Guidance of a Small-Scale Overactuated Marine Platform – Experimental results

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Abstract - This paper presents the continuation of a project first presented at MIPRO'10 conference. The project includes a small-scale marine platform (*PlaDyPos*) developed at the Laboratory for Underwater Systems and Technologies (LABUST), University of Zagreb which is used for testing control and guidance algorithms for marine vehicles. The paper focuses on the analysis of experimental results obtained on a real overactuated platform. The experiments have exhibited satisfactory behaviour. The proposed guidance algorithm consists of a line following controller decoupled from heading control, enabling motion in arbitrary directions while keeping a predefined orientation. The greatest contribution of the paper is in providing the proof-of-concept of the proposed guidance algorithms. Other experiments performed on the laboratory platform are available online. The following steps of research include collaborative behaviour between the platform and human divers.

I. INTRODUCTION

Marine robotics in general presents 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 control guidance of surface marine platforms, [1], [2].

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 (LABUST) by a group of students. Some technical characteristics of the platform are shown in Table I. 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. 1b).

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. 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.

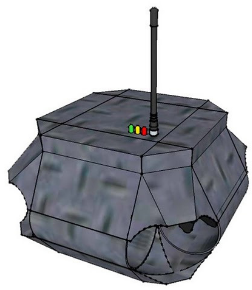
The main motivation for building this type of a platform was, firstly, to introduce students to the area of marine robotics. As the project evolved, the task was to build a rather small, portable platform which will be used in the field for the purpose of assisting divers in underwater navigation and communication with the ground station. Further on, the developed platform will be used in cooperative guidance of unmanned underwater vehicles. This application would allow more precise underwater localization and online mission replanning. The relevance of the envisioned project is significant from the educational side, and the interdisciplinarity through marine robotics.

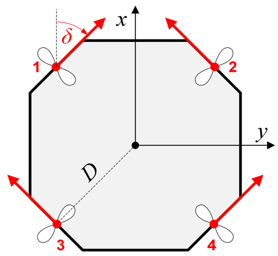
The authors' intention is to divide this research into three steps:

- Step 1 includes the design of the small-scale laboratory platform, communication structure and building a confident simulator which is used to test basic guidance algorithms;
- Step 2 includes testing the algorithms on a real small-scale platform in laboratory conditions, with simultaneous guidance and heading control;
- Step 3 includes building a platform capable of operating in field conditions and testing of guidance algorithms using GPS signals.

Results of Step 1 were reported in [3] presented at the MIPRO'10 conference where the authors proved the feasibility of the concept which is recapitulated in the first part of this paper. This work included mathematical modelling, control design and simulation results of following a straight line. In should be mentioned that the developed simulation model assumed that the dynamics of the platform were uncoupled.

This paper presents the next step in research activities regarding the guidance algorithms which includes experiments on a real vehicle. These results are of great





a) b)

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

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

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

importance since they prove that the simulation model describes the dynamics of the platform in a satisfactory manner. In addition to that, the results presented here show that the proposed control structure can be used on a real system, with all unmodelled dynamics taken into account.

Step 3 is work currently in progress and the results will be reported in near future.

The paper is organized as follows. Section II describes the mathematical model of the basic motion of the laboratory platform. In addition to that, the line following model is given. Section III presents the controller design. Both heading controllers and line following controllers are addressed since the application assumes that the platform keeps arbitrary heading while performing line following. Section IV gives experimental results obtained in the laboratory pool on the real platform and schematically depicts the implementation of the proposed control and guidance algorithm. The paper is concluded with Section V.

II. MATHEMATICAL MODEL

A. The PlaDyPos 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, [4]. 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 the surge and sway (Y) force and yaw (N) moment.

The schematic representation of the mathematical model is given in Fig. 2. where $\mathbf{n}_i = \begin{bmatrix} n_1 & n_2 & n_3 & n_4 \end{bmatrix}^T$ represents the vector of each thruster's control input (commanded rotation speed, input voltage, etc.),

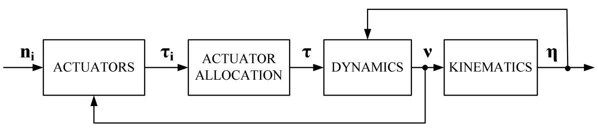


Fig. 2. Block-diagram of the mathematical model used to describe marine vessels.

