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COMPUTERS IN TECHNICAL SYSTEMS
RAČUNALA U TEHNIČKIM SUSTAVIMA

Guidance of Laboratory Marine Platforms

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Abstract - Marine robotics is an interesting area for control engineers since these systems are complex, nonlinear and operate in highly unpredictable environment (winds, currents, waves). This paper present a laboratory model of a surface platform for dynamic positioning which has been developed at the Laboratory for Underwater Systems and Technologies, University of Zagreb. The full mathematical model consisting of actuator allocation, dynamic model and kinematic model is described. The platform has primarily been developed for testing and comparison of different control, guidance and navigation algorithms. The platform is overactuated which makes it suitable for fault tolerant control design. The paper describes the procedure of model based line following controller design which ensures stability and zero error line following under the influence of external disturbances.

I. INTRODUCTION

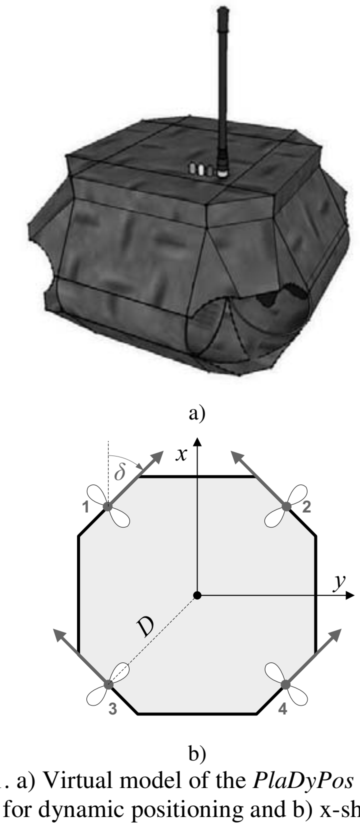
Marine robotics in general present an interesting and challenging area where the application of control theory presents an essential part. This comes directly as a consequence of harsh environment in which marine vehicles operate, characterized with unpredictable disturbances (waves, winds and currents). While marine robotics are roughly divided in underwater and surface marine robotics, this paper deals with guidance of surface marine platforms.

The general control hierarchy for marine vehicles can roughly be divided into three levels: low level (or control), mid level (or guidance) and high level (or mission planning). Fully autonomous systems demand that all three levels of control are carefully designed, [1]. While low level control usually includes design of heading controllers and speed controllers, [9], mid level control is designated to path or trajectory following algorithms, [3], [2]. The authors have published papers on line following for small unmanned rudder--actuated surface marine vehicles, [10], [8], and small unmanned underwater vehicles [6]. Experimental results have shown that the proposed methodology can be applied to vessels operating in field conditions. This paper deals with straight line following algorithms for overactuated surface marine platforms. The main characteristic of these platforms is that the excitation force vector can be directed in any direction in the horizontal plane, what allows for the design of complex guidance and control algorithms.

The paper is organized as follows: in the continuing part of the introduction the laboratory model of a marine platform is described. Section II presents the mathematical model which is used to describe behavior of the platform. Section III formulates the problem of line following for marine surface platforms while Section IV presents a model-based line following controller design. Section IV gives simulation results and Section V concludes the paper.

A. PlaDyPos - The Laboratory Marine Platform for Dynamic Positioning

The work presented in this paper will be elaborated on an overactuated marine surface platform called *PlaDyPos* (see Fig. 1a)). The platform is developed at the Laboratory for Underwater Systems and Technologies by a group of students. The main purpose of the platform is the testing of different control and guidance strategies for marine surface vehicles such as dynamic positioning, point-to-point guidance, line-following and path-following algorithms. Some technical characteristics of the platform are shown in Table I.



b)
Fig. 1. a) Virtual model of the *PlaDyPos* laboratory platform for dynamic positioning and b) x-shape actuator configuration.

TABLE I
TSOME CHARACTERISTICS OF THE *PlaDyPos* MARINE PLATFORM.

Height [m]	0.18
Width [m]	0.31
Length [m]	0.31
Weight [kg]	≈ 7

The platform is actuated by cheap, commercially available bilge pumps positioned in such a way that the form an x--shaped thruster configuration as shown schematically in Fig. 0. The platform operates in the laboratory pool which has a video camera positioned above it. The platform has an onboard radio receiver which is used to decode thrusters' command signals sent from the ground station. An image processing algorithms has been developed in order to determine position of the platform within the laboratory pool. The camera placed above the pool tracks the marker placed on top of the platform and serves as the position and orientation sensor. This systems configuration has proved to be convenient for laboratory use and testing of control and guidance algorithms.

