

# Prototyping and Simulation Environment of Ship Motion Control System

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**ABSTRACT:** Authors of this paper describe the test-bench used for ship motion control system prototyping. This tool is built with the PC-type hardware and the Matlab-Simulink software. The scale model of the VLCC tanker was chosen as a control object. This model is used on a lake as a shiphandling training vessel. The complex, nonlinear mathematical model of this training vessel was used in the test-bench simulations. Authors describe two types of them: the non-real-time (software) and the real-time (hardware-in-the-loop) one. As an example of usability, results of the MIMO LMI controller tests of the ship velocities in 3DOF were shown.

## 1 INTRODUCTION

In the beginning of the 21st century the researchers in the field of ship motion control engineering started to focus on the concept of an autonomous cargo vessel. Vessel which will be able to, autonomously or semi-autonomously, pass the route "berth to berth" in a safe, economical and reliable way. This concept is complex enough by its nature and has to integrate multiple aspects of economy, management, law and engineering to accomplish tasks specific to such a process.

Designing and building a control system for any of the above tasks requires multiple repetitions of verification and testing cycles on every step of the prototyping process.

Performing such verification on a real controlled object (ship) is extremely expensive and due to the, usually, international nature of sea voyages also very time consuming. To overcome these difficulties it is common practice to perform verification of the control system using simulated model instead of a controlled object. Following sections of this paper

describe both the method as well as hardware and software tools that allow simulation, testing and verification of designed ship motion control systems in a convenient manner. The tool is built in a standard programming environment for modelling, analysis and multi-domain simulations of dynamic systems: Matlab-Simulink.

Matlab, along with its extensions, is a platform commonly used for simulating and design of control systems. In a field of ship motion control it is often used for ship dynamics identification (Miller 2016, Perez & Fossen 2011), ship motion simulation (Perez & Blanke 2003, Perez et al. 2006) and controller synthesis (Fossen 2002, Tomera 2015), or even multi-task complex, marine control systems. (Łebkowski 2018)

## 2 SETUP OF THE SIMULATION AND PROTOTYPING ENVIRONMENT

One of the assumptions of the described project was that it will be done on a universal, cost effective, hardware platform and with the use of standard simulating software. The next section describes the controlled object for which the testing environment and controlled system were designed.

Software simulations were the first step of components' verification. The main advantage of this step was the possibility to perform experiments in an accelerated time scale and without the need for specialized equipment. A computer with simulation software installed was only necessary equipment.

In the next step HIL simulations were performed. They allowed components to be tested in the presence of disturbances, delays and inaccuracies of sampling and quantization introduced by hardware components of measurement systems. During HIL simulations the controlled object was simulated on a separate computer using a complex nonlinear mathematical model. This model and simulation methods are described, in more detail, in the next sections of the paper.

### 2.1 Scale model of the VLCC tanker

State space controller synthesis was performed for a multidimensional object; a floating, isomorphous manned model of a VLCC (Very Large Crude Carrier) tanker, built in 1:24 scale. It is a training ship used for deck officers and harbour pilots shiphandling exercises. Main particulars of this ship model are shown in Table 1.

Table 1. Main particulars of the shiphandling training model „Blue Lady”

Parameter	Symbol	Value
Length over all	$L_{OA}$	13.78 [m]
Length between pp.	$L$	13.50 [m]
Beam	$B$	2.38 [m]
Average draft (loaded)	$T_l$	0.86 [m]
Average draft (ballast)	$T_b$	0.50 [m]
Displacement (loaded)	$\Delta_l$	22.83 [T]
Displacement (ballast)	$\Delta_b$	12.46 [T]
Speed	$V$	3.1 [kn]

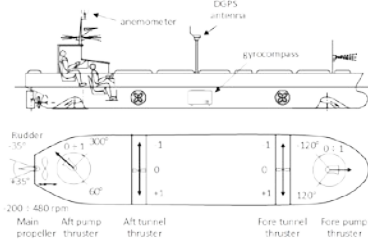


Figure 1. Blue Lady silhouette on the Silm Lake; navigational equipment layout on board and actuators' locations.

Model actuators are driven by DC electric motors and powered by a batteries packs. They are:

- one main engine,
- one aft rudder,
- two tunnel thrusters (fore and aft),
- two rotating pump thrusters (fore and aft).