$\boldsymbol{\tau}_i = \begin{bmatrix} \tau_1 & \tau_2 & \tau_3 & \tau_4 \end{bmatrix}^T$ is vector of forces exerted by each thrusters, $\boldsymbol{\tau} = \begin{bmatrix} X & Y & N \end{bmatrix}^T$ is vector of forces and moments that act on the platform, $\mathbf{v} = \begin{bmatrix} u & v & r \end{bmatrix}^T$ is vector of speeds and $\boldsymbol{\eta} = \begin{bmatrix} x & y & \psi \end{bmatrix}^T$ vector of positions and orientation. The *kinematic model* in the horizontal plane is given with (1). The *dynamic model* is assumed to be uncoupled so each controllable degree of freedom (DOF) can be modelled separately. In addition to that, since the platform is symmetric in the horizontal plane, the same model (and the parameters) can be used to describe surge and sway dynamics, as shown with (2) and (3) where α_u is a constant parameter and $\beta(u)$ and $\beta(v)$ are drag parameter which are speed dependant and include all hydrodynamic effects. If the platform is operating at small speeds, the drag parameter can be approximated with a constant term, i.e. $\beta(u) = \beta(v) = \beta_u$, [5]. 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.

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

$$\alpha_u \dot{u} + \beta(u) \cdot u = \tau_{uE} + X, \tag{2}$$

$$\alpha_u \dot{v} + \beta(v) \cdot v = \tau_{vE} + Y, \tag{3}$$

$$\alpha_r \dot{r} + \beta(r) \cdot r = \tau_{rE} + N. \tag{4}$$

The *actuator allocation* matrix gives relation between vectors $\boldsymbol{\tau}_i$ and $\boldsymbol{\tau}$. For the case of the *PlaDyPos*, whose actuator configuration is given in Fig. 1b) and $\delta = 45°$, the actuator matrix is given with

$$\begin{bmatrix} X \\ Y \\ N \end{bmatrix} = \begin{bmatrix} \cos 45° & \cos 45° & \cos 45° & \cos 45° \\ \sin 45° & -\sin 45° & -\sin 45° & \sin 45° \\ D & -D & D & -D \end{bmatrix} \begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \\ \tau_4 \end{bmatrix}. \tag{5}$$

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, [6]. The inverse actuator allocation matrix cannot be found (since the matrix is not square), but a pseudoinverse can be calculated instead.

The actuators can be simply modelled using an affine model given with (6) where K_T is the thruster coefficient and τ_i is thrust exerted by the i-th thruster.

$$\tau_i = K_T |n_i| n_i \tag{6}$$

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

B. The line following model

The line following model can be described using the schematic representation given in Fig. 3. The oriented line to be followed is uniquely defined by it's angle of rotation Γ within the {E} coordinate system and by the distance d between the platform and the line. Once the mathematical model of the marine platform is described, the line following problem can be defined. Having said that, the task of line following is to ensure convergence of d to 0.

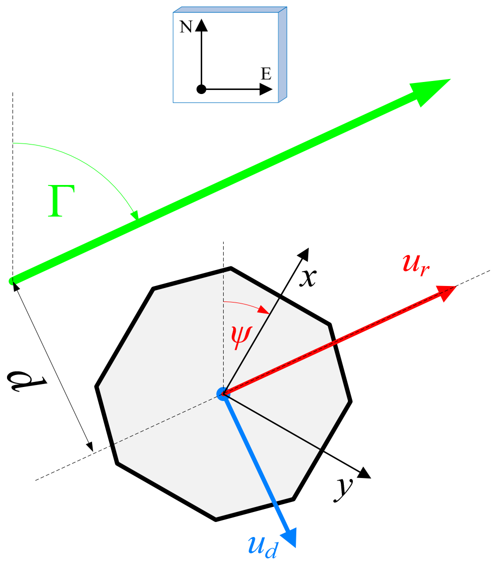


Fig. 3. The line following concept.

