JMR

Journal of Maritime Research, Vol. VIII. No. 2, pp. 29-46, 2011

ISSN: 1697-4840

AUTONOMOUS SHIP MODEL TO PERFORM MANOEUVRING TESTS

L. Moreira[1,2] and **C. Guedes Soares**[1,3]

Received 24 November 2010; in revised form 07 December 2010; accepted 09 June 2011

Abstract

The paper describes the development of one guidance, control and navigation platform for autonomous surface vehicles, as well as a specific application of using it in a vehicle for performing a set of manoeuvring tests autonomously. In order to be possible to guide the model from land and in a back-up manual mode or to transmit a mission profile for operation in automatic mode a bidirectional communication is established via radio. A set of experiments have been conducted in a lake and the first set of results is presented here. The experiments were performed successfully and have shown the validity of the whole system.

Key words: Autonomous surface vehicle; Manoeuvring tests; Ship control; Navigation systems.

INTRODUCTION

While the knowledge of the manoeuvring capabilities of vessels have always been required in the ship design process, presently there are even stricter requirements that have been imposed by IMO (2002, 1994, 1993), which require all ships to have results of their manoeuvring tests on board. This implies that the need to perform manoeuvring tests will increase in the future.

The knowledge of the manoeuvring characteristics of a ship allows time simulations of its path as a function of its control settings (Sutulo *et al.*, 2002). Presently the

[1] Centre for Marine Technology and Engineering (CENTEC), Technical University of Lisbon, Instituto Superior Técnico, Av. Rovisco Pais, 1049-001 Lisbon, Portugal. [2] Pos doc researcher, Email: lucia@mar.ist.utl.pt. Tel. 351218413548. Fax. 3518474015. [3] Professor, Email: guedess@mar.ist.utl.pt. Tel. 351218417607. Fax. 351218474015.

assessment of the coefficients of the manoeuvring equations is mostly done experimentally. Captive-model tests, in which at least three components (surge and sway forces and yaw moment) must be measured, are the most popular and currently the most adequate mean for creating ship mathematical models.

Circulating tanks with a rotating-arm facility were the first to appear to perform these tests. However to avoid having one specific tank just for this type of tests, the Planar Motion Mechanisms (PMM) allows carrying out captive-model tests in traditional towing tanks and this made it very popular. This mechanism imposes an oscillating motion to the model while it is towed along the tank (Brix, 1993).

To determine the manoeuvring coefficients from these tests a large number of them need to be carried out, even if experimental design techniques are used to reduce the number of tests and to extract the maximum information from them (Sutulo and Guedes Soares, 2004, 2006).

The experimental studies of ship manoeuvring can be performed with full scale ships. Some tests of this type have been performed by the authors (Guedes Soares *et al.*, 1999, 2004), but this method only serves to confirm the qualities of an existing ship, while at design stage tests must be made with models, so as to improve their performance if necessary.

An alternative to the use of models in captive tests in laboratories is to test remote controlled scaled models equipped with appropriate rudders and propulsion plants (Shin *et al.*, 2002, Luo and Zhang, 2007, Philips *et al.*, 2009).

Free-running model tests are often preferred Moreover, often these experiments are preferred as they confirm manoeuvring properties of a ship configuration in the most direct and convincing way. Furthermore, this approach does not require the large investments in laboratory infrastructures. The obvious conclusion is that development of an experimental setup dedicated to scaled manoeuvring experiments with self-running models even nowadays is a wise way to develop experimental studies in the field of ship manoeuvring.

This is the option that has motivated the application described in this paper which intends to substitute the remote control of such models by a system that allows performing all those tests in an autonomous way.

This paper presents the results of the development of a system that is envisioned for Autonomous Surface Vehicles (ASVs) to perform automatically a set of manoeuvring tests, which would otherwise be possible only with radio controlled models. For this task, the design and implementation of an accurate and reliable navigation, guidance and control system is fundamental.

The development of the ASV included control designs, guidance algorithm development, navigation system implementation in the ship model and respective validation through experimental results, making possible the identification of the new hydrodynamic coefficients for the autonomous model. The main idea focused on this research was to develop a control system to turn the ship model operation into an autonomous one and at the same time to become possible to determine its manoeuvring characteristics.

The developed guidance, control and navigation platform can also be applied in vehicles aiming at other kind of missions such ports surveillance, hydrographical activities, bathymetry survey, among others.

The system presented here would represent a simulator that can be applied to any pre-fabricated model of a surface ship (Moreira, 2008). One of the new developments implemented in this system is the vessel manoeuvring guidance design based on a waypoint guidance algorithm by Light of Sight (LOS) (Moreira *et al.*, 2007), which is used to compute the desired heading angle. A new approach concerning the calculation of a dynamic LOS vector norm was implemented in order to improve the convergence of the LOS algorithm.

The developed system was implemented in a model of the "Esso Osaka" ship (see Figure 1) to demonstrate the execution of manoeuvring tests in a controlled and autonomous way, which means that the model must perform predefined manoeuvres in a sequential and operator independent way, acquiring simultaneously the records of the data obtained through the onboard sensors. In addition to this, the system allows the remote control of the manoeuvres and respective parameters from a fixed position onshore (Moreira *et al.*, 2008, 2007).

