An Automatic Track Control for an Autonomous Model for Towing Tank Tests

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ABSTRACT: In this paper, the development of an autopilot integrated within a system for carrying out seakeeping and resistance tests in towing tanks without the need of a towing carriage, is described. This autopilot is based on the use of the data obtained from an Inertial Measurement Unit (IMU) and a set of sonars installed onboard, which are part of the whole system and that characterize the heading and the distance to the tank walls. In order to show the performance of the system, results obtained from a towing test campaign, where the development of parametric roll resonance was analyzed, are also presented.

1 INTRODUCTION

Scale model tests are very common for analyzing resistance, maneuvering and seakeeping characteristics of ships. Maneuvering and seakeeping tests are usually carried out in the so called ocean basins, where the model freely sails radio controlled from inshore, while resistance tests are done in towing tanks, where the model is restrained and moved by a towing carriage. However, there are some seakeeping tests, such as parametric roll resonance ones, which could be done in those towing tanks, as they mainly occur in head waves. In this cases, the coupling between the model and the carriage could limit the possibility of studying the whole phenomenon, as some degrees of freedom are restrained and very large motions could appear.

With the objective of avoiding the use of the towing carriage in these type of seakeeping towing tank tests, a system to be installed on board of self-propelled scale ship models has been developed. At first the system was planned aiming to carry out just parametric roll tests (Míguez González et al., 2012, López Peña et al., 2013b) and later on its applicability has been broadened. The main characteristic of this system is that it can perform seakeeping and resistance tests without having any material link between the ship model and the towing device. When this system is installed, the model gets fully instrumented and capable of measuring the propulsive force as well as acquiring all the significant raw data needed for a specific test, process it onboard, and communicate with an inshore station. The system is modular and is conceived such to be easily mounted and removed, so minimizing the work needed to be repeatedly used on different ship models

The system includes an Inertial Measurement Unit (IMU) with 3-axis accelerometers and gyroscopes, and a 3-axis magnetometer. This IMU is the core of an autopilot that is in charge of controlling the speed and course as well as maintaining the ship model well centered in the tank. A description of the whole system has been presented elsewhere (López Peña et al., 2013a) and the general arrangement of its first implementation can be seen in Figure 1.

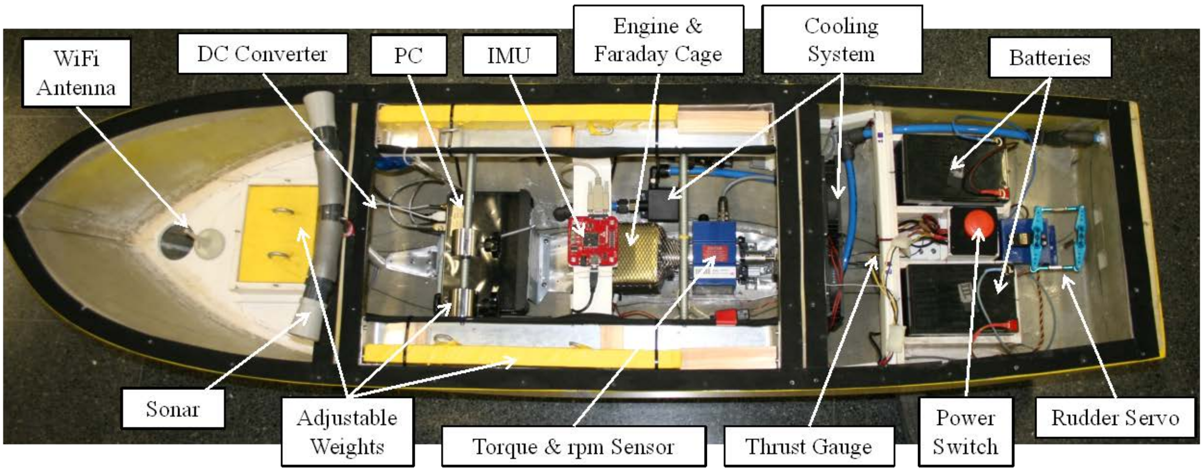

Figure 1. Ship scale model general arrangement.

For its initial implementation an additional instrument module aiming to measure the propulsive torque, and rotational speed has been included, thus allowing also to perform propeller tests. This additional implementation serves as a practical example on how the modularity of the proposed system allows it to extend its capabilities by adding new modules aiming to specific tasks.

One of the most distinctive characteristics of the proposed system is the autopilot. This autopilot should perform two main tasks; the first one is to maintain a constant vessel speed at the value specified for a given test. This task is quite easy to accomplish when testing in calm waters, but it has some difficulties when performing tests on waves.

