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Modeling, identification and control of a Boat Parking Assistance system

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Abstract— **In this paper, the problem of designing a Boat Parking Assistance (BPA) system for a small-scale vessel is addressed. A control-oriented model is derived from the physics underlying the system and gray-box identification is carried out by designing suitable experiments. A 3 DOF cascade control scheme is then implemented to achieve semi-automatic parking and station-keeping. The latter is also shown to be a solid groundwork for future research on fully automatic maneuvering. The proposed strategy is finally tested on stationkeeping and parking of a real vessel.**

I. INTRODUCTION AND MOTIVATION

In marine and oceanic engineering, the advantages of using automatic systems to maintain the position of a vessel by means of active actuators are well-known since the 1960s [2]. Throughout the years, several control strategies based on a large variety of technological solutions have been studied, see *e.g.* [4] and [3] for an overview of the topic. Some early works to control a vessel using a 3 degrees of freedom (DOF) model can be found *e.g.* in [9] and [6], whereas a more advanced strategy using time-varying control is illustrated, *e.g.* in [8].

In general, most of the strategies proposed in the literature are for large-scale vessels or marine platforms, for which the economical investment for the study of an automatic control system is worth. However, in the last decade, the use of electronic devices for control purposes in small-scale boats is spreading over, due to the availability of low-cost electronics. This means that also some *ad-hoc* problems of small-scale boats can be addressed and solved using automatic control. One of the most important problems is how to perform the parking maneuvers in the harbor.

In this paper, a Boat Parking Assistance (BPA) system for a small-scale boat is designed and its performance is experimentally assessed on a real vessel. To design the control system, a simplified control-oriented model is introduced starting from a complete mathematical description of the motion of the boat. The physical parameters of such a model are derived via gray-box identification and then used to tune the parameters of a nested-loop control architecture. The control algorithms are studied to achieve two main operating modes: the *semi-automatic mode* and the *stationkeeping mode*. In the first mode, the boat is manually guided to the parking spot, while the controller helps the user in keeping the heading and the position, by rejecting disturbances, *e.g.* the wind. In the *stationkeeping mode*, the controller maintains the position and the heading of the vessel in the harbor. In this work, it will be also shown how the latter mode can be used to implement a first prototype of a complete *automatic mode*.

A similar work for parking assistance can be found in [10], where the heading is controlled (with no rudder) using the propellers only. Specifically, a constant thrust is given depending on the distance between the boat and the harbor. It should be noted that in [10], no sway control is implemented, unlike in this paper. A stationkeeping strategy for a small-scale boat with experimental test can instead be found in [7]. In that case, the position reference is kept by compensating for the wind disturbance using the longitudinal actuators. No sway control is considered and the heading is not regulated.

As far as the authors are aware, this is the first work that provides a complete analysis of a small-scale boat dynamics with the aim of designing a BPA system, using physical modeling and gray-box identification. Moreover, in this work the control strategy is implemented on a real boat (and not on a physical model). Finally, for all the operating conditions, the sway and yaw motions are taken into account in the control design procedure.

The remainder of the paper is as follows. In Section II, the full scale vessel and its equipment used for the experimental tests are described in detail. Physical modeling and gray-box identification are carried out in Section III. In Section IV, the control layout is devised and every control block is described in detail. The results of the experimental tests are illustrated and commented in Section V. The paper is ended by some concluding remarks.

II. EXPERIMENTAL SETUP

The *Seacode Cabin 28* is the full scale vessel used for experimental sea tests and evaluation of control designed performance. It is a recreational boat with hull length 8.5 m, hull width 2.6 m and maximum displacement 3570 kg.

The experimental setup is equipped with two engines coupled with two outdrives placed in the rear of the hull. These actuators are controlled by a local ECU to generate the longitudinal thrust. Once the local ECU receives a suitable command, the gear is inserted to reach the maximum speed allowed in the harbor (*i.e.* 3 knots).

The boat is also equipped with two propellers, near the bow and at the stern, respectively. Both of them are located on the longitudinal axis of the hull and can generate a lateral

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force and a yaw moment. Notice that the propellers are under-dimensioned for the given boat, that is they cannot fully reject the environmental disturbances acting on the boat (*i.e.* wind and current forces). This fact will become visible in the experimental tests of Section V.

In detail, the boat is equipped with a weather station placed in the bow that includes a GPS, a wind sensor and a magnetometer compass. The wind sensor is used to measure the intensity and to estimate its direction, whereas the magnetometer compass provides the measurement of the yaw angle. Moreover an Inertial Measurement Unit is placed on flat surface close to the dashboard of the boat to provide a reference frame to the sensors. Finally, the vessel is equipped with six ultrasonic sensors to detect possible items in proximity of the hull during the mooring procedures.