Figure 1: The "Esso Osaka" ship model.

The missions could be predefined based on waypoints, with the guidance developed through a LOS algorithm or, alternatively, through commands of advance speed and rudder angle. The missions will be controlled and monitored by the user through a server computer located onshore. If necessary the user can abort the mission at any time. The data obtained by the sensors which are relevant to the user actions will be transmitted via radio by the on board computer (client) to the server. The connection between computers and radios uses TCP/IP communication, making it possible to use standard Ethernet connection for long distance operation, and all data will be stored in the on board computer for posterior analysis. The tests could be performed in lakes, with proper depth and within an area that allows the execution of trajectories without danger of collision.

The sensors used for data acquisition during the first set of tests presented here were an inertial sensor – Crossbow's NAV420 combined GPS Navigation and GPS_Aided AHRS (Attitude and Heading Reference System), and an anemometer. The sensor data was collected in real time by a computer running a MatLab/Simulink Real-Time application developed for this purpose.

DESCRIPTION OF THE EQUIPMENT

The construction of the model hull was made by using balsa wood coated with a 3 mm thick layer of polyester resin. Inside the model, polyester resin was applied and strengthened with fibre glass.

During each manoeuvre the model's heading and advance speed is controlled through the rudder position and propeller rotations, respectively. The propeller shaft is driven by a brushed DC motor mounted on the stern compartment and is excited by a Pulse Width Modulated (PWM) signal. This motor is connected to a transmission gear and the motion is imposed on the propeller shaft through a universal joint. The whole propulsion system consists of the motor, a cardan joint, two shaft adaptors, a shaft, a propeller and specific hardware for its control. Regarding the vehicle's manoeuvring system, this is constituted by a rudder, a shaft, an electric stepper motor and hardware for its control. Figure 2 illustrates the model's manoeuvring actuator system.

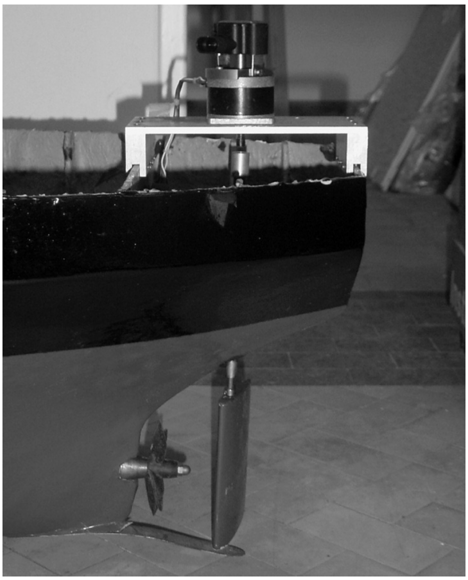

Figure 2: Manoeuvring actuator system of the "Esso Osaka" model.

The system allows the control of the ship model through the components and the respective information flow is represented in Figure 3. The control system architecture and hardware configuration can be seen in this illustration.

To better understand the whole system, each element will be explained separately but always keeping in focus the interactions between each other, namely:

Computer (on shore)

More relevant when the system is used in manual (or remote) mode, that is, the mode in which the command orders are given by the user, making it possible to guide the model through

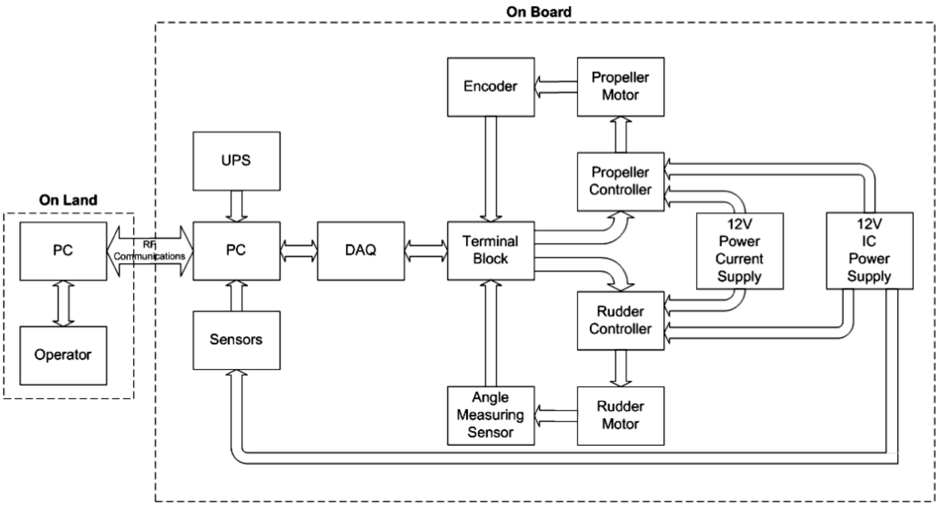

Figure 3: Control system of the "Esso Osaka" tanker model

advance speed and rudder angle orders, according to the intended objectives and paying attention to the sensor information provided on the monitor.