Ship motion parameters and environmental disturbances are measured by navigational equipment installed on board:

- LEICA DGPS System 500 receiver working in HPN (High Precision Network) mode,
- Anschütz Standard 20 gyrocompass,
- GILL WindObserver II ultrasonic anemometer.

This equipment communicates with the measurement system using serial communication links in NMEA-0183 standard.

Simulation model of the training ship was created using well known ship motion equations in 3DOF space (Abkowitz 1964). It was assumed that heave, roll and pitch may be neglected while the ship goes on the lake (Eq. 1).

$$\begin{aligned}
 (M + m_x)u - Mvr &= X_{tot} \\
 (M + m_y)v + (M + m_x)ur &= Y_{tot} \\
 (I_z + i_{zz})r &= N_{tot}
 \end{aligned} \tag{1}$$

Dynamics described by equations (1) have been supplemented with the ship's kinematical terms and both dynamic and kinematic models of all actuators. Block diagram of the subsequent, complex, nonlinear model of the training ship is shown on Figure 2.

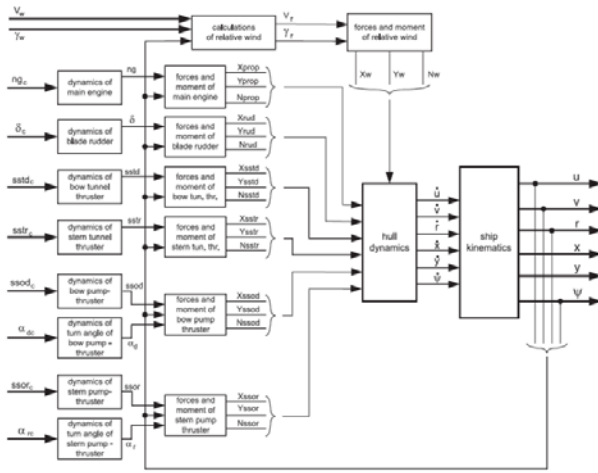


Figure 2. Block diagram of complex, nonlinear model of the training ship.

Reference signals:  $n_{g_c}$ ,  $\delta_c$ ,  $sstd_c$ ,  $sstr_c$ ,  $ssod_c$ ,  $\alpha_{dc}$ ,  $ssor_c$ ,  $\alpha_{rc}$ , are connected to dynamic modelling blocks of specific actuators: rudder, forward and aft tunnel thrusters, forward and aft pump rotating thrusters. Next column of blocks calculates forces and moments based on transient values of their input signals. These are then fed to the block responsible for calculating dynamic ship parameters based on equations (1). Final model output signals are:

- $u$  : ship's longitudinal velocity,
- $v$  : ship's lateral velocity,
- $r$  : ship's angular velocity,
- $x$  : position coordinate in North axis of the local reference frame,
- $y$  : position coordinate in East axis of the local reference frame,
- $\psi$  : ship's heading.

Detailed description of this model along with the values of hydrodynamic coefficients of "Blue Lady" ship model can be found in the paper by Gierusz (2002).

### 2.2 Non real-time software simulation and testing

Software simulations for the described system have been done entirely in Matlab-Simulink software environment.

In the above diagram (Fig. 3), the large block on the left represents the mathematical model of ship dynamics, built accordingly with the description from section 2.1. The large, grey block in lower right corner contains the controller elements. The smaller blocks model operation of AD/DA converters of the actual measurement system and communication

delays. In the real hardware configuration these delays have random values from a certain range. In this model a mean value of these delays was applied. The navigational equipment measurements were not simulated since the mathematical model of the ship delivers these signals directly.

Layout of the main Simulink diagram was designed in such a way that its left side corresponds to the block diagram of the simulator from Figure 6 and its right side to the controller arrangement from Figure 5. Therefore, users who change the type of simulator used in their work can easily operate it.

### 2.3 Real-time HIL simulation and testing

Real time simulations have been managed in Matlab-Simulink environment too. Main module of this system is an industrial PC, marked on the Figure 4 with the bold line.