II. MATHEMATICAL MODEL

The mathematical model of a marine platform is defined using two coordinate frames: an Earth-fixed (inertial) frame {E} described with axes N (pointing to the north), E (pointing to the east) and D (pointing down so that the NED frame forms a positively oriented coordinate system); a body-fixed coordinate system {B}, which is usually attached to the centre of gravity (CG) of the vehicle and is described with three axis x, y and z pointing respectively in the same directions as the NED frame when x and N are aligned, [5]. The mathematical model of a marine platform is described with an assumption that the platform is moving only in the horizontal plane, i.e. only translation in the $N-E$ plane and rotation about the z axis is possible.

The platform's speeds are defined in the fixed coordinate frame {B}: surge u and sway v speeds are translation speeds in the x and y axis directions, respectively, and yaw speed r is rotational speed around the z axis. Earth-fixed coordinate frame is used to define positions x and y in the horizontal plane and orientation ψ of the platform. The motion of the platform is achieved by applying surge (X) and sway (Y) force and yaw (N) moment.

The schematic representation of the mathematical model is given in Fig. 2. The *kinematic model* gives the relations between the speeds $\mathbf{v}$ in a body-fixed coordinate frame

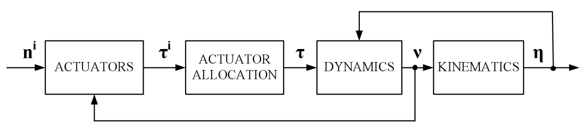


Fig. 2. Block-diagram of the mathematical model used to describe marine vessels.

{B} and first derivative of positions and angles $\boldsymbol{\eta}$ in an Earth-fixed coordinate system {E}. For the horizontal plane, this model is given with

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u \\ v \\ r \end{bmatrix}. \qquad (1)$$

Relations between velocities $\mathbf{v}$ and accelerations $\dot{\mathbf{v}}$ of the vehicle and forces $\boldsymbol{\tau}$ that act on it are given with the *dynamical model*. The dynamic equation describing surge DOF is given with (2) where α_u is a constant parameter and $\beta(u)$ is a drag parameter which is speed dependant and includes all hydrodynamic effects. For control design purposes this parameter can be estimated as $\beta(u) = \beta_u + \beta_{uu} |u|$. If the platform is operating at small speeds, the drag parameter can be approximated with a constant term, i.e. $\beta(u) = \beta_u$, [11]. Since the platform is symmetric in the horizontal plane, the same parameters can be used to describe the sway DOF dynamic model (3). In a similar manner, yaw model is given with (4) where α_r is inertia and $\alpha(r)$ drag. The τ_{uE}, τ_{vE} and τ_{rE} represent external disturbances and unmodelled dynamics of the system.

$$\alpha_u \dot{u} + \beta(u) \cdot u = \tau_{uE} + X, \qquad (2)$$
$$\alpha_u \dot{v} + \beta(v) \cdot v = \tau_{vE} + Y, \qquad (3)$$
$$\alpha_r \dot{r} + \beta(r) \cdot r = \tau_{rE} + N. \qquad (4)$$

The *actuator allocation* matrix gives relation between the forces exerted by thrusters (τ_1, τ_2, τ_3 and τ_4) and the forces that act on the rigid body (X, Y, N). For the case of the *PlaDyPos*, whose actuator configuration is given in Fig. 1b), the actuator matrix is given with

$$\begin{bmatrix} X \\ Y \\ N \end{bmatrix} = \begin{bmatrix} \sin\delta & \sin\delta & \sin\delta & \sin\delta \\ -\sin\delta & \sin\delta & \sin\delta & -\sin\delta \\ D & -D & -D & D \end{bmatrix} \begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \\ \tau_4 \end{bmatrix}. \qquad (5)$$

Since four actuators are used to control three degrees of freedom, this presents an overactuated system. This allows for the design of fault tolerant control algorithms, [12]. The inverse actuator allocation matrix cannot be found (since the matrix is not square), but a pseudoinverse can be calculated instead.