The communication among all electronic devices is achieved by CANbus protocol. A programmable electronic unit (ECU) is devoted to the implementation of the control law. The user can determine the reference behaviour of the boat by using a joystick connected with the control unit.

III. Modeling and identification

This section presents a *control-oriented mathematical model* able to describe the motion of the boat in a 3D environment characterized by disturbances such as wind and current. It will be shown that such a model is very suitable for the identification of the physical parameters and the control design phase.

The motion of the ship is described by a 6 degrees of freedom (6 DOF) system. The notation used in this paper is as follows: x is the surge motion, y is the sway, z is the heave, ϕ is the roll angle, θ is the pitch angle and ψ is the yaw angle. Specifically, x, y and z describe the position of the boat, whereas ϕ, θ and ψ the orientation.

The following assumptions are introduced to model the physical system, in order to obtain a model that is both simple and reliable:

- roll and pitch motions are neglected assuming that the ship is longitudinally and laterally metacentrically stable (*i.e.*, $\dot{\phi} = \phi = \dot{\theta} = \theta \cong 0$);
- the heave motion is neglected under the assumption that (reasonably) $z = 0$;
- the influence of the waves (*i.e.* the high frequency motion) is neglected as the harbor is a "closed" environment, so the waves have low impact on the parking maneuvers;
- the interaction between vessel and environmental disturbances (wind and current) is described using the equation of viscous friction, according to the maneuvering theory (see *e.g.* [4], [2] and [3]);
- the dynamics of the actuators are neglected as they are usually much faster than the boat dynamics;
- the boat has homogeneous mass distribution and xz-plane symmetry;
- see [4, §6], Equation (6.2) for a full model of the boat motion according to the Maneuvering Theory. In this work the hydrostatic and hydrodynamic forces are neglected because, as it will be seen later, the maximum velocity reachable in the harbor is 3 knots. Nevertheless the proposed model will be shown to be able to describe the dynamics of interest.

In conclusion, the model used to describe the low-frequency motion of the boat on a horizontal plane becomes a 3 DOF model.

A. The 3 DOF mathematical model

The 3 DOF mathematical model is related to an inertial reference frame $\{l\}$ fixed on the vessel. Thus the states of the boat can be described with the vector $\mathbf{x} = [x\, y\, \psi]^T$ that expresses the surge, sway and yaw velocity on the boat-fixed frame $\{l\}$. Obviously, the state vector x can be reported on a earth-fixed reference frame $\{e\}$.

The forces acting on the vessel are:

- the thrust generated by the actuators. These can be reduced to three (virtual) actuators positioned in the center of gravity (CG), such that the input forces f_x along longitudinal direction, f_y along lateral direction and τ along yaw direction are all applied to CG;
- the fluid dynamic forces (due to wind and current), F_{xc} and F_{xw} along longitudinal direction, F_{yc} and F_{yw} along lateral direction.

Notice that the intensity and the direction of the wind and current are defined on the earth-fixed reference frame $\{e\}$ and then projected on the boat-fixed frame $\{l\}$. For clarity, see Figure 1 in which the inertial frames and the conventions of the forces acting on the boat are illustrated.

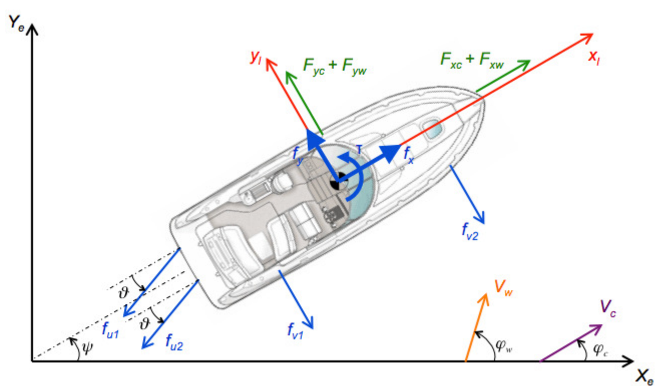

Fig. 1. The earth-fixed reference frame $\{e\}$, the boat-fixed reference frame $\{l\}$ and the forces acting on the system: the actuators forces (thin blue arrows), fluid dynamic forces (green arrows) and the forces generated by three apparent actuator positioned in the CG (thick blue arrows).

