execute circle tests, zigzag tests and stop tests according to different configurations as shown in figure 2, 3, 4 and 5.

During the execution of such tests, a plot of the ship motion evolution is drawn on the screen and sensible data as speed, drift angle, yaw rate, acceleration, heading, position are recorded on text files. This tool has proved itself very useful. Since the preliminary tests carried out at the earlier validation stages were not in agreement with the empirical data that have been used as test-bed, the mathematical model has been carefully reviewed and some parameters, such as the dimensionless derivatives, where suitably calibrated. Even during calibration, the C++ tool has been used to assess whether the applied adjustments had improved the output results to achieve closer empirical evidence. Thus after tuning, the results are better suited to the existing data collected on tests for container carrier. Figure 2 and 3 show the trajectory for two Circle tests executed by the tool, moreover they provide a comparison with empirical data given by two circle tests executed at the same conditions of speed and rudder angle. Empirical data are taken from The Specialist Committee on Esso Osaka, Final Report and Recommendations to the 23rd ITTC.

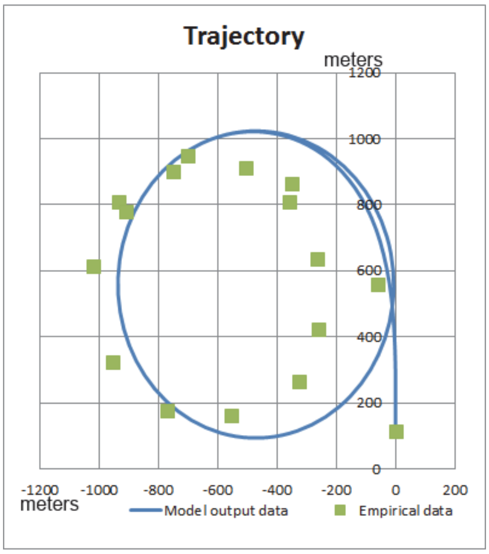

Figure 2: Turning trajectory in port side circle test, speed 8kn, rudder angle 35°.

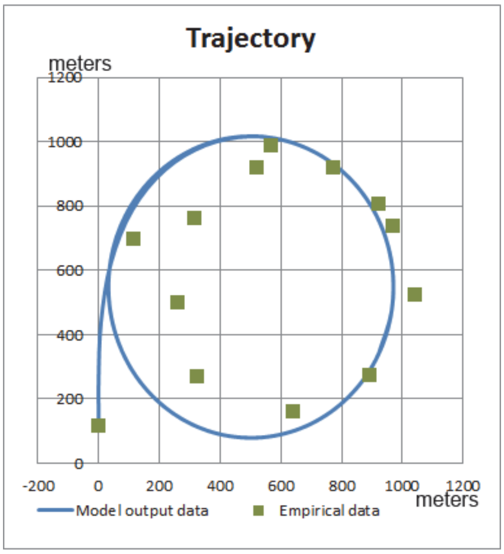

Figure 3: Turning trajectory in starboard side circle test, speed 10kn, rudder angle 35°

Figure 4 and 5 show two zigzag tests. They reflect the empirical data that can be seen on The Specialist Committee on Esso Osaka, Final Report and Recommendations to the 23rd ITTC.

As for heave, pitch and roll validation activities have been based on the comparison of the ship empirical Response Amplitude Operators (RAOs) to the model-based RAOs. Such comparison led to deem the model outputs enough accurate and therefore suitable to achieve the research goals behind the simulator development.