The actuators present control elements which ensure a specified force on the vessel. If the actuating elements are thrusters, their characteristic can be described with (6) where n^i represents the individual thruster's control input (commanded rotation speed, input voltage, etc.), K_T is the thruster coefficient and τ^i is thrust exerted by the i -th thruster.

$$\tau^i = K_T \left| n^i \right| n^i \qquad (6)$$

The nonlinear static thruster characteristic can easily be compensated within the control algorithm, [7].

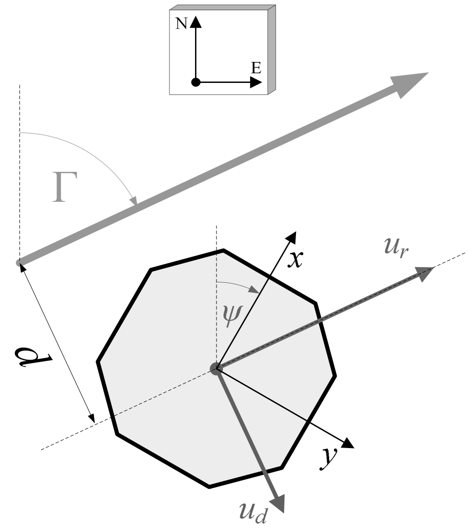


Fig. 3. The line following concept.

III. PROBLEM FORMULATION

Once the mathematical model of the marine platform is described, the line following problem can be defined. The oriented line which is to be followed can be described with two points in space T_1 and T_2, where the orientation is from T_1 to T_2 by convention. Such a line is rotated by the angle Γ with regard to the $\{E\}$ coordinate system. If the distance of the vehicle to the line is denoted with d, the task of line following is to ensure convergence of d to 0.

For this purpose, the speeds of the vessels can be represented with two speed vectors: vector u_r parallel to the line and vector u_d perpendicular to the line as it is shown in Fig. 3.

The relation between these two speeds and speeds in the vessels coordinate frame $\{B\}$ is given with

$$\begin{bmatrix} u_r \\ u_d \end{bmatrix} = \underbrace{\begin{bmatrix} \cos\gamma & \sin\gamma \\ \sin\gamma & \cos\gamma \end{bmatrix}}_{\mathbf{\Phi}} \begin{bmatrix} u \\ v \end{bmatrix} \tag{7}$$

where $\gamma = \Gamma - \psi$ is the angle of the vessel relative to the line. In the same manner, the relation between the forces in the $\{B\}$ coordinate frame and forces X_r and X_d is given with

$$\begin{bmatrix} X \\ Y \end{bmatrix} = \mathbf{\Phi}^{-1} \begin{bmatrix} X_r \\ Y_r \end{bmatrix}. \tag{8}$$

It should be mentioned that $\mathbf{\Phi} = \mathbf{\Phi}^{-1}$. The scheme of the dynamic model of the vehicle can than be represented with Fig. 4 and equation

$$\begin{bmatrix} u_r \\ u_d \end{bmatrix} = \mathbf{\Phi}^{-1} \underbrace{\begin{bmatrix} G_1 & 0 \\ 0 & G_2 \end{bmatrix}}_{\mathbf{G}} \mathbf{\Phi} \begin{bmatrix} X_r \\ Y_r \end{bmatrix} \tag{9}$$

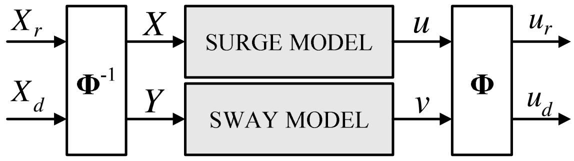


Fig. 4. Line following.

where G_1 and G_2 represent surge and sway dynamic models, respectively. Only if $G_1 = G_2$, it can be written that

$$\mathbf{\Phi}^{-1}\mathbf{G}\mathbf{\Phi} = \mathbf{G}. \tag{10}$$

In other words, the dynamic model relating u_r to X_r and u_d to X_d is the same as the surge (or sway, since they are the same) dynamic model of the vessel.

The full mathematical model of line following, under the assumption that the speed u_r is constant, is then given with

$$\alpha_u \dot{u}_d + \beta(u) \cdot u_d = X_d \tag{11}$$

$$\dot{d} = u_d + \xi \tag{12}$$

where ξ represents the current perpendicular to the direction of the line which is acting on the vessel.