The mathematical model is

$$\begin{cases} M\ddot{x} = F_{xw} + F_{xc} - f_x \\ M\ddot{y} = F_{yw} + F_{yc} - f_y \\ J\ddot{\psi} = -K_\psi \dot{\psi} + b_{xw}F_{xw} + b_{xc}F_{xc} + b_{yw}F_{yw} + b_{yc}F_{yc} + \tau, \end{cases} \tag{1}$$

where the equations are obtained computing the lateral and longitudinal equilibrium of forces and the balance of the moments with respect to the z-axis. In (1), f_x, f_y and τ are the input of the model, $\ddot{x}$ and $\ddot{y}$ are the surge and sway accelerations, $\ddot{\psi}$ is the yaw acceleration, $\dot{\psi}$ is the yaw rate,

M is the mass of the boat, J is the inertial moment, K_ψ is the equivalent rigid-body Coriolis and centripetal coefficient and $b_{xw}(t)$, $b_{xc}(t)$, $b_{yw}(t)$ and $b_{yc}(t)$ are the time-varying distances between CG and CP, that is the application point of fluid dynamic forces. Throughout the paper, the subscript w refers to "wind", whereas the subscript c refers to "current".

Now let the moment generated by fluid dynamic forces acting on longitudinal direction in {l} be described by $\tau_x = b_{xw}F_{xw} + b_{xc}F_{xc}$ and the moment generated by fluid dynamic forces acting in the lateral direction be described by $\tau_y = b_{yw}F_{yw} + b_{yc}F_{yc}$. Since it is assumed here that the length of the hull is much greater than its width, $\tau_y \gg \tau_x$ and CP lies on the longitudinal axis of the vessel, thus yielding $b_{xw}(t) = 0$ and $b_{xc}(t) = 0$. Finally, the functions $b_{yc}(t)$ and $b_{yw}(t)$ will be considered constant in the linearization procedure and their values will be incorporated in the gains and time constants of the transfer functions in the gray-box identification procedure.

The fluid dynamic forces are defined as (see [4])

$$\begin{array}{l} F_{xw} = -K_{xw}\left(\dot{x}-\dot{x}_w\right)\left|\dot{x}-\dot{x}_w\right| \\ F_{xc} = -K_{xc}\left(\dot{x}-\dot{x}_c\right)\left|\dot{x}-\dot{x}_c\right| \\ F_{yw} = -K_{yw}\left(\dot{y}-\dot{y}_w\right)\left|\dot{y}-\dot{y}_w\right| \\ F_{yc} = -K_{yc}\left(\dot{y}-\dot{y}_c\right)\left|\dot{y}-\dot{y}_c\right| \end{array} \tag{2}$$

where

$$\begin{array}{l} \dot{x}_w = V_w \cos\left(\varphi_w - \psi\right) \\ \dot{x}_c = V_c \cos\left(\varphi_c - \psi\right) \\ \dot{y}_w = V_w \sin\left(\varphi_w - \psi\right) \\ \dot{y}_c = V_c \sin\left(\varphi_c - \psi\right). \end{array} \tag{3}$$

The fluid dynamic derivatives are instead expressed as $K_{ij} = 0.5\rho_j S_{ij} C_{ij}\ \forall i,j$ where $i = \{x,y\}$, $j = \{w,c\}$, C_{ij}, $\forall i,j$ are the fluid dynamic coefficients, ρ_c and ρ_w are the air and water density, whereas S_{ij}, $\forall i,j$ are the fluid/contact surfaces.

A 3 DOF state-space model of the form

$$\begin{cases} \dot{\mathbf{x}} = \mathbf{f}(\mathbf{x},\mathbf{d}) + \mathbf{g}(\mathbf{u}) \\ \mathbf{y} = \mathbf{x} \end{cases} \tag{4}$$

can then be written, where $\mathbf{x} = [\dot{x}\ \dot{y}\ \dot{\psi}]^T$ is the state vector, $\mathbf{d} = [\dot{x_c}\ \dot{y_c}\ \dot{x_w}\ \dot{y_w}]^T$ is the disturbance vector, $\mathbf{u} = [f_x\ f_y\ \tau]^T$ is the input vector and $\mathbf{y}$ is the output vector. Recalling from Section II that the boat is equipped with two lateral propellers that generate f_{v1} and f_{v2} and two aft outdrives that generate $f_u = f_{u1} + f_{u2}$ (while the direction is defined by the rudder angle ϑ) (see Figure 1), the relationship between the apparent forces (f_x, f_y and τ) and the real trusts can be written as

$$\Delta(\vartheta): \begin{cases} f_x = f_u \cos(\vartheta) \\ f_y = f_{v1} + f_{v2} + f_u \sin(\vartheta) \\ \tau = a_1 f_{v1} - a_2 f_{v2} + a_3 f_u \sin(\vartheta) + b_1 f_u \cos(\vartheta) \end{cases} \tag{5}$$