The speed measurement system determines the velocity by differentiating the data coming from an onshore Laser Range Finder (LRF) placed at one end of the tank and pointing to the ship model moving along the tank centerline. The LRF transmits the measured distance data via a radio modem to the onboard computer where its time derivative is performed to get the ship velocity. The final velocity value used by the controller is obtained as an output of a complementary filter that makes use of the differentiated LRF signal as well as of the acceleration signal coming from the IMU.

The second task of the autopilot consists in maintaining the model course straight while keeping it centered in the tank. The present work is focused on this second autopilot task, which is its most significant and complex feature, as it is going to be highlighted in the following sections.

2 HEADING AND POSITIONING SYSTEM TOPOLOGY

The proposed system has two side sonars that are intended to measure the distance to the towing tank walls. Their signals are used by the autopilot's heading and positioning control unit for keeping the model well centered and directed along the towing tank. In a first attempt, sonar data was used to keep the model centered in the tank while data coming from the magnetometers in the IMU were used to keep the course.

However, the magnetometers signals result to be affected in a great deal by the magnetic disturbances produced by the towing side rails (soft iron distortions) as well as by the electromagnetic fields originated by some electrical power lines crossing beneath the tank (hard iron distortions).

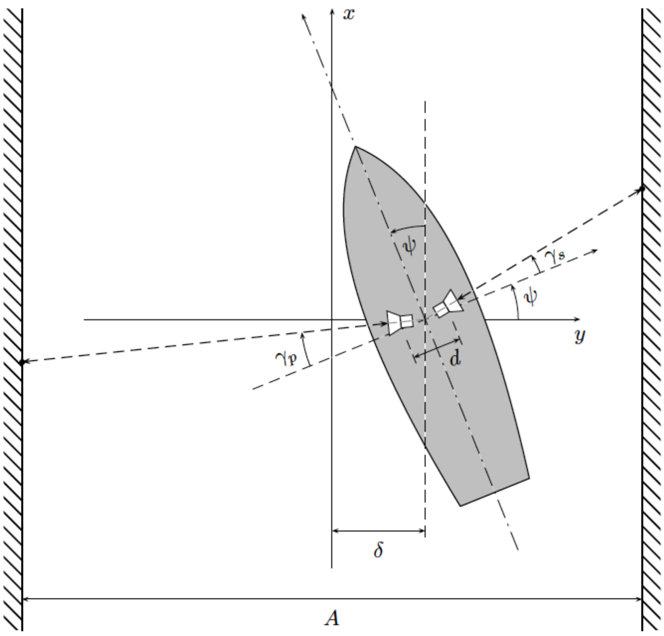

Figure 2. Course and position of the ship model along the tank.

The calibration of such distortions, though possible (Guo et al., 2008), is hard to accomplish and depends on several factors such as the three-dimensional position of the vessel or the uncontrollable current in the power lines, thus rendering the magnetometer roughly useless for the intended purpose. For this reason, a heading control system based solely on data coming from the sonars has been implemented.

In order to have sonar sensitivity to course variations, and not just to the side displacements from the tank centerline, the sonars have been pointed with an angle γ towards the sides of the tank (Figure 2). In this way, any course change with respect to the tank orientation (ψ) will produce a change in the sonar readings even if the model did not move apart from the middle of the tank yet.

With this configuration, some simple geometrical considerations lead to the following relationship between the sonar readings, the course angle (ψ) and the deviation from the tank centerline (δ):

$$d_p \cos\psi \cos\gamma_p + d_p \sin\psi \sin\gamma_p = \Lambda/2 + \delta \qquad (1)$$

$$d_s \cos\psi \cos\gamma_s - d_s \sin\psi \sin\gamma_s = \Lambda/2 - \delta \qquad (2)$$

Solving this equation system for the course angle (ψ) and the deviation from the tank centerline (δ):

$$\psi = \sin^{-1}\left(\frac{[illegible]}{[illegible]} \right) - \tan^{-1}\left(\frac{d_p \cos\gamma_p + d_s \cos\gamma_s}{[illegible]} \right) \qquad (3)$$

$$\delta = \frac{[illegible]}{[illegible]} \cdot \sin\left(\psi + \tan^{-1}\left(\frac{d_p \cos\gamma_p - d_s \cos\gamma_s}{[illegible]} \right) \right) \qquad (4)$$