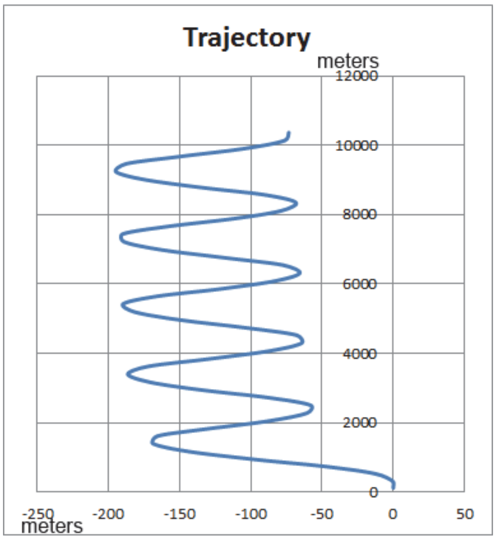

Figure 4: Turning trajectory in port side 20/20 zigzag test, speed 5kn

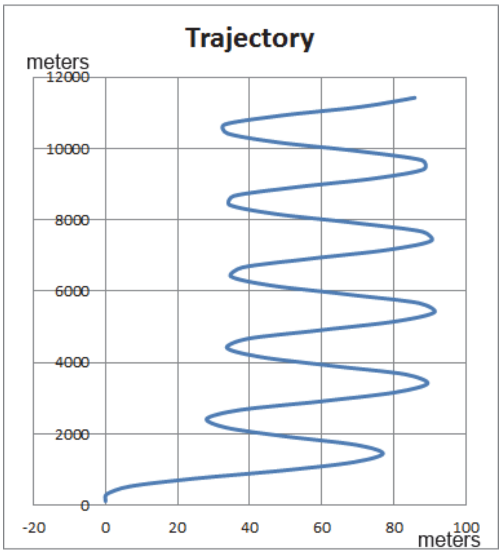

Figure 5: Turning trajectory in starboard side 10/10 zigzag test, speed 5kn

5. THE TRAINING SIMULATOR

Control and support of ship navigation in the second last/ last mile of navigation are very complex activities. The high number of ships and vessels that usually enter to and exit from a marine port, the adverse visibility and weather conditions that may occur, the type of ship (i.e. container carriers, passengers ships, etc.), the docking times, the loading/unloading times, are examples of factors that slow down the traffic. These factors also increase the risk of collisions during the navigation in the harbour area. In this scenario, the proposed simulator aims at providing a concrete support by leveraging the role of pilots training. As a matter of facts, manoeuvring a ship while it is exiting from or entering into a port area is quite difficult and may cause terrible losses. To this end, it is crucial that ship pilots are well trained and fully aware of the consequences of their actions. Since simulation provides a safe training environment where trainees can gain experience and explore possibilities, simulation-based training has great potentials in this application domain. However, it is worth saying that the effectiveness of simulation based training increases as the trainee's feeling of realism increases. Hence, greater attention has been paid on the virtual environment that recreates with accuracy the port of Salerno and on modelling the dynamic behaviour of the ship that has been extensively validated by the comparison with empirical data. This way the simulator conceptual and operational model has been developed. Afterwards such models have been encoded into a computerized model written in the C++ programming language within the Visual Studio 2008 Integrated Development Environment. Moreover, the Vega Prime by Presagis and the Creator by Presagis have been used forcreating highly optimized 3D geometric models and high-fidelity 3D real-time simulations respectively. As a result the simulator gives the possibility to steer a container carrier in the last mile of navigation, as well as offshore, setting the rudder angle and the propeller rate dynamically.

Furthermore, different viewpoints are available: inside the bridge, outside the ship (therefore it is possible to see the whole ship from different points of view) and the control tower. Figures 6, 7 and 8 show three different points of view of the ship.

In addition, the simulator has been conceived in order to provide the users with a large spectrum of operative scenarios; in fact, the trainer can set weather and marine conditions before the training session starts or even during the execution. Data such us main engine RPM, side thrusters utilization levels, rudder positions, wind intensity and directions, compass, 2D map of the port areas including the other ships (Automatic Identification System – AIS) are always available during the simulation. Performance measures such as mission time (average and standard deviation values over multiple training sessions), collisions, and wrong manoeuvres are recorded and are available at the end of the simulation. Besides, the accuracy and quality of the simulator has been guaranteed by Verification, Validation and Accreditation (VV&A) processes that have been carried out during the entire development period (Bruzzone et al. 2010). As mentioned before, the ship dynamic has been verified and an ad-hoc tool has been developed to this purpose. As for the computer simulation model a preliminary verification has been carried out by using the debugging technique to ensure high levels of accuracy and quality.