Finally, the motion of the vessel referred to the earth-fixed frame {e} can be expressed as

$$[X\ Y\ \Psi]^T = R(\psi)\,[x\ y\ \psi]^T \tag{6}$$

$$R(\psi) = \begin{bmatrix} \cos(\psi) & \sin(\psi) & 0 \\ -\sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix}, \tag{7}$$

where R is the rotation matrix (see (7)).

The 3 DOF mathematical model obtained is non-linear and strongly coupled. The model depends on some uncertain parameters such as the fluid dynamic derivatives and time-varying parameters such as the application point of the fluid dynamic forces. For control design, a simplified model will be therefore employed.

B. Control Oriented model

From the non-linear model (1), it is possible to calculate a simplified (decoupled) linear model that describes the motion of the boat in the horizontal plane, such that it is possible to design three decoupled regulators to control the motions of surge, sway and yaw.

The starting point to derive such a simplified model is very standard. Consider the operating point defined by constant speed, *i.e.* $\ddot{x} = \ddot{y} = \ddot{\psi} = 0$, that is, $\dot{x} = \bar{\dot{x}}$, $\dot{y} = \bar{\dot{y}}$ and $\dot{\psi} = \bar{\dot{\psi}}$.

The linear dynamics of the boat linking the three input apparent forces to the three output velocities is obtained by linearizing the non-linear model (4) with respect to the considered steady-state condition. The resulting model can be written in compact form as

$$\begin{cases} \delta\dot{\mathbf{x}} = A\delta\mathbf{x} + B\delta\mathbf{u} + F\delta\mathbf{d} \\ \delta\mathbf{y} = C\delta\mathbf{x} \end{cases} \tag{8}$$

where $\delta\mathbf{x} = \mathbf{x} - \bar{\mathbf{x}}$, $\delta\mathbf{u} = \mathbf{u} - \bar{\mathbf{u}}$, $\delta\mathbf{d} = \mathbf{d} - \bar{\mathbf{d}}$, $\delta\mathbf{y} = \mathbf{y} - \bar{\mathbf{y}}$ and the matrices A, B, F and C are calculated as:

$$A = \left.\frac{\partial f(\mathbf{x},\mathbf{d})}{\partial \mathbf{x}}\right|_{\bar{\mathbf{x}},\bar{\mathbf{d}}}\quad B = \left.\frac{\partial g(\mathbf{u})}{\partial \mathbf{u}}\right|_{\bar{\mathbf{x}},\bar{\mathbf{d}}}\quad F = \left.\frac{\partial f(\mathbf{x},\mathbf{d})}{\partial \mathbf{d}}\right|_{\bar{\mathbf{x}},\bar{\mathbf{d}}}\quad C = I_{3\times 3}\ . \tag{9}$$

The input-output model is achieved by applying the Laplace operator to the linearized state-space model. It follows that $\delta\mathbf{y}(t)$ can be expressed as

$$\delta\mathbf{y}(t) = G(s)\delta\mathbf{u}(t) + H(s)\delta\mathbf{d}(t) \tag{10}$$

where

$$G(s) = \begin{bmatrix} G_{\dot{x}f_x}(s) & 0 & 0 \\ 0 & G_{\dot{y}f_y}(s) & 0 \\ 0 & G_{\dot{\psi}f_y}(s) & G_{\dot{\psi}\tau}(s) \end{bmatrix} \tag{11}$$

$$H(s) = \begin{bmatrix} H_{\dot{x}\dot{x}_c}(s) & 0 & H_{\dot{x}\dot{x}_w}(s) & 0 \\ 0 & H_{\dot{y}\dot{y}_c}(s) & 0 & H_{\dot{y}\dot{y}_w}(s) \\ 0 & H_{\dot{\psi}\dot{y}_c}(s) & 0 & H_{\dot{\psi}\dot{y}_w}(s) \end{bmatrix} \tag{12}$$

and their elements are straightforwardly defined using the Laplace operator.

It is important to note that the matrix $G(s)$ is not diagonal. As a matter of fact, the transfer function $G_{\dot{\psi}f_y} \neq 0$ makes the sway and the yaw motion coupled. Generally CG is different from CP, then the fluid dynamic forces acting on the lateral motion generate also a yaw moment. Moreover, when CG coincides with CP, the gain of $G_{\dot{\psi}f_y}$ is zero and the matrix $G(s)$ becomes diagonal.