Let us define two speed vectors: vector u_r parallel to the line and vector u_d perpendicular to the line as 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} coordinates frame and forces X_r and X_d is given with

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

It should be mentioned that $\mathbf{\Phi} = \mathbf{\Phi}^{-1}$. It was shown in [3] that only if the dynamics of the surge and sway motion are equal, the dynamics of motion perpendicular to the line (dynamics relating u_d to X_d) will be the same as the surge and sway dynamics. This is also valid for the dynamics of motion parallel to the line (dynamics relating u_r to X_r).

Having this in mind, line following can be modelled with

$$\alpha_u \dot{u}_d + \beta(u) \cdot u_d = X_d \tag{9}$$

$$\dot{d} = u_d + \xi \tag{10}$$

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

III. CONTROLLER DESIGN

Based on the line following mathematical model given with (9) and (10), the line following closed loop is shown in Fig. 4. For the sake of simplicity, the u_d speed is controlled in open loop by setting a constant value X_d. In addition to that, Fig. 4. includes the heading control loop which ensures constant heading throughout the mission regardless of the line following control effort. From Fig. 4. and from (1), (4), (9) and (10) it is clear that the heading model and the line following model have the same structure. That is why the control algorithm which is described in the following part will be given for general variables $x(t)$ (should not be mistaken for the position in the {E} coordinate system) and general controller output $u(t)$ where $x(t) = d(t)$, $\dot{x}(t) = \dot{d}(t)$ and $u(t) = X_d(t)$ for line following, and $x(t) = \psi(t)$, $\dot{x}(t) = \dot{\psi}(t) = r(t)$ and $u(t) = N(t)$ for heading control.

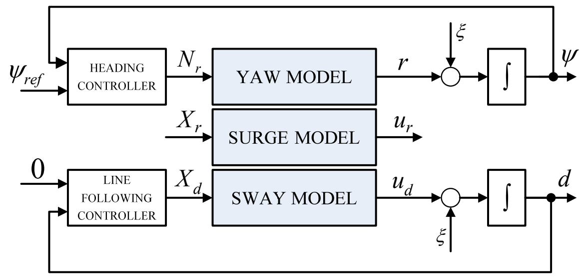


Fig. 4: The control system consisting of heading control and line following.

The controller which is used in this paper is of I-PD type given with (11). This controller is chosen since it compensates for external disturbances and ensures zero steady state error both in heading control and line following. It should be mentioned that this structure is the same as the classical PID controller if $x_{ref} = 0$ which is the case in line following. However, the I-PD structure is convenient in marine applications since the abrupt changes in reference value are smoothed at the controller output.

$$u = K_I \int_0^t \left(x_{ref} - x \right) dt - K_P x - K_D \frac{d}{dt} x \tag{11}$$

Under the assumption that the dynamic model of the platform is liner, i.e. $\beta(u) = \beta_u$ and $\beta(r) = \beta_r$ the general closed loop form is than given with (12) where $\alpha_x = \alpha_r$ and $\beta_x = \beta_r$ for the case of heading control, and $\alpha_x = \alpha_u$ and $\beta_x = \beta_u$ for the case of line following.

The controller parameters can be obtained from here if model based approach is used, [8]. If the closed loop is set to be equal to some desired closed loop transfer function (e.g. Bessel filter), a_3, a_2 and a_1 are desired line following closed loop transfer function parameters.

$$\frac{x}{x_{ref}} = \frac{1}{\underbrace{\frac{\alpha_x}{K_I}}_{a_3} s^3 + \underbrace{\frac{\beta_x + K_D}{K_I}}_{a_2} s^2 + \underbrace{\frac{K_P}{K_I}}_{a_1} s + 1}. \tag{12}$$

The controller parameters can then be calculated as

$$\begin{aligned} K_I &= \frac{\alpha_x}{a_3}, \\ K_P &= \alpha_x \frac{a_1}{a_3}, \\ K_D &= \alpha_x \frac{a_2}{a_3} - \beta_x \end{aligned} \tag{13}$$

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

An important issue which should be addresses when designing controllers is integrator windup, [9], [10]. The characteristic of thrusters determines the maximal thrust which can be exerted. Consequently, maximal thrust 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 behaviour. This is why integrator antiwindup techniques are implemented within the controller. The antiwindup algorithm is based on the fact that the integrator within the controller should stop integrating when controller output $u(t)$ is greater than feasible action u_{max} . This procedure is usually implemented programmatically with integration condition, [11].