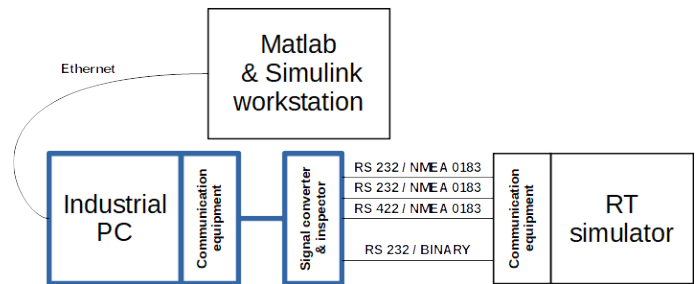


Figure 4. Block diagram of hardware components arrangement of HIL simulation.

This computer is fitted with a multiport serial interface card which is connected to the on-line serial transmission inspection device that is also responsible for serial signal conversion between RS 232 and RS 422/485 standards on selected channels. These hardware elements, as well as their configuration, are taken directly from the final ship motion control system. This is why the system can be considered a HIL - Hardware-In the Loop system.

The industrial computer, which works as a controller, has real time software running that was created based on Simulink block diagram from Figure 5. This diagram was converted into the code of C programming language with Simulink Coder and Simulink Real Time libraries and then compiled by an external C language compiler. The industrial computer is connected by four serial links (Fig. 4) to the ship motion simulator.



### 3 MIMO SHIP MOTION CONTROL SYSTEM

When considering a ship navigating open waters, accuracy of its motion control (heading and position) is not a key factor in control quality evaluation. Usually the relevant factors are derived from the voyage economical parameters as fuel consumption or total voyage costs. In that case, control system action is usually limited to heading stabilization with an assumed accuracy, with the use of only the stern rudder. Then the whole heading control is SISO (Single Input Single Output) system only.

On the other hand, when the ship is maneuvering at low velocities, for example in a harbour, or performs DSP operations, then stern rudder action has marginal impact on a hull motion. Active devices are used and usually all ship's velocities are controlled in a 3DOF system.

While heading control systems for open water navigation are quite well examined, MIMO systems are still subject to studying and investigation (Erol, B. & Delibasi, A. 2018).

Next sections of this paper present example of implementation of the above described simulation and prototyping environment for building a multidimensional control system for longitudinal, lateral and rotational velocities of the shiphandling training vessel "Blue Lady".

#### 3.1 General arrangement of the ship MIMO control

A multidimensional dynamic system is described by operators relative to at least two input and two output variables. It is then commonly called MIMO (Multiple Input, Multiple Output).

Building such a control system requires the integration of its three main components:

- measurement subsystem with signal filters;
- control subsystem, consisting of a positioning system, controller and thrust allocation system;
- propulsion subsystem, consisting of stern rudder, main propeller and thrusters.

In case of the "Blue Lady" training ship, described in section 2.1, measurement and propulsion systems are integral parts of the model and cannot be modified. Thus in the HIL simulation system, described in section 2.3, only signal filtering components, controller and thrust allocation systems have been modelled and tested, as marked with grey colour on Figure 7. These components have been modelled in the "Controller" block (Fig. 5) and after compiling their base elements, they have been executed on an industrial computer (Fig. 4).