This equations show that ψ and δ can be obtained from the measurements of both sonars. In these relations we don't consider the increase in sonar measurements (d_p and d_s) due to the roll angle of the vessel. Even so, these equations can be further simplified if we assume that γ_p and γ_s are small, thus:

$$\cos(\gamma_p + \gamma_s) \sim 1 \qquad (5)$$

$$\tan^{-1}\left(\frac{[illegible]}{[illegible]} \right) \sim \pm \frac{[illegible]}{[illegible]} \qquad (6)$$

$$\tan^{-1}\left(\frac{[illegible]}{[illegible]} \right) \sim \mp \frac{[illegible]}{[illegible]} \qquad (7)$$

leading to:

$$\psi = \sin^{-1} \frac{[illegible]}{[illegible]} \mp \frac{[illegible]}{[illegible]} \qquad (8)$$

$$\delta = \frac{d_p - d_s}{[illegible]} \sin\left(\psi \mp \frac{[illegible]}{[illegible]} \right) \qquad (9)$$

3 TRACK CONTROLLER

The automatic track control of our system have some slight similarities with commercial ship track controllers (Sandler et al., 1996) as well as for some developments made for scale ship model (Lee et al., 2010). However, all these controllers made use of GPS, and this cannot be used in the present application as towing tank tests are commonly performed in places where GPS signals are not present. In addition, magnetometers result to be useless in the present application for the reasons exposed earlier. In general, and in the best knowledge of the authors, the track controller for the present application appears to be quite different from any other published ship or model ship track control.

In the present application a PID controller is used. This PID takes as inputs the estimations of course and distance to the tank centerline obtained as explained in the previous section.

In order to have a platform in which to test the heading controller of the ship scale model, a mathematical maneuvering model has been set up. Traditionally, ship maneuverability models take into account the three horizontal motions (surge, sway and yaw), disregarding any coupling effect between vertical motions (heave, roll and pitch) and the former ones.

These three equations of motion, following the notation in Yoshimura & Masumoto (2012), can be written in the following way:

$$(m + m_x)\dot{u}_G - (m + m_y) v_G r_G = X \qquad (10)$$

$$(m + m_y)\dot{v}_G - (m + m_x) u_G r_G = Y \qquad (11)$$

$$(I_{zz} + J_{zz})\dot{r} = N - x_G Y \qquad (12)$$

Where u_G, v_G and r_G are respectively ship surge, sway and yaw speeds with respect to its center of gravity, m and I_{zz} are the mass and yaw inertia of the ship, m_x, m_y and J_{zz} are the hydrodynamic added masses and inertias and x_G is the position of the center of gravity of the ship in the OX direction forward of amidships. Finally, X, Y and N are the hydrodynamic forces and moments acting on the ship, referred to the midship section. Each of these forces can be divided into those acting in the hull (H subscript), those due to the effect of the propeller (P subscript) and those due to the rudder (R subscript).

$$X = X_H + X_R + X_P \qquad (13)$$

$$Y = Y_H + Y_R + Y_P \qquad (14)$$

$$N = N_H + N_R + N_P \qquad (15)$$

The ones acting on the hull can be computed as a series of polynomials function of drift angle (β) and dimensionless turning rate (r'), which comprise a series of hydrodynamic derivatives and coefficients, that include nonlinear terms:

$$X_H + m_y v_G r_G = \left(\frac{\rho}{2} L d_{em} U^2\right)\left[X'_0 + X'_{\beta\beta}\beta^2 + (X'_{\beta r} - m'_y)\beta \ldots \qquad (16)$$

$$Y_H + m_x u_G r_G = \left(\frac{\rho}{2} L d_{em} U^2\right)\left[Y'_\beta \beta + (Y'_r - m'_x) r' + Y'_{\beta\beta\beta}\beta \ldots \qquad (17)$$

$$N_H = \left(\frac{\rho}{2} L^2 d_{em} U^2\right)\left[N'_\beta \beta + N'_r r' + N'_{\beta\beta\beta}\beta^3 + N'_{\beta\beta r}\beta^2 r' + \ldots \qquad (18)$$

Here, ρ is water density, d_{em} is mean draft, U is the resultant speed amidships and

$$m'_x, m'_y = m_x, m_y / \tfrac{\rho}{2} L^2 d_{em}$$

$$x'_G = x_G / L$$

The hydrodynamic derivatives contained in the described model, are usually obtained from captive model tests; in this work, the database presented in Yoshimura & Masumoto (2012) has been applied. The data from the “European Fishing Vessel”, which is the most similar to the ship used in this work, were selected.

Regarding propeller and rudder forces, also the approximation found in the reference above was taken, were the interaction between propeller and rudder is considered.