IV. EXPERIMENTAL RESULTS

In this section, experimental results are presented in order to illustrate the performance of the previously proposed guidance algorithm on a real vessel. All experiments were performed in the laboratory pool at the Laboratory for Underwater Systems and Technologies, University of Zagreb. The experimental area inside the pool is limited with field of view of camera placed above the pool. The guidance algorithm is based on extracting the platform's positions and orientation from camera images. Numerous scenarios have been tested with different mission paths. Videos and results of all these paths are available online at http://labust.fer.hr/media/pladypos. This paper focuses on one of these experiments.

All the control and guidance algorithms were developed using LabVIEW and the general scheme is shown in Fig. 5. All the elements of the scheme are described in the previous sections of the paper. The experiment which is presented and analyzed in this paper consists in following three lines, as it is clearly visible from the camera view during the experiment shown in Fig. 6. Each line is defined with a starting and an ending point. The task of the laboratory platform is to move from one point to another one, following the shortest path, regardless of external disturbances.

When the platform reaches the end of the current line, automatically switching to the next line is activated. The switching between the lines is position based relatively to the ending point. When the platform is relatively close to the ending point of a line, the task of following the next line is initiated. For this purpose, a finite-state machine is developed. Each state is characterized with two points and the associated line. Switching procedure has as many states as there are lines to be followed. Switching between two lines can be compared with transition between two states and transition condition is relative distance between the platform and the end point of a line. The switching distance in this case is set to 25 pixels (which is about 5 cm).

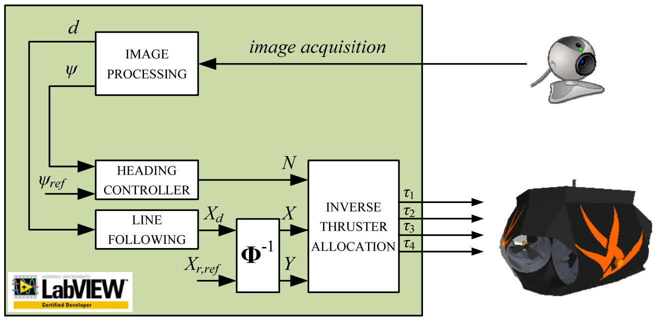


Fig. 5: Schematic representation of the implemented control and guidance algorithm.

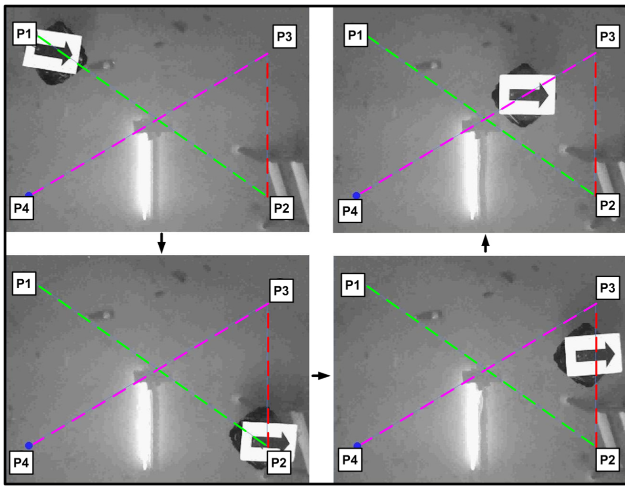


Fig. 6. View from the camera positioned above the laboratory pool during the presented experiment.