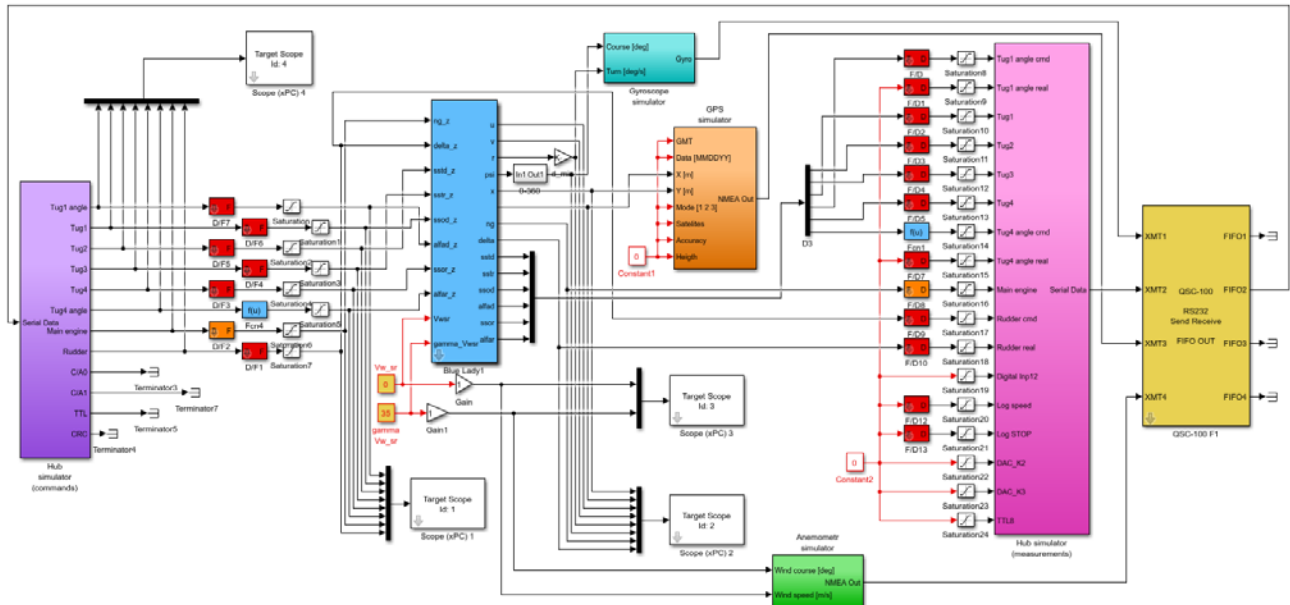


Figure 6. Simulink block diagram for ship motion simulator.

The environment described above was used for investigation of several types of ship motion control systems, i.e. MPC (Miller & Rybczak 2015), LMI (Rybczak 2018), PID-type (Tomera 2015) controllers.

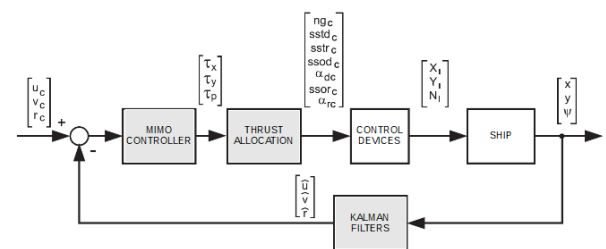


Figure 7. Block diagram of MIMO control system fitted to "Blue Lady" training ship.

### 3.2 Ship slow speed controller using LMI technique

“Blue Lady” ship model is a highly nonlinear object. During ship dynamics identification, for controller synthesis purposes, linearization near the operating point was used. This process took into consideration thruster dynamics, hull construction, thrust allocation module and a Kalman filter.

As a case-study this paper shows results of testing and simulations of a multidimensional controller for ship motions in a 3DOF space with the use of Linear Matrix Inequalities. After taking into account average values of coefficients a state space model of the controlled object was created that is a nominal (average) model. State space equations and output equations of that model are presented below:

$$\begin{aligned} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} &= \begin{bmatrix} a_{uu} & 0 & 0 \\ 0 & a_{vv} & a_{rv} \\ a_{ur} & a_{vr} & a_{rr} \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} b_{uu} & 0 & 0 \\ 0 & b_{vv} & b_{rv} \\ b_{ur} & b_{vr} & b_{rr} \end{bmatrix} \cdot \begin{bmatrix} \tau_x \\ \tau_y \\ \tau_p \end{bmatrix} \\ \begin{bmatrix} u \\ v \\ r \end{bmatrix} &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} \end{aligned} \quad (2)$$

In the identification, process, numerical values of coefficients were calculated for “Blue Lady” vessel based on the real object experiments. Then they were included in equations (2)

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = A \cdot \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + B \cdot \begin{bmatrix} \tau_x \\ \tau_y \\ \tau_p \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} u \\ v \\ r \end{bmatrix} = C \cdot \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + D \quad (4)$$

Values of matrices **A**, **B** and **C** of the controlled object, “Blue Lady” have the below form:

$$A = \begin{bmatrix} -3.36 \cdot 10^{-5} & 0 & 0 \\ 0 & -9.0 \cdot 10^{-3} & -2.0 \cdot 10^{-4} \\ -3.0 \cdot 10^{-3} & -1.0 \cdot 10^{-2} & -7.75 \cdot 10^{-3} \end{bmatrix}, \quad (5)$$

$$B = \begin{bmatrix} 3.62 \cdot 10^{-3} & 0 & 0 \\ 0 & 2.06 \cdot 10^{-3} & -1.28 \cdot 10^{-5} \\ 3.00 \cdot 10^{-5} & 1.15 \cdot 10^{-5} & 8.00 \cdot 10^{-3} \end{bmatrix}, \quad (6)$$

$$C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, D = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (7)$$