In the automatic guidance mode, the control is performed based on predefined parameters and by two distinct options: either by insertion of the waypoints to follow in a table or, optionally, files with pre-programmed missions (manoeuvres) can be made and uploaded later. In the same way, the files can contain either the waypoints of the trajectory to follow or, alternatively, the rudder and speed command to execute during the manoeuvre. In order to guide the model from land and in any of the working modes a bidirectional communication is established via radio, between the server computer (on shore) and the client (on board).

Computer (on board)

This behaves as a bridge for the computer on shore and supervisor to the low level controllers on board the model. It receives the orders from the computer on shore, processes them, and through the Data Acquisition card (DAQ) and the rest of the hardware, controls the model, also sending, to the computer on shore, relevant information collected by the onboard sensors. It is convenient to notice that this information is recorded on the hard disk of the on board computer.

DAQ

The DAQ card (National Instruments DAQCARD 6024E) is connected to the on board computer and to a terminal block, it performs the A/D and D/A conversion. The desired values (in voltage) for the rudder angle and for the propeller rotations are given through this card. The DAQ has, as input, the signal from the sensors. Its internal clock is used to calculate the propeller rotation speed. This signal comes directly from the encoder optical sensor.

NI Terminal Block

The DAQ card is connected to the microcontrollers responsible for the control of the rudder and propulsion motors through a 68-pin National Instruments digital and trigger I/O terminal block. This accessory allows an easy connection of field I/O signals to the counter/timer devices.

Rudder motor controller

The command signal for the rudder angle, provided by the computer, and the signal of the angle measuring sensor (potentiometer) are compared by the computer on board software in order to control the rudder positioning through the PIC16F877 microcontroller which receives the command order. From this comparison results an error. When either this error is null or it lies within a certain tolerance interval (one step) the rudder motor has reached the desired position. The above mentioned potentiometer is solidary with the rudder stepper motor shaft. Amongst several components, the rudder controller printed circuit board (PCB) has the microcontroller and a stepper driver placed in it.

Propulsion motor controller

The main objective of the PIC18F4620-I/P microcontroller is to control the rotational speed of the propulsion motor by using a PWM signal. This kind of signal and control has the advantage of generating a higher momentum than other solutions. Until the error from the software comparison between the computer command signal for the propeller speed and the encoder signal is null the microcontroller manages to control the propulsion motor in order to achieve the desired rotational speed. Through the terminal block-DAQ the commuter will receive an encoder input signal. This way the DAQ is able to count the impulses by unit time for rps calculation purposes. Amongst several components, the propeller controller PCB has the microcontroller and a MOSFET (Metal Oxide Semiconductor Field Effect Transistor) H-bridge placed on it, allowing two rotational directions.

These boards fully developed for the control system, have other main features, as follows:

- Automatic and manual switching control mode (one pushbutton) and two pushbuttons for manual control;
- Power switch button;
- By default, and as a safety measure, the motors are left in manual control mode;
- Basic hardware debugging possibility (LCD display interface) by the user;
- Motor and IC power LEDs.

Encoder

The encoder coupled to the propulsion motor shaft is constituted by an aluminium disk with 120 teeth and an opto switch (with infrared wavelength). The disk rotation provides a square wave as output of the optical sensor, allowing the counting of the pulses by the DAQ hardware and the rps calculation.

UPS

The Uninterruptible Power Supply (UPS) supplies the on board computer by converting 24V DC into a 220/230V AC modified sine wave.

12 V power supplies

There are two 12V power supplies, one for the motors power supply and the other for the two control boards.

Sensors

The following digital sensors will be used on board the model:

- Crossbow's NAV420 combined GPS Navigation and GPS_Aided AHRS (Attitude and Heading Reference System), which allows one to obtain:

— the vehicle's position coordinates (latitude, longitude, altitude);
— the heading, roll and pitch angles;
— the surge and sway velocities;
— the yaw rate;
— the surge and sway accelerations;

- Anemometer – velocity and direction of the wind.

The sensors listed above are the ones that comprise the navigation system which allows the model of the "Esso Osaka" tanker ship to perform trajectories in an autonomous way. Several successful tests to the equipment were performed on land before going to execute the initial set of experiments in the lake.

SOFTWARE

The existing software, developed both in LabView and MatLab, allows sending the control signals to the microcontrollers, through the NI-DAQ card, needed to control the motion of the rudder and propulsion motors. The architecture is designed to operate using a computer on shore (server) and another on board (client), connected to each other through a wireless network interface. An Extended Kalman Filter (EKF) and a Second Order Filter (SOF) are incorporated in the navigation process which will provide filtered estimates of positions, heading, sway and yaw velocities and advance speed of the vehicle through the data obtained by the sensors. The information acquired and computed on the onboard computer will be transmitted to the server computer on shore through radio modems with Ethernet interface.

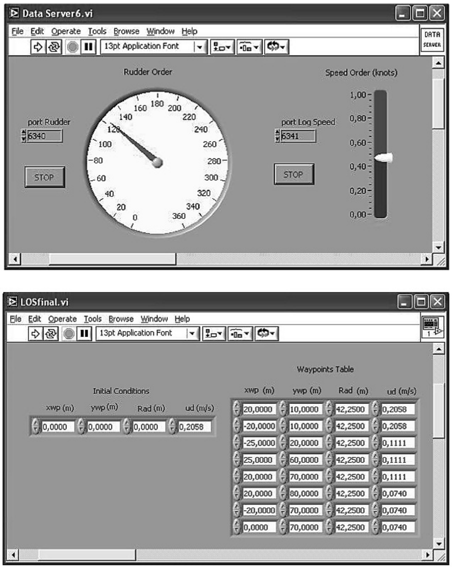

Figure 4: User interface screens for manual command and definition of the trajectory waypoints to be travelled.