Propeller forces are obtained as a function of propeller diameter (D_p), revolutions (n), wake fraction (w), thrust deduction (t) and ship speed (u), so that:

$$X_P = (1-t)\rho\left([illegible] \right) D_P^4 n^2 \quad (19)$$

$$Y_P = N_P = 0 \quad (20)$$

Regarding rudder longitudinal and transversal forces and rudder moment, they are obtained as a function of rudder angle (θ), rudder location (x'_R) and rudder normal force (F'_N).

$$X_R = -(1-t_R)\left(\tfrac{\rho}{2} L d_{em} U^2\right) F'_N \sin\theta \quad (21)$$

$$Y_R = -(1+a_H)\left(\tfrac{\rho}{2} L d_{em} U^2\right) F'_N \cos\theta \quad (22)$$

$$N_R = -(x'_R + a_H x'_H)\left(\tfrac{\rho}{2} L^2 d_{em} U^2\right) F'_N \cos\theta \quad (23)$$

The coefficients t_R, a_H and x'_H, represent the interactions between hull, rudder and propeller. Finally, rudder normal force, depends on the rudder area, lift coefficient and the inflow speed and angle. All these parameters are also described in the aforementioned reference.

This model is considered as a high fidelity tool for determining ship maneuvering characteristics. In this work, it has been used as a substitute of maneuvering towing tank experiments, which were not available for this ship.

However, for the design of the autopilot, simpler models are usually applied. In fact, if yaw response to rudder is the effect that wants to be analyzed, and yaw motions are supposed to be small, nonlinear effects can be neglected and the uncoupled yaw motion equation could be written as that simpler model:

$$T\dot{r} + r = K\theta \quad (24)$$

which is the well known Nomoto model (Nomoto, 1960). There, coefficient T represents an inertia coefficient nondimensionalized by a damping term, in which both yaw and sway effects are considered, and K is the response constant that relates rudder excitation with rudder angle. Usually this model is considered as an adequate tool for the design of autopilots, where rudder angle, and so yaw motion, is supposed to be small. The model parameters could be easily obtained if maneuvering tests results in towing tanks are available; in our case, the results from the Yoshimura & Masumoto (2012) model has been applied for this purpose.

4 SIMULATIONS

A simulator based on the above-described mathematical model has been developed and implemented. This simulator has two main purposes; firstly, it is used as a bench work for setting up the parameters for the PID controller, and secondly, it is used for preliminary testing of the system prior to its implementation in real towing tank tests.

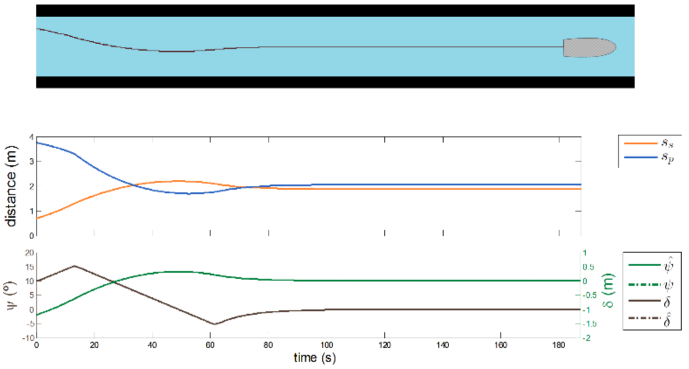

Figure 3. Ship motion simulator interface.

Figure 3 presents an example of the output of a simulation; at the top of the figure it is represented the trajectory of the ship as it is shown by the simulator. In the middle, the simulated sonar measurements are represented. Finally, at the bottom, both the estimated course angle and estimated distance to de middle of the tank are represented. As it can be seen, both the estimation of course angle ψ and distance to the centerline δ are correct. However, it should be said that in this simulation the γ_P and γ_S angles differ by 20 degrees.

If these angles would be taken equal of very close to each then important errors in the estimation of the course angle would appear. These discrepancies in the estimation of the course angle would appear in those cases as a consequence of the ambiguity of the solution of equation 8. An analysis of both this equation and the geometry presented in Figure 2, leads to the conclusion that the indetermination in obtaining ψ arises when the divisor in the $\tan^{-1}$ term of equation 3 equals zero. As the ship model course is always near the tank centerline, this will happen when the line determined by the points where the sonars spot on both sides of the tank is nearly perpendicular to the tank centerline. For that reason the angles γ_P and γ_S where set different in such a way that the variations of the course angle in typical maneuvers do not reach the uncertainty point.

For the estimation of the distance to the track, there are also two possible solutions, but they also disappear when these angles are different to each other. In any case, for the current geometrical configuration the unambiguity in determining δ is quite small when compared with that of ψ.