The next step after the controlled object linearization is the controller synthesis with the use of Linear Matrix Inequalities. They are applied, among others, in synthesis of controllers in different configurations. For example, as static state space controller, dynamic controller placed in main line or in feedback loop (Duan & Yu 2013, Boyd et al. 1994, Tapia et al. 2017). Based on mathematical description of the controlled object (2), taking into consideration a controller designed using Linear Matrix Inequalities a simplified block diagram of the control system can be presented as Figure 8.

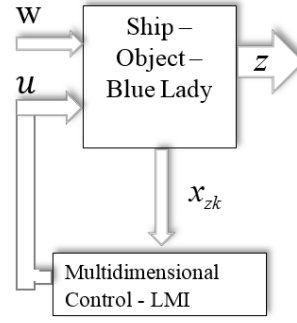


Figure 8. Simplified block diagram of controlled object and controller based on mathematical LMI construction.

Due to the complexity of the controller synthesis this procedure have not been printed in this paper, but can be founded in (Rybczak 2018). Finally, gain matrix for the controller synthesized using Linear Matrix Inequalities has the below form:

$$K = 10^3 \cdot \begin{bmatrix} 1532 & 0.010 & 0.000 & -772 & 0.000 & -0.100 \\ -0.01 & 1664 & -3.60 & 0.00 & -897 & 2.0 \\ -5.90 & -2.801 & 435 & 3.40 & 1.600 & -234 \end{bmatrix} \quad (8)$$

Proposed LMI controller output signals are transformed into actuators reference values by the thrust allocation block. Operation algorithm of this block can be found in work of Gierusz & Tomera (2006).

## 4 TESTS RESULTS OF THE PROPOSED CONTROLLER

As mentioned above, the experiments were carried out on a test-bench in Gdynia Maritime University using two separate methods:

- software simulation
- HIL simulation

Four graphs are compared; the first two have been obtained using SIMULATION – SOFT method



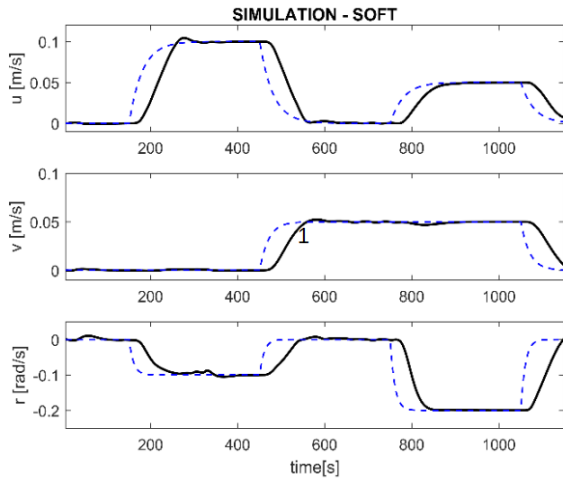


Figure 9. Reference values of longitudinal –  $u$ , lateral –  $v$  and angular –  $r$  velocities (dotted lines) and closed loop system output values (solid lines) in SIMULATION – SOFT mode.

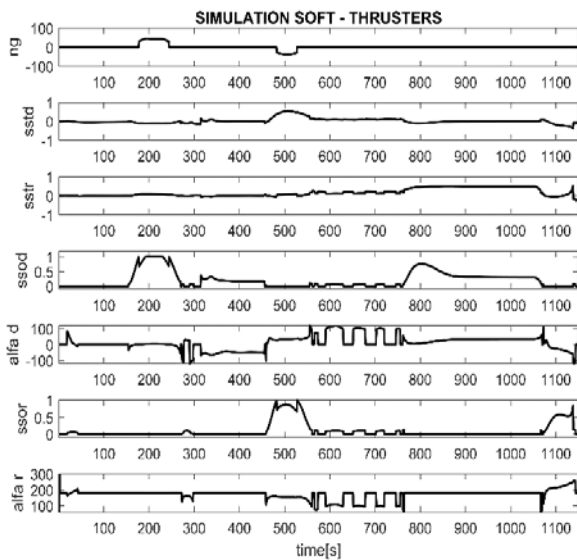


Figure 10. Main propeller and thrusters operation in SIMULATION – SOFT mode.