As previously mentioned, the behaviour of the vehicle can be determined by the user either through an interface for manual command or through the insertion of the waypoints to be travelled. Optionally, files with preprogrammed missions (manoeuvres) can be uploaded. These files can equally contain either the waypoints of the trajectory to be travelled or, alternatively the rudder and speed commands to be executed during the manoeuvre. Figure 4 illustrates an interface screen of the manual command and a screen with waypoints pre-definition in LabView.

Summarizing, in LabView, the modules with the description of the developed Virtual Instrument files (VIs) which are implemented in the system are the following:

Communications and Manual Command Module

Its function comprises the verification, synchronization and management of the communications between the server computer (on shore) and the client (on board). It is responsible for the transmission of the command orders and monitoring of the outputs acquired by the sensors. The correct establishment of the remote communications is performed through the TCP/IP protocol.

This module contains the software that allows the direct command of the model through the rudder and vehicle's speed orders provided, by the user, through an interface specifically designed for that purpose. The orders given through this model have priority relatively to the ones of the automatic command module. It is also in this model that the VIs allowing acquisition of NMEA codes from the sensors were developed.

Estimation Parameters Module

This module allows the estimation of the values of the parameters either in case of failure in the acquisition of the information provided by the sensors or failure of the sensors themselves.

For this, a VI with an EKF and a SOF was developed in order to estimate positions values (x and y), advance speed (U), sway velocity (v) and yaw rate (r) and heading angle (Ψ) of the model based on the records of these parameters.

Guidance and Manoeuvring Module

This module is responsible by the automatic guidance of the vehicle, either by passing through predefined waypoints or through the execution of manoeuvres following certain pre-programmed rudder and speed orders. The automatic guidance mode comprises two distinct algorithms: a LOS algorithm for the definition of the pre-established trajectory by waypoints, to be followed by the model, and an algorithm of the quadrant correction where the heading angle lies, which is directly related to the previous algorithm.

Control Module

This module contains the code whose function is the direct control of the propeller and rudder, accordingly with the commands received from the server, from the guidance algorithm or from the pre-defined manoeuvres. This module runs on the client computer, on board the model. On it are included the VIs which are responsible by the speed control, heading control, as well as the respective reference models. This module also has a VI that uses the data acquisition (DAQ) card clock to count the number impulses from the encoder, in order to compute the rps of the propulsion motor, and the VI that performs the respective control of the rps.

Recording and Monitoring Module

This module is responsible for the recording of the parameters of interest in text-files and for their monitoring on the server computer screen. It allows the selection of the sampling time in each test. Figure 5 illustrates a scheme of the architecture and system information flow.

Due to the fact that the developed LabView code is interpreted and provided very slow communication timing rates, which were not realistic for the system, and it was not possible to compile that code it was decided to change to a MatLab platform. The LabView code is still valuable when TCP/IP communication is not used as it is the case, for instance, when the tests with the model are performed with one person on board.

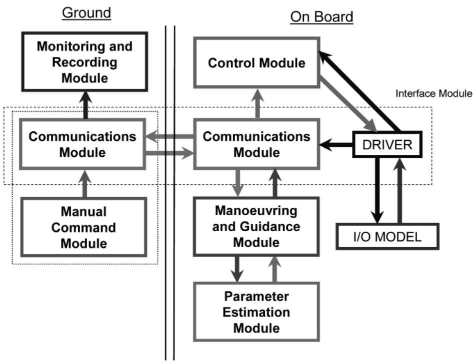

Figure 5: Schematic representation of the architecture and system information flow.

Within MatLab, the Real-Time Windows Target is used, which enables Simulink models to run in real time on desktop or laptop computers for rapid prototyping or hardware-in-the-loop simulation of control system and signal processing algorithms. In this way, a real-time executable with the whole system entirely through Simulink was created and controlled. With the Real-Time Workshop, C code is generated and compiled, and then the real-time execution is started on the Windows-based computer, while interfacing with real hardware using computer I/O boards.

The Real-Time Workshop provides code to implement bidirectional communication based on TCP/IP. Figure 6 shows the structure of the TCP/IP-based implementation. In external mode, Real-Time Workshop establishes a communication link between the model running in Simulink and the code executing on a target system.

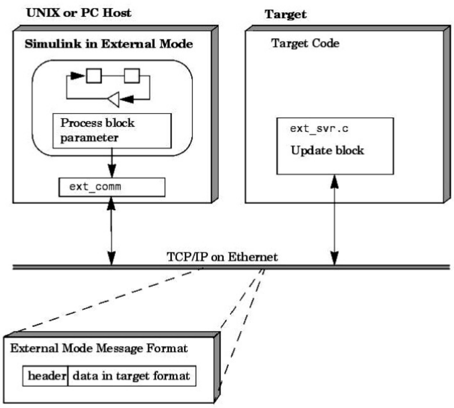

Figure 6: TCP/IP-Based Client/Server implementation for external mode.