IV. CONTROLLER DESIGN

Based on the line following mathematical model given with (11) and (12), the line following closed loop is shown in Fig. 5. For the sake of simplicity, the u_d speed is controlled in open loop by setting a constant value X_d. Also, the assumption which is made in this paper is that the heading controller is designed and that the platform's heading ψ is constant during the line following experiment.

The proposed line following controller output is the X_r force and its algorithm is of I-PD type given with (13). This controller is chosen since it compensates for external disturbances and ensures zero steady state error. It should be mentioned that this structure is the same as the classical PID controller if $d_{ref} = 0$ which is the case if line following is required. However, the I-PD structure is convenient in marine applications since the abrupt changes in reference value are smoothed at the controller output.

$$X_r = K_{Id} \int_0^t \left(d_{ref} - d\right) dt - K_{Pd} d - \frac{d}{dt} d \tag{13}$$

Under the assumption that the dynamic model of the platform is liner, i.e. $\beta(u) = \beta_u$, the closed loop form is than given with (14). The controller parameters can be

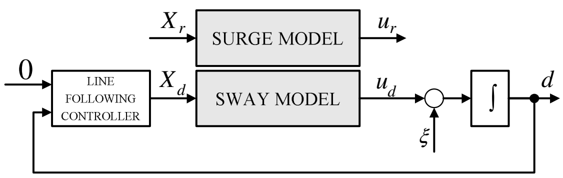


Fig. 5: The line following closed loop.

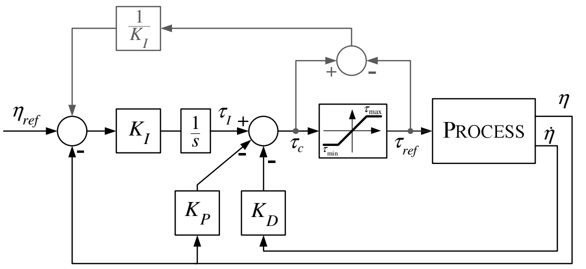


Fig. 6. The antiwindup controller scheme.

obtained from here if model based approach is used, [10]. If the closed loop is set to be equal to some desired closed loop transfer function (e.g. Bessel filter), a_{3d}, a_{2d} and a_{1d} are desired line following closed loop transfer function parameters.

$$\frac{d}{d_{ref}}=\frac{1}{\underbrace{\alpha_u K_{Id}}_{a_{3d}}s^3+\underbrace{\beta_u+K_{Dd}K_{Id}}_{a_{2d}}s^2+\underbrace{K_{Pd}K_{Id}}_{a_{1d}}s+1}. \quad (14)$$

The controller parameters can then be calculated as

$$\begin{aligned} K_{Iv} &= \frac{\alpha_u}{a_{3d}}, \\ K_{Pv} &= \alpha_u\frac{a_{1d}}{a_{3d}}, \\ K_{Dv} &= \alpha_u\frac{a_{2d}}{a_{3d}}-\beta_u \end{aligned} \quad (15)$$

It should again be mentioned that the choice of the desired closed loop function parameters depend on the feasible dynamics of the marine vessel.

A. Antiwindup algorithm

An important issue which should be addresses when designing controllers is integrator windup, [13]. The characteristic of thrusters determines the maximal thrust which can be exerted. Consequently, maximal thruster generated by the controller should be taken into account. If the controller would generate thrust greater than the feasible thrust, oscillations may appear in the closed loop behavior. This is why integrator antiwindup techniques are implemented within the controller, [4].The antiwindup algorithm is based on the fact that the integrator within the controller should stop integrating when controller output τ_c is greater than feasible action τ_{ref}. This procedure can be implemented as shown in Fig. 6 and the integral channel output in this case is

$$\tau_I = K_I\int_0^t\left(\eta_{ref}-\eta\right)dt-\int_0^t\left[\tau_c-sat(\tau_c,\tau_{min},\tau_{max})\right]dt \quad (16)$$

where τ_{min} and τ_{max} are upper and lower saturation bound of the input signal to the vehicle.

TABLE II
SWITCHING TIMES AND THE LINE PARAMETERS DURING THE SIMULATED MISSION.