Figure 9 shows the time histories of the reference and output values of longitudinal –  $u$ , lateral –  $v$  and angular –  $r$  velocities in this experiment.

Figure 10 shows “Blue Lady” main propeller and thrusters’ actions while performing speed changes depicted on Figure 9. Stern rudder remains inactive in all slow speed experiments as mentioned in section 3.

The following two graphs illustrate HIL – real time simulator operation in SIMULATION – HIL mode.

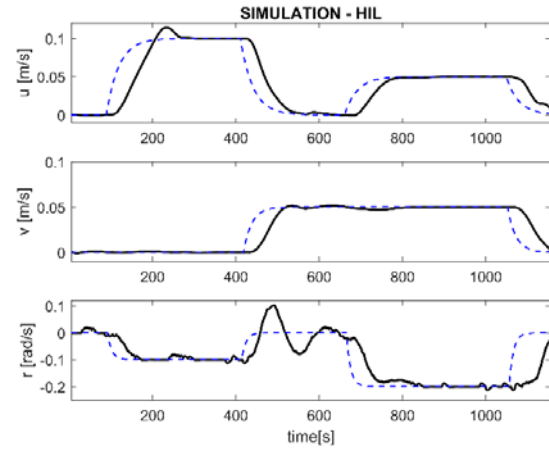


Figure 11. Reference values of longitudinal –  $u$ , lateral –  $v$  and angular –  $r$  velocities (dotted lines) and closed loop system output values (solid lines) in SIMULATION – HIL mode.

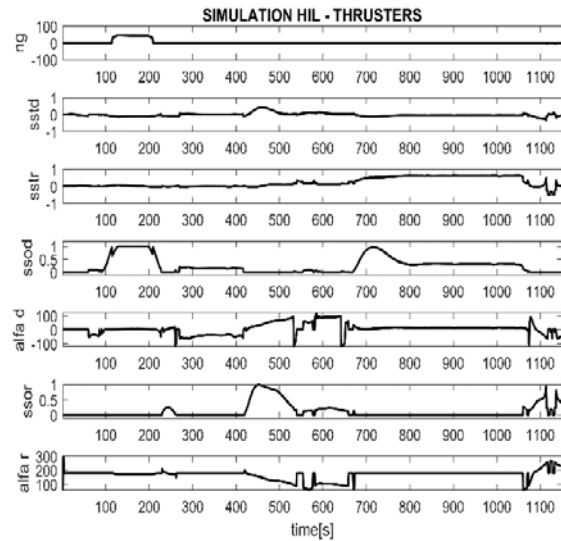


Figure 12. Main propeller and thrusters operation in SIMULATION – HIL mode.

Figure 11 shows the reference values of longitudinal –  $u$ , lateral –  $v$  and angular –  $r$  velocities. Lines are marked in the same way like in Figure 9.

Figure 12 illustrates “Blue Lady” main propeller and thrusters’ actions while performing speed changes depicted on Figure 11.

The aim of the comparison of the two methods was to discover potential differences in  $u, v, r$  velocities control and thrusters operation. Inconsistencies of the results between the two methods of simulation are clearly seen on the Figures 9-12. Main difference appears in the angular velocity channel “ $r$ ” (Figures 9 and 11). In case of HIL test, during the second turn, overshoot of 100% occurred.

The source of this impermissible performance are delays in hardware communication channels which can have random values between 1 and 2 seconds (maximum is a double fundamental sample time of the system). Minor disturbances come also from measurement inaccuracies especially in the angular velocity channel.

The controller which in software simulation works fine, in practice has to be synthesized once again taking into account hardware properties before application to the final control system on the material ship model.

## 5 CONCLUSIONS

The paper describes the test-bench for ship motion control systems verification and validation. This tool was built with the Matlab-Simulink software and limited-cost hardware. As a controlled object the manned model of VLCC tanker, used for shiphandling training was adopted.

The experiments were based on two types of simulation: pure software non-real-time and hardware in the loop, real time one. Analysis of the differences in the performance of the same maneuver for both tests allows to identify components of the control system which needs improvement or reconstruction.

Results of both type simulations clearly show that it is beneficial to use and intermediate tests between pure software computer simulations and real world trials.

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