The external mode allows the two separate systems – the host and the target – to communicate. The host is the computer where MATLAB and Simulink are executing. The target is the computer where the executable created by Real-Time Workshop runs. The host (Simulink) transmits messages requesting the target to accept parameter changes or to upload signal data. The target responds by executing the request. External mode communication is based on a client/server architecture, in which Simulink is the client and the target is the server. External mode allows modifying, or tuning, the block parameters in real time. In external mode, whenever the parameters are changed in the block diagram, Simulink automatically downloads them to the executing target program. This allows tuning of the parameters of the program without recompiling. In external mode, the Simulink model becomes a graphical front end to the target program.

It is possible to view and log block outputs in many types of blocks and subsystems. Signal data from the executing target program can be monitored and/or stored, without writing special interface code. Also, the conditions under which data is uploaded from target to host can be defined. For example, data uploading could be triggered by a selected signal zero upcrossing. Alternatively, data uploading can be triggered manually. External mode works by establishing a communication channel between Simulink and the code generated by Real-Time Workshop. This channel is implemented by a low-level transport layer that handles physical transmission of messages. Both Simulink and the generated model code are independent of this layer. The transport layer and the code directly interfacing with the transport layer are isolated in separate modules that format, transmit, receive messages and data packages. The Real-Time Windows Target implements external mode communication via shared memory.

DESCRIPTION OF THE MANOEUVRING TESTS

A photo of the model used in the experiments is shown in Figure 7. The main particulars of the tanker model "Esso Osaka" are presented in Table 1. The propulsion system of the real tanker consists of a single shaft arrangement with fix pitch propeller, driven through a reduction gear, by a diesel engine. In the model the diesel engine is substituted by an electric motor. The rudder of the model was built based on a NACA 0015 airfoil.

Figure 7: Photo of "Esso Osaka" model during the manoeuvring tests.

"Esso Osaka" Model	
Length overall	3.430 m
Length between perpendiculars	3.250 m
Breadth	0.530 m
Depth	0.283 m
Draft (estimated at trials)	0.063 m
Block coefficient	0.831
Number of rudders	1
Displacement (estimated at trials)	90.18 kg
Rudder Area	0.0120 m^2
Propeller Area	0.0065 m^2
Longitudinal CG (fw of midship)	0.103 m

Table 1: Esso Osaka model particulars.

The first set of manoeuvring tests with the "Esso Osaka" model was carried out during one day on the "Estufa Fria" lake, in the centre of Lisbon. The weather conditions were good. The absolute wind speed was varying between 0 and 4 knots (wind force between 0 and 2 in the Beaufort scale).

The manoeuvres performed in manual mode were the turning circles and several trajectories were performed in automatic mode.

Altogether 9 test runs were executed with "Esso Osaka" model. As a result, 3 turning circles (1 was aborted), and 5 automatic trajectories were considered suitable data for analysis.

#	Parameter	Unit	Measuring tool	Range	Estimated uncertainty
1	Geographical Coordinates	m	Inertial Sensor	—	± 3
2	Surge and sway velocities	m/s	Inertial Sensor	—	< 0.4
3	Roll and pitch angles	degs	Inertial Sensor	± 180, ± 90	< 0.75
4	Heading angle	deg	Inertial Sensor	± 180	< 3
5	Yaw rate	deg/s	Inertial Sensor	± 200	< ± 0.1
6	Rel. Wind speed	knots	Anemometer	0 –60	± 2
7	Rel. Wind Direction	deg	Anemometer	± 180	± 5

Table 2: Measured parameters.

Measurement and registration of the kinematical parameters listed in Table 2 were envisaged and all parameters indicated in the table were measured during the tests. The uncertainty estimates are approximate and were obtained from the instruments documentation.

The inertial sensor unit generated instantaneous ship coordinates, latitude φ and longitude λ. These were transformed to the standard Cartesian Earth coordinates of the ship's origin, x_{eC} and y_{eC} (Figure 8), coinciding with the location of the sensor antenna, placed in the ship centre plane, near the midship plane by:

$$\begin{aligned} x_{eC} &= x_{eC0} + \kappa(\varphi - \varphi_0), \\ y_{eC} &= y_{eC0} + \kappa(\lambda - \lambda_0)\cos\varphi_0, \end{aligned} \tag{1}$$

where the subscript '0' denotes the initial values of the corresponding variables and κ is the conversion coefficient equal to 1852m/arc.min. After this initial transformation the coordinate x_e is supposed to be measured along the true meridian while y_e is along the parallel. However, when analyzing the trajectories the coordinates were transformed further so that the origin of the Earth axes matches the ship's position at the start of a manoeuvre and the X_e-axis is directed along the approach path.