Now introduce the following assumptions:

- $\dot{x}_c = \dot{y}_c = 0$ (the transfer functions $H_{\dot{x}\dot{x}_c}(s)$, $H_{\dot{y}\dot{y}_c}(s)$ and $H_{\dot{\psi}\dot{y}_c}(s)$ can be neglected);
- CP coincides with CG (the transfer functions $H_{\dot{\psi}\dot{y}_c}(s)$, $H_{\dot{\psi}\dot{y}_w}(s)$ and $G_{\dot{\psi}f_y}(s)$ can be neglected);

- $\vartheta = 0$ (the equations in (5) can be simplified).

Since the BPA system is designed to work close to the harbor at low speed, the rudder angle has little impact on yaw motion, thus the simplifications above are more than reasonable. The simplified model is shown in Figure 2, where K_{PP} and K_{PROP} are constant terms that represent the maximum thrust along the longitudinal and lateral directions, respectively, com_i represents the command signal of the real i^{th} actuator, while $G_{\dot{x}f_x}(s)$, $G_{\dot{y}f_y}(s)$, $G_{\dot{\psi}\tau}(s)$, $H_{\dot{x}\dot{x}_w}(s)$ and $H_{\dot{y}\dot{y}_w}(s)$ are first-order transfer functions.

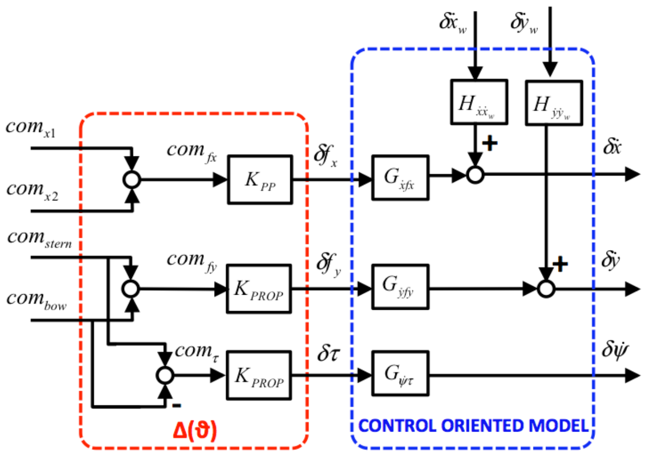

Fig. 2. Block diagram of the linear model. Inputs: actuators commands and disturbances; Outputs: boat velocities. Particularly the first block ($\Delta(\bar{\vartheta})$) yields the fictitious forces applied to the CG, the second block represents the linear model to be identified.

C. Gray-box identification

The identification procedure aims at finding the physical parameters of the model and is composed of three steps:

1) identify gain and time-constant of the transfer functions of the *control-oriented model*;
2) identify the gain terms from the apparent forces to the boat velocities;
3) identify the physical parameters of the mathematical model.

Different sea tests were conducted to identify the physical parameters of the mathematical model (1). As an example, the following discussion shows the technique used to identify the transfer function $G_{\dot{x}com_x}(s)$ relative to the longitudinal motion. Firstly, the linearized model equation is rewritten as

$$\delta\dot{x} = \frac{1}{1+s\,\tau_{\dot{x}}}\left[\mu_{\dot{x}com_x}\cdot com_x + \mu_{\dot{x}w}\cdot\delta\dot{x}_w\right] \qquad (13)$$

where $\mu_{\dot{x}com_x}$ is the gain between com_x and $\dot{x}$, $\mu_{\dot{x}w}$ is the gain between $\dot{x}_w$ and $\dot{x}$, $\tau_{\dot{x}}$ is the time-constant of the surge motion. Secondly, the time-constant $\tau_{\dot{x}}$ is estimated from a sea test in which both the outdrives are turned on. Thirdly, the gain of the transfer function between the wind speed and the surge speed ($\mu_{\dot{x}\dot{x}_w}$) is identified from an experimental test where all the actuators are turned off. Finally, the gain of the transfer function between the actuator command and the surge speed is calculated by minimizing, with respect to $\mu_{\dot{x}com_x}$, the cost function

$$V_i(\mu_{\dot{x}com_x}) = \frac{1}{N}\sum\left(\delta\dot{x} - \left[\frac{\mu_{\dot{x}com_x}}{1+s\,\tau_{\dot{x}}}\cdot com_x + \frac{\mu_{\dot{x}\dot{x}_w}}{1+s\,\tau_{\dot{x}}}\cdot\delta\dot{x}_w\right]\right)^2 \qquad (14)$$

which takes into account the wind effect, too.