Figure 6: Inside the commercial containership bridge

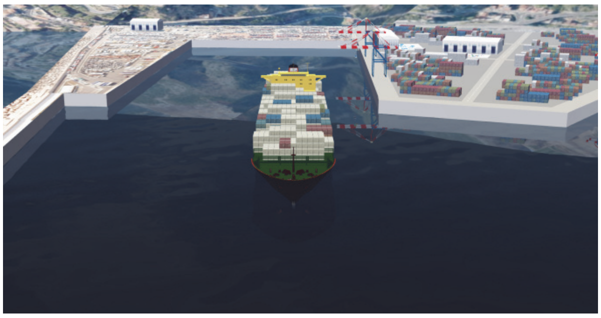

Figure 7: Front view of the commercial containership

Figure 8: the commercial containership back view

6. CONCLUSIONS

This paper proposes the implementation within a simulator of a 6 DOF model for the motion of a containership at sea. Throughout the paper, the equations that allow recreating the motion of the ship are proposed and commented. Before their implementation within the ship simulator, the equations have been tested by using an ad-hoc tool developed by authors to give the possibility to tune the equations and obtain a realistic behaviour of the ship at sea. The 6 DOF models has been then implemented within the ship simulator with the aim of developing a simulation based training tool for ship pilots involved in the last/second last mile of navigation. To this end, the simulator has been conceived in order to provide the trainees with an experience as much realistic as possible. In this way, the simulation-based approach seeks to maximize training effectiveness, lesson learned and at the same time reduces the need for training on the real system with real equipment. As a matter of facts, the trainee can safely exercise on ship manoeuvring in any desired condition and at any time so that he/she canimprove his/her skills and develop the capability of predicting the possible outcomes related to the course of actions he/she undertakes. In addition, the simulator can be used by inexperienced pilots but also by expert's pilots who wish to be acquainted with a never steered kind of ship or simply learn the entry/ exit procedures that are adopted in a specific port.

In fact, it is possible to replace the current scenario and or the kind of vessel with a moderate effort. To this end, it is worth saying that the current ship can be changed but it would require the calibration of the dynamic model and as a consequence, a new validation process.

The simulator dynamic behaviour has been recreated by implementing the MMG model for surge, sway and yaw, while simplified differential equations have been solved numerically for evaluating ship response in terms of roll, pitch and heave. The simulator conceptual and operational model has been implemented in Visual Studio 2008 IDE using Vega Prime graphic engine while the virtual environment (Salerno port) and all the geometric models (included the container carrier model) have been made with Creator by Presagis.

Furthermore for VV&A purposes an ad-hoc tool has been developed. This tool allows carrying out manoeuvrability tests such as circle, zigzag and stop tests in any desired ship configuration.

Currently, further research activities are still on-going in order to include as part of the simulator additional ships, including a tanker and a ro-ro ship.

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AUTHOR BIOGRAPHIES

Francesco Longo received his Ph.D. in Mechanical Engineering from University of Calabria in January 2006. He is currently Assistant Professor at DIMEG University of Calabria and Director of the Modelling & Simulation Center – Laboratory of Enterprise Solutions (MSC-LES). He has published more than 80 papers on international journals and conferences. His research interests include Modeling & Simulation tools for training procedures in complex environment, supply chain management and security. He is Associate Editor of the “Simulation: Transaction of the society for Modeling & Simulation International”. For the same journal he is Guest Editor of the special issue on Advances of Modeling & Simulation in Supply Chain and Industry. He is Guest Editor of the “International Journal of Simulation and Process Modelling”, special issue on Industry and Supply Chain: Technical, Economic and Environmental Sustainability.

Roberto Musmanno is full Professor at DIMEG University of Calabria. He currently follows as Principle Investigator and Scientific Responsible different national and international research project in the Operations Research area in the field of Logistics and Supply Chain Design and Management. He is scientific Responsible of the TESEO lab at University of Calabria and President of the ITACA company a spin-off of the University of Calabria. He has published more than 60 international journals articles and many conferences papers.

Alessandro Chiurco is Researcher at MSC-LES, Department of Mechanical, Energy and Management Engineering, University of Calabria. His research activities concern the development of 3D immersive and interoperable simulators for training based on the HLA standard. He is also used simulation for investigating problems related to supply chain and marine ports security.

Letizia Nicoletti is PhD student at MSC-LES, Department of Mechanical, Energy and Management Engineering, University of Calabria. Her research interests include Modelling & Simulation for training in complex system with particular attention to marine ports and container terminals. She is also using Modelling & Simulation based approaches for inventory management problems in industrial plants and supply chains. From 2010, she actively supports the organization of the I3M Multi-conference where she is co-chairing the Inventory Management Simulation track.