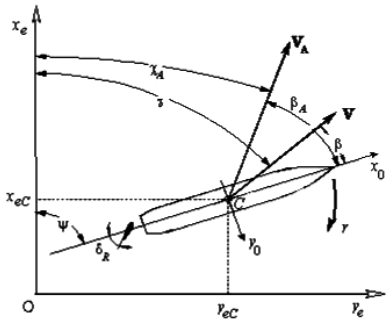

Figure 8: Definition of kinematical parameters (all shown quantities are positive)

The recording and simulation sampling time was equal to 0.1 second for all the instruments that comprise the system.

The relative wind speed $V_A=|\mathbf{V_A}|$ and the wind drift angle β_A (relative wind speed) were measured directly with an anemometer.

The MatLab/Simulink software stores the collected data in the ".mat" format (in workspace) and it is transformed to in ".txt" format (text) with the post processing software.

ANALYSIS OF TESTS RESULTS

In this section the results of the are presented. In manual mode three time histories of turning circles are presented. In automatic mode the plots of time histories of the five trajectories performed are shown.

Manual Mode

Figure 9 presents the time histories for a turning manoeuvre of the model with an average speed of 0.7 knots and rudder angle of 30 degrees. Also presented is the speed estimated time history computed using the EKF.

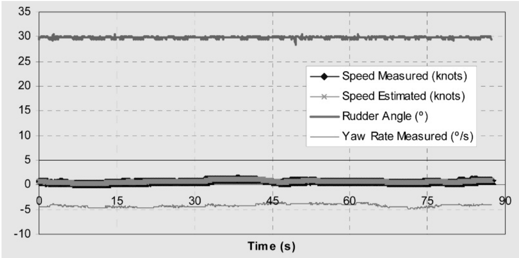

Figure 9: Turning 30º (≈ 85% Full), average speed 0.7 kn.

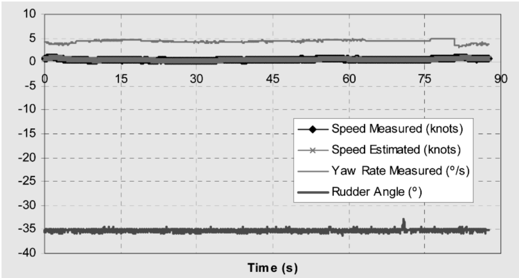

Figure 10: Turning 35º (Full), average speed 0.54 kn.

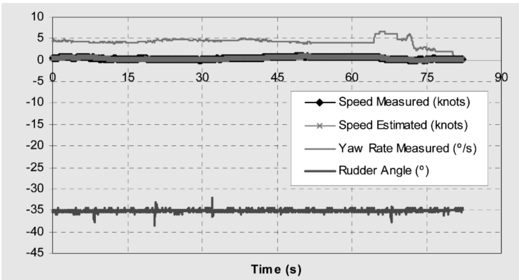

Figure 11: Turning 35º (Full), average speed 0.42 kn.

Figure 10 presents the time histories for other turning manoeuvre of the model with an average speed of 0.54 knots and rudder angle of -35 degrees.

Figure 11 presents the time histories for the last turning manoeuvre of the model with an average speed of 0.42 knots and rudder angle of -35 degrees.

Notice that in Figures 9-11 the speed measured (dark) and speed estimated (light) are approximately superimposed. From these figures the good performance of the heading and speed controllers can be verified. The results confirmed the system performance characteristics previously acquired from simulations.

Automatic Mode

The first, second, third, fourth and fifth desired paths will consist of a total of 7, 7, 5, 8 and 7 way-points, respectively, as given in Table 3:

1st and 2nd trajectories:	3rd trajectory:	4th trajectory:	5th trajectory:
Wpt_1 = (0, 0) m	Wpt_1 = (0, 0) m	Wpt_1 = (0, 0) m	Wpt_1 = (0, 0) m
Wpt_2 = (0, 5) m	Wpt_2 = (5, 0) m	Wpt_2 = (-1.5, 1.5) m	Wpt_2 = (-1.5, 0) m
Wpt_3 = (-2.5, 12.5) m	Wpt_3 = (6, 2.5) m	Wpt_3 = (-3, 3) m	Wpt_3 = (-3, 0) m
Wpt_4 = (-5, 17.5) m	Wpt_4 = (7.5, 5) m	Wpt_4 = (-4, 4) m	Wpt_4 = (-4, 0) m
Wpt_5 = (-10, 20) m	Wpt_5 = (12.5, 10) m	Wpt_5 = (-5, 5) m	Wpt_5 = (-5, 0) m
Wpt_6 = (-20, 17.5) m		Wpt_6 = (-6, 6) m	Wpt_6 = (-6, 0) m
Wpt_7 = (-20, 5) m		Wpt_7 = (-8, 8) m	Wpt_7 = (-8, 0) m
		Wpt_8 = (-10, 10) m	

Table 3: Way-points of the desired paths.

The ship's initial states for the trajectories are:

$(x_0, y_0, \Psi_0) = (0\text{ m}, 0\text{ m}, 0\text{ rad})$ for the 1st, 2nd and 4th trajectories;
$(x_0, y_0, \Psi_0) = (0\text{ m}, 0\text{ m}, 2\text{ rad})$ for the 3rd trajectory;
$(x_0, y_0, \Psi_0) = (0\text{ m}, 0\text{ m}, -3\text{ rad})$ for the 5th trajectory;
$(u_0, v_0, r_0) = (0.23\text{ m/s}, 0\text{ m/s}, 0\text{ rad/s})$ for all the trajectories.