Switch time	$T_1(x_1, y_1)$	$T_2(x_2, y_2)$
$t_0 = 0s$	(0, 1)	(3, 1)
$t_1 = 40s$	(4, 1)	(4, 3)
$t_2 = 60s$	(5, 5)	(0, 2)

V. RESULTS

The simulation case study which is presented here consists in the vehicle to follow three lines. The switching between the lines is time based, i.e. at the specific moments in time the desired line changes. The switching times together with two points T_1 and T_2 that describe the line are given in Table 2. It should be mentioned that the switching can be position based: when the vehicle approaches the final point T_2, the following line is set to be followed. As it was mentioned before, the control of speed u_r is performed in open loop.

Fig. 5 gives the vessel path (blue solid line) during the simulated mission. The oriented lines which are to be followed are given with dashed lines. During the mission the reference force X_r is kept at a constant value through the whole experiment. Switching times are clearly indicated in the figure with black arrows. The orientation of the platform is indicated with a yellow arrow: throughout the whole experiment the orientation was kept at $\psi=-\frac{\pi}{4}$. The saturation level of the applied X_r force was set to be double the nominal X_d force during the experiment. Fig. 7 shows commanded forces X_r and X_d as well as the platform's speeds u_r and u_d during the experiment.

At the moment $t = 0s$ the platform is positioned at the origin of the NE coordinate frame and it is commanded to follow the first line. The controller immediately applies the maximal X_r force causing the platform to approach the line. The antiwindup algorithm ensures smooth approach. The results shown in Fig. 5 demonstrate that the line following is achieved with zero steady state error and that convergence to the line is successfully achieved.

VI. CONCLUSION AND FUTURE WORK

The paper presents the application of the line following algorithm to a laboratory model of a marine platform. The platform is a result of a student project at the Laboratory for Underwater Systems and Technologies at the University of Zagreb and it is designed with the purpose of testing different control and guidance algorithms. The overactuated platform has the ability to point the desired force vector anywhere in the horizontal plane. This properties was used to design a line following algorithm which will ensure zero steady state error and compensate for external disturbances such as wind and currents. The paper gives the mathematical model of the platforms and describes the line following model. Line following controller is described in detail and simulation results are presented.

The future work includes the implementation of the

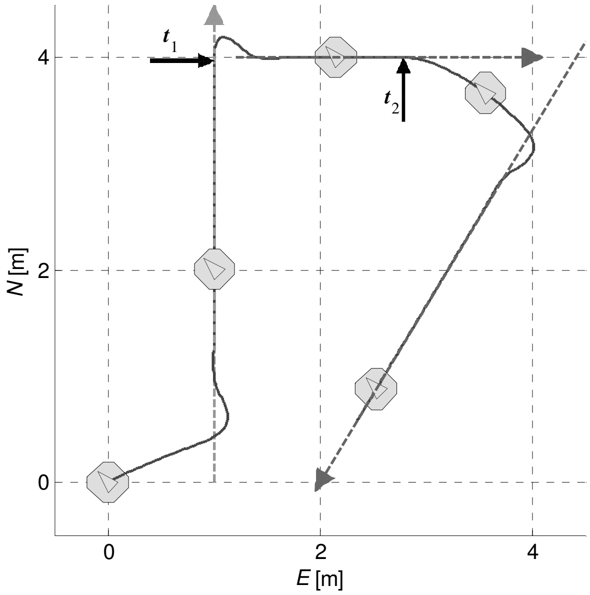


Fig. 6. The path of the marine platform during the simulated mission.

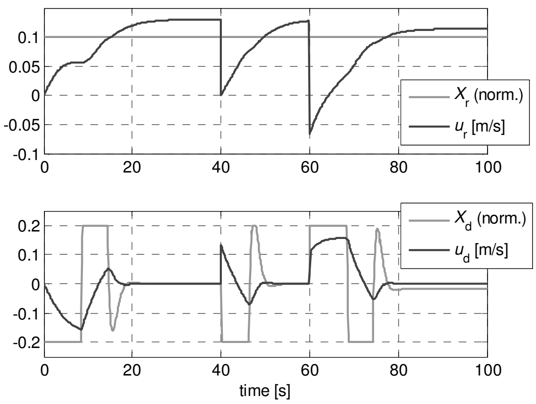


Fig. 7. The commanded forces and the platform's speeds during the simulated mission.

proposed algorithm to the real vessel. Similar algorithms have already been tested on small unmanned rudder--actuated surface marine vehicles and the results show their feasibility. In addition to this, the next implementation steps will include close loop control of the speed u_r at which the platform is cruising in the direction of the desired line.

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