The so-identified transfer functions describe the dynamic between actuators commands and boat speeds. Then, in order to achieve the physical parameters of the mathematical model, it is necessary to calculate the gains between apparent forces and boat speeds $\mu_{\dot{x}f_x}$, $\mu_{\dot{y}f_y}$ and $\mu_{\dot{\psi}\tau}$. For instance, consider the surge motion. Using the equation $\mu_{\dot{x}com_x} = K_{PP}\cdot\mu_{\dot{x}f_x}$ and the relation between the gain from the apparent force and surge motion time-constant $\mu_{\dot{x}f_x} = \tau_{\dot{x}}/M$, $K_{PP} = (\mu_{\dot{x}com_x}M)/\tau_{\dot{x}}$. Analogously, for the sway motion, it can be shown that $K_{PROP} = (\mu_{\dot{y}com_y}M)/\tau_{\dot{y}}$.

Since the mass is known, the gain can be calculated by inverting the basic relationships as

$$\mu_{\dot{x}f_x} = \frac{\mu_{\dot{x}com_x}}{K_{PP}} \quad \mu_{\dot{y}f_y} = \frac{\mu_{\dot{y}com_y}}{K_{PROP}} \quad \mu_{\dot{\psi}\tau} = \frac{\mu_{\dot{\psi}com_\psi}}{a\cdot K_{PP}}, \qquad (15)$$

where a is the distance between lateral propellers and CG.

Notice that, since the gains $\mu_{\dot{x}com_x}$, $\mu_{\dot{x}\dot{x}_w}$ and the surge time-constant $\tau_{\dot{x}}$ are linear with respect to the fluid dynamic derivatives K_{xc} and K_{xw}, the linear system

$$\begin{bmatrix} 2|\bar{x}| & 2|\bar{x}-\bar{x}_w| \\ 2|\bar{x}| & 2|\bar{x}-\bar{x}_w| \\ 0 & 1 \end{bmatrix}\begin{bmatrix} K_{xc} \\ K_{xw} \end{bmatrix} = \begin{bmatrix} \frac{1}{\mu_{\dot{x}f_x}} \\ \frac{M}{\tau_{\dot{x}}} \\ \frac{\mu_{\dot{x}w}}{2|\bar{x}-\bar{x}_w|\mu_{\dot{x}f_x}} \end{bmatrix} \qquad (16)$$

can be defined and easily solved using least squares techniques after defining an operating condition ($\bar{x}$ and $\bar{x}_w$). Analogously, also the fluid dynamic derivatives K_{yc} and K_{yw} for the sway motion can be calculated.

In conclusion, $\mu_{\dot{\psi}\tau} = 1/K_{\dot{\psi}}$ and $\tau_{\dot{\psi}} = 1/K_{\psi}$ straightforwardly yield the inertial moment J and the yaw equivalent rigid-body Coriolis and centripetal coefficient $K_{\dot{\psi}}$. For instance, Figure 3 assesses the quality of the model fitting on an experimental test with step excitation.

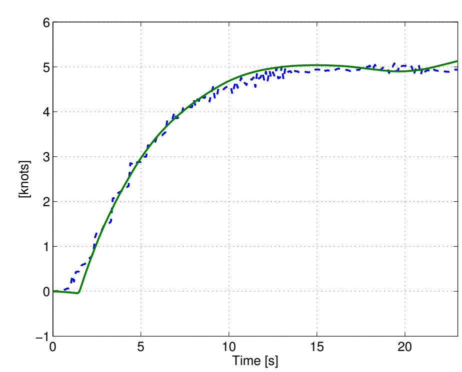

Fig. 3. Data-fitting in a step response test: measured surge speed (dotted line) and simulated surge speed using the identified model (solid line).

In the Table I, the numerical values obtained with the identification procedure are illustrated in detail.