The desired speed is kept constant along the fifth trajectory with a value of 0.21 m/s, that corresponds to a Froude number F_n equal to 0.0372. From the first up to the fourth paths the desired speed will be considered as follows:

$$r^b = \begin{cases} 0.05\text{ m/s} \;\; (F_n = 0.0089) & if \quad t_1 < t < t_3 \\ 0.38\text{ m/s} \;\; (F_n = 0.0673) & if \quad t_3 \le t < t_5 \\ 0.12\text{ m/s} \;\; (F_n = 0.0213) & if \quad t_5 \le t < t_6 \\ 0.23\text{ m/s} \;\; (F_n = 0.0407) & if \quad t_6 \le t \le t_7 \end{cases} \quad \text{for the } 1^{st} \text{ trajectory ;}$$

$$r^b = \begin{cases} 0.13\text{ m/s} \;\; (F_n = 0.0230) & if \quad t_1 < t \le t_4 \\ 0.46\text{ m/s} \;\; (F_n = 0.0815) & if \quad t_4 < t \le t_6 \\ 0.16\text{ m/s} \;\; (F_n = 0.0283) & if \quad t_6 < t \le t_7 \end{cases} \quad \text{for the } 2^{nd} \text{ trajectory ;}$$

$$r^b = \begin{cases} 0.53\text{ m/s} \;\; (F_n = 0.0939) & if \quad t_1 < t \le t_2 \\ 0.15\text{ m/s} \;\; (F_n = 0.0266) & if \quad t_2 < t \le t_4 \\ 0.01\text{ m/s} \;\; (F_n = 0.0018) & if \quad t_4 < t \le t_5 \end{cases} \quad \text{for the } 3^{rd} \text{ trajectory ;}$$

and

$$r^b = \begin{cases} 0.13\text{ m/s} \;\; (F_n = 0.0230) & if \quad t_1 < t \le t_2 \\ 0.16\text{ m/s} \;\; (F_n = 0.0283) & if \quad t_2 < t \le t_5 \\ 0.18\text{ m/s} \;\; (F_n = 0.0319) & if \quad t_5 < t \le t_8 \end{cases} \quad \text{for the } 4^{th} \text{ trajectory .}$$

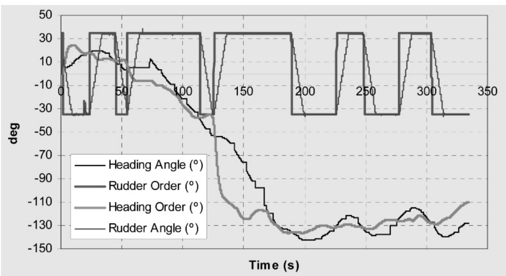

Figure 12: Time histories trajectory 1.

For all trajectories the radius of acceptance for all way-points was set to two ship lengths ($R_0 = 2L_{pp}$).

Figures 12 up to 16 show the time histories of heading and rudder angles and respective command orders.

Figures 12-16 show the good performance of the LOS algorithm

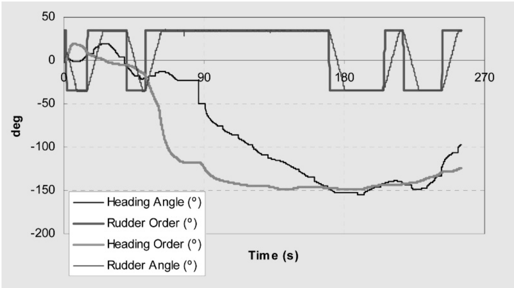

Figure 13: Time histories trajectory 2

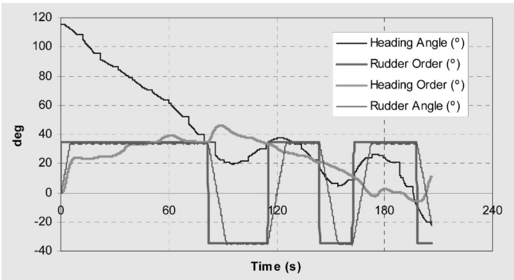

Figure 14: Time histories trajectory 3.

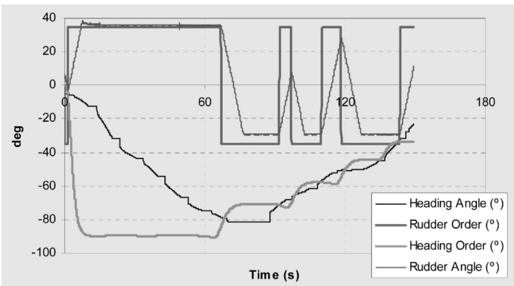

Figure 15: Time histories trajectory 4.