5 EXPERIMENTAL RESULTS

In order to check the whole system, some experimental tests have been carried out in the test basin of the School for Naval Architecture of the Technical University of Madrid on a medium sized stern trawler ship model (López Peña et al., 2013a). The selected hull forms are those corresponding to the MFV Trident, a British trawler that sank in October 1974. This vessel has also been subjected to extensive research by other authors, including towing tank testing as in Neves et al. (2003) and Young (2011).

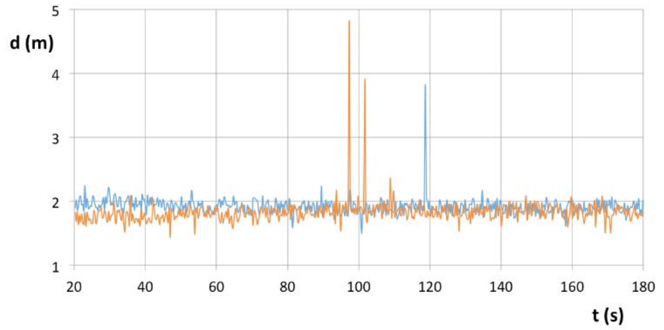

Figure 4. Raw sonar measurements.

Figure 4 presents the raw data of the distance measured by both sonars during a test that corresponds to a Froude Number of 0.15, wave height of 0.750 m and length wave of 31.7 m. In these conditions, the ship model had roll oscillations of up to 12 degrees. As can be seen in Figures 1 and 2, sonars are placed in the after part of the ship, pointing slightly forward of the perpendicular. Data from the sonars is send to the inboard PC, where they´re processed and stored, and where the autopilot is implemented.

As it can be seen in this figure, there are some spurious measurements that are induced by the ship roll oscillations that made the sonars point towards the tank rails or even to the distant sidewalls, thus they should not be taken into account. These outliers are removed by using a simple "3σ-rule", that appears to be enough for the present case. The results obtained after this filtering are presented in Figure 5 together with the resulting estimation of the model position measured from the tank centreline.

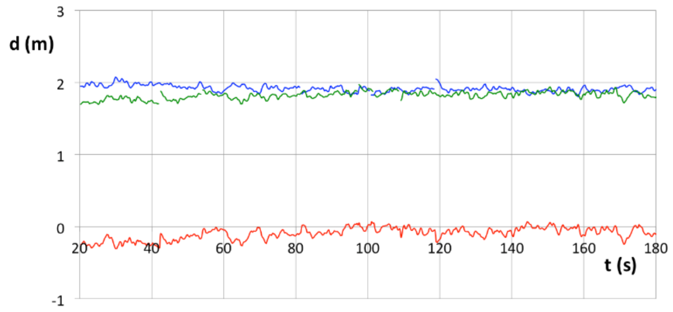

Figure 5. Processed sonar measurements (upper lines) and resulting distance to the track (bottom line).

For practical reasons, course deviations up to one fourth of the ship beam from the tank centerline have been allowed during the tests sessions. These deviations do not affect the tests results and simplify the control of the ship model. The allowed deviations are quite large compared with the accuracy in the position measurement. Thus this accuracy is not an issue in the current application.

Overall the tests results show that, in general, the system performs correctly except in situations where the ship model roll oscillations are larger than 15 degrees. In those cases the number of spurious sonar measurements increases and thus the performance diminishes. These large roll oscillations frequently appear when performing tests on parametric roll resonance or on some other tests aiming to analyze the dynamic behaviour of the ship, and where large motions are expected.

6 CONCLUSSIONS AND FUTURE WORK

The automatic track control presented here is a part of an autopilot for an autonomous ship model for towing tank testing. The input data for this track control are coming from two side sonars exclusively and it is based on a PID controller that is adjusted by using a simulator based on a simple mathematical maneuvering model of the ship. The simulation and experimental results have shown that the proposed system can perform well in most situations. However the experiments show that the sonar data can get a poor quality in cases of large roll oscillations, in addition the simulator shows that the two possible solutions for both the course angle and the distance to the track can introduce some errors.

To overtake these shortcomings, a new controller based on a Kalman filter is being developed. The Kalman filter will take data not only from the side sonars but from the IMU rate gyros as well. The data coming from the gyros would serve to fill the readings of the sonar data in those cases where they perform badly. In addition the filter will include a mathematical maneuvering model for the ship model that will take into account its dynamical behavior and would serve for the disambiguation.

7 ACKNOWLEDGEMENT

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