TABLE I

NUMERICAL VALUES OF THE IDENTIFIED PHYSICAL PARAMETERS

Symbol	Description	Numerical value
K_{xc}	Current fluid dynamic derivatives along longitudinal direction	$715.14\ kg/m$
K_{xw}	Wind fluid dynamic derivatives along longitudinal direction	$42\ kg/m$
K_{yc}	Current fluid dynamic derivatives along lateral direction	$500\ kg/m$
K_{yw}	Wind fluid dynamic derivatives along lateral direction	$32.7\ kg/m$
K_{ψ}	Hydrodynamic derivatives of the yaw motion	$233.8\ kg/m$
J	Boat inertial moment	$1351.3\ kg \cdot m$
K_{PP}	Maximum thrust along longitudinal direction	$376\ N/com_x$
K_{PROP}	Maximum thrust along lateral direction	$748\ N/com_y$

IV. THE CONTROL ARCHITECTURE

The BPA system operates in *semi-automatic mode* or *station-keeping*. The control architecture is designed with two loops in cascade for each DOF as shown in Figure 4: the inner speed loop is devoted to the *semi-automatic mode*, whereas the *stationkeeping mode* is achieved via the outer position loop. It should be noted that the set point of the inner speed loop can be provided in two different ways: in the *stationkeeping mode*, the speed set point is given by the position regulators, whereas in the *semi-automatic mode*, the speed set point is given by the user via joystick.

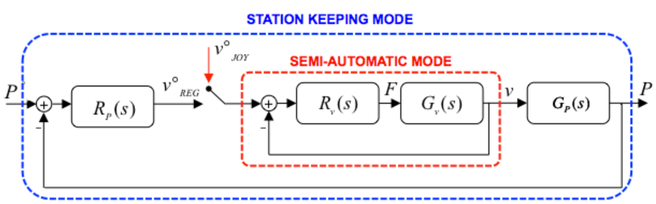

Fig. 4. The control system architecture: outer position loop to achieve *stationkeeping mode* (dotted blue line) and inner speed loop to achieve *semi automatic mode* (dotted red line).

In particular, the command variable of the control system are the gear of the outdrives and the lateral propellers. The former is employed to control the surge motion because the boat reaches the maximum speed allowed near the harbor (3 knots) only with gear trigger, whereas the latter are used to control sway and yaw motion because they are the most efficient at low speed. This choice is due to the fact that during experimental tests it was found that the rudder has a little impact on motion.

Figure 5 shows the detail of the block diagram of the control system, where:

- the *Coordinate Transformation* block transforms the variables of interest from the earth-reference frame to the boat-reference frame considering Equation 7;
- the *Position Regulators* block is achieved by three proportional regulators which generate the set point for the inner speed loop (closed-loop bandwidth about $0.001\ Hz$ and phase margin about 80°, [1], [5]),
- the *Speed Regulators* block is achieved by three proportional-integral regulators manually tuned on the transfer functions of the *Control Oriented model*, under the assumption that the boat motions are decoupled (closed-loop bandwidth about $0.01\ Hz$ and phase margin about 90°, [1], [5]);
- the *Decoupler* block converts the output forces of the speed controllers into commands for the available actuators;
- the *Pulse Width Modulation* block generates pulses of variable length in order to control ON/OFF actuators and modulate the force.

In Table II, the numerical values for control parameters are given.

TABLE II

NUMERICAL VALUES OF THE CONTROL PARAMETERS

Symbol	Description	Numerical value
$K_{P\dot{x}}$	Proportional gain of the surge motion speed controller	$109\ Ns/m$
$T_{I\dot{x}}$	Integral gain of the surge motion speed controller	$3.93\ s$
$K_{P\dot{y}}$	Proportional gain of the sway motion speed controller	$150\ Ns/m$
$T_{I\dot{y}}$	Integral gain of the sway motion speed controller	$7\ s$
$K_{P\dot{\psi}}$	Proportional gain of the yaw motion speed controller	$70\ Ns/m$
$T_{I\dot{\psi}}$	Integral gain of the yaw motion speed controller	$5.78\ s$
K_{Px}	Proportional gain of the surge motion position controller	$0.0226\ 1/s$
K_{Py}	Proportional gain of the sway motion position controller	$0.0126\ 1/s$
$K_{P\psi}$	Proportional gain of the yaw motion position controller	$0.0157\ 1/s$

V. EXPERIMENTAL RESULTS

Some sea tests performed on the boat described in Section II are now presented to show the performance of BPA system in both the *stationkeeping mode* and the *semi-automatic mode*.

To evaluate the performance of the *stationkeeping mode*, the circumference centered in the desired reference point and which inscribes the path of the vessel is considered. The related quantitative indicator of the performance is the radius of this circumference.

In Figure 6, the performance of the BPA system is compared to that of a neophyte pilot. Specifically, in the first case, the radius is $11\ m$, while in the second case it is $41\ m$, that is the BPA system yields an improvement in performance of about 70 %. The red line in Figure 7 shows the boat trajectory obtained by the BPA system active in the *semi-automatic mode* during mooring.