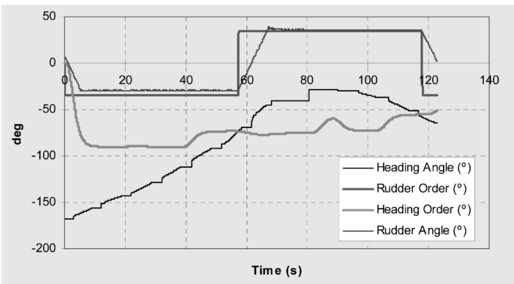

Figure 16: Time histories trajectory 5.

and the heading and speed controllers. With the results of these experiments in automatic mode in addition to the ones performed in manual mode one can say that the first set of the "Esso Osaka" tanker model manoeuvring tests were performed successfully and have shown the validity of the control, guidance and navigation systems.

FINAL REMARKS AND CONCLUSIONS

The control, navigation and guidance system of the "Esso Osaka" tanker model was described which allows it to perform trajectories in an autonomous way. An architecture was described that allows the vehicle to receive commands from a computer on shore to the one on board, using TCP/IP network communication. The vehicle is able to control its heading and advance speed, both through manual commands or through pre-programmed missions.

After the manoeuvring tests performed in calm waters, some conclusions may be drawn:

The results confirmed the system performance characteristics previously acquired from simulations. The guidance, control and observer systems have shown to work satisfactorily except the loss of accuracy in the measurements at low speeds and the presence of environmental disturbances.The first set of the "manoeuvring tests were performed successfully and have shown the validity of the control, guidance and navigation. In future tests the data obtained can safely be used for the identification, simulation and validation of the model manoeuvring mathematical model.

ACKNOWLEDGEMENTS

The experiments with the "Esso Osaka" model were not possible without the collaboration of Mrs. Alexandra Canha, from the Lisbon City Council, who allowed the realization of the manoeuvring tests in the "Estufa Fria" lake. We are especially grateful to her and the rest of the staff for all the support and availability given to our team in the preparation and execution of the tests. Also, thanks to Ricardo Pascoal, Fernando Santos, António Paço, João Pessoa and Filipe Pedroso for the help given during the experiments. The first author has been financed by the Portuguese Foundation for Science and Technology (Fundação para a Ciência e Tecnologia) under contract number SFRH/BPD/48088/2008.

REFERENCES

Brix J. (1993). *Manoeuvring Technical Manual*. Seehafen Verlag, Eds.

Guedes Soares, C; Francisco, R. A.; Moreira, L. and Laranjinha, M. (2004). Full-Scale Measurements of the Manoeuvering Capabilities of Fast Patrol Vessels, Argos Class. *Marine Technology*, 41(1), 7-16.

Guedes Soares, C.; Sutulo, S.; Francisco, R.; Santos, F. and Moreira, L. (1999). Full Scale Measurements of the Manoeuvring Capabilities of a Catamaran. *Proceedings of the RINA International Conference on Hydrodynamics of High-Speed Craft*, London, UK.

IMO (2002). *Explanatory Notes to the Standards for Ship Manoeuvrability*. IMO Circular MSC/Circ. 1053.

IMO (1994). *Explanatory Notes to the Interim Standards for Ship Manoeuvrability*. IMO Circular MSC/Circ. 644.

IMO (1993). *Interim Standards for Ship Manoeuvrability*. IMO Resolution A.751 (18) adopted on 4 November 1993.

Luo, W. and Zhang, P. (2007). Evaluating the Maneuverability of a New Type of Self-propelled Barge. *Journal of Marine Science and Application*, 6(4), 44-47.

Moreira, L. (2008). *Guidance, Control and Navigation of Autonomous Vehicles in Coastal and Inland Waters*. PhD. Dissertation, Instituto Superior Tecnico, Technical University of Lisbon, Portugal.

Moreira, L.; Santos, F.; Mocanu, A.; Liberato, M.; Pascoal, R. and Guedes Soares, C. (2008). Instrumentation used on Guidance, Control and Navigation of a Ship Model. *Proceedings of the 8th Portuguese Conference on Automatic Control (CONTROLO 2008)*, Vila Real, Portugal.

Moreira, L.; Fossen, T. I. and Guedes Soares, C. (2007). Path Following Control System for a Tanker Ship Model. *Ocean Engineering*, 34(14-15), 2074-2085.

Philips, A. B.; Stephen, R. T. and Furlong, M. (2009). Evaluation of Manoeuvring Coefficients of a Self-propelled Ship using a Blade Element Momentum Propeller Model Coupled to a Reynolds Averaged Navier Stokes Flow Solver. *Ocean Engineering*, 36 (15-16), 1217-1225.

Shin, H.; Park, H. S.; Yang, C. S. and Lee, H. L. (2002). Motion Analysis by Free-Running Model Test. *Proceeding of the 12th International Offshore and Polar Engineering Conference*, Kitakyushu, Japan.

Sutulo, S. and Guedes Soares, C. (2004). Synthesis of Experimental Designs of Manouevring Captive-Model Tests with Large Number of Factors. *Journal of Marine Science and Technology*, 9 (1), 32-42.

Sutulo, S. and Guedes Soares, C. (2006). Development of a Multifactor Regression Model of Ship Maneuvering Forces Based on Optimized Captive-Model Tests. *Journal of Ship Research*, 50 (4), 311-333.

Sutulo, S.; Moreira, L. and Guedes Soares. C. (2002). Mathematical Models for Ship Path Prediction in Manoeuvring Simulation Systems. *Ocean Engineering*, 29 (1), 1-19.