The same trajectory can be obtained automatically by varying the position set points (green dots) with the BPA system active in *stationkeeping mode*. This "time-varying" *stationkeeping mode* can be see as a prototype of a completely "automatic mode". Specifically, the position set points are updated when the ship gets into some confidence intervals, defined off-line (and indicated with the light green areas). The blue dashed line in Figure 7 shows the trajectory actually achieved by the boat with the BPA system. It should be noted that in the final part of the experimental test lateral propellers are not able to overcome the disturbances (due to the wind) in the lateral direction. However, the system is able to keep the boat inside the confidence region for each reference point.

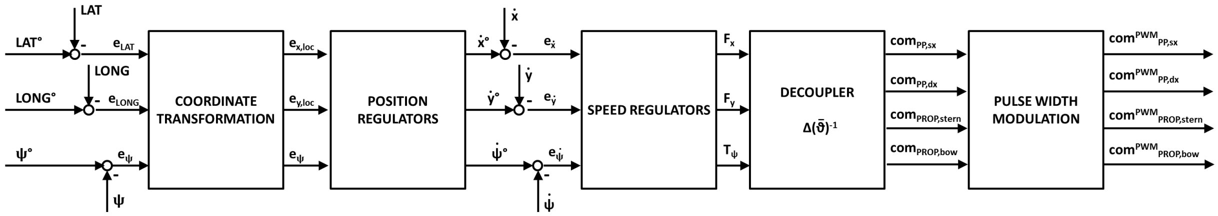

Fig. 5. Block diagram of the control system.

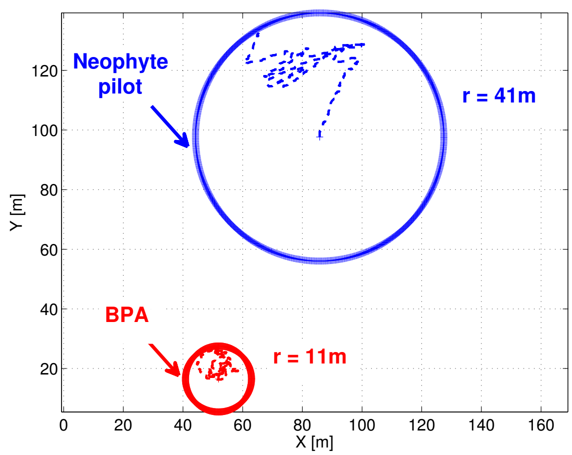

Fig. 6. Figure showing the performance of the BPA system active in *stationkeeping mode*. Blue circumference is achieved by a neophyte pilot, red circumference is achieved by BPA system

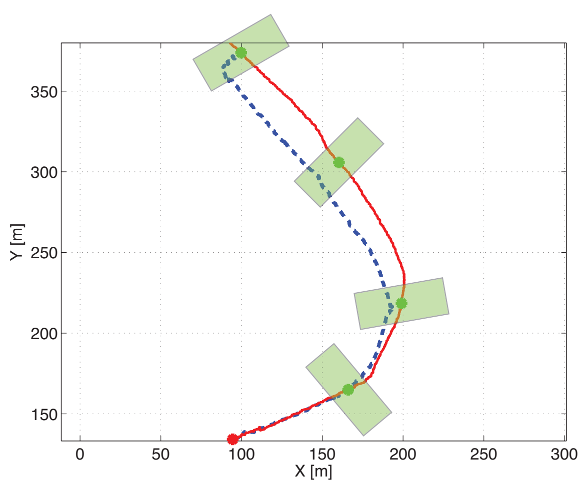

Fig. 7. Figure showing a mooring procedure obtained with BPA system. Red trajectory is achieved with BPA system active in *semi-automatic mode*, blue path is achieved automatically with BPA system active in *stationkeeping mode*

VI. Conclusions

In this paper, the problems of modeling, identification and control of a BPA system have been dealt with. Specifically, a 3 DOF model has been derived from force balances and physical parameters have been identified via *ad-hoc* experimental tests. A control architecture implementing two different operating modes has then been developed. In the *stationkeeping mode*, the vessel is maintained in a given point and the heading is regulated. In the *semi-automatic mode*, the boat is guided in the harbor by the user and the control system acts as a virtual assistant that rejects disturbances such as wind and current. Both the strategies have been tested on a real vessel, on which it has also been shown that the *stationkeeping mode* is a promising starting point to study a completely automatic parking system. The latter will be the subject of future research, as well as some more complicated control strategies for the *stationkeeping* and *semi-automatic modes*.

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