Fig. 7. shows the platform path during the experiment. Dashed lines represent three different lines to be followed. The lines are positioned so that there are two sharp turns which occurs at the moments T_2 = 20.4 s and T_3 = 33.7 s. The duration of the whole experiment is 50 s.

Throughout the whole experiment reference orientation was kept at $\psi = 90°$. For this purpose, an I-PD heading controller based on the binomial model transfer function is designed and implement. This choice of controller structure and model dynamics resulted in smooth signal at the controller output. Fig. 8.a) shows heading during the experiment. Switching to the next line did not significantly change the orientation of the platform what leads to the conclusion that the task of heading keeping is accomplished in satisfactory manner.

Commanded normalized force X_r in the direction parallel to the desired line was kept constant throughout the experiment, which resulted in a constant steady-state cruising speed u_r .

The performance of the control system can be seen in Figs 8. a), b) and c). The control error (negative distance to the line) is shown in Fig.8.b) and it is clear that after initial acceptable oscillations the platform reaches a zero steady state error relatively fast, implying that the convergence is successfully achieved. The jumps of about 5cm at moments t_1, t_2 and t_2 are a direct consequence of line switching

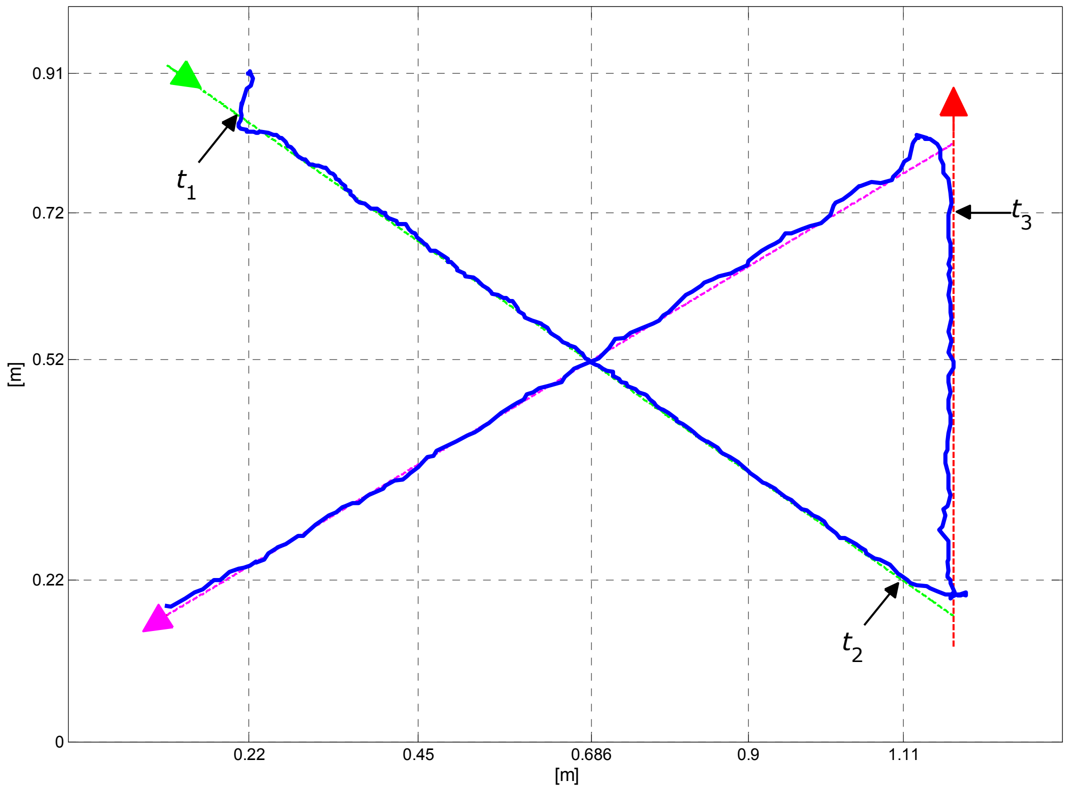


Fig. 7. The path of the marine platform during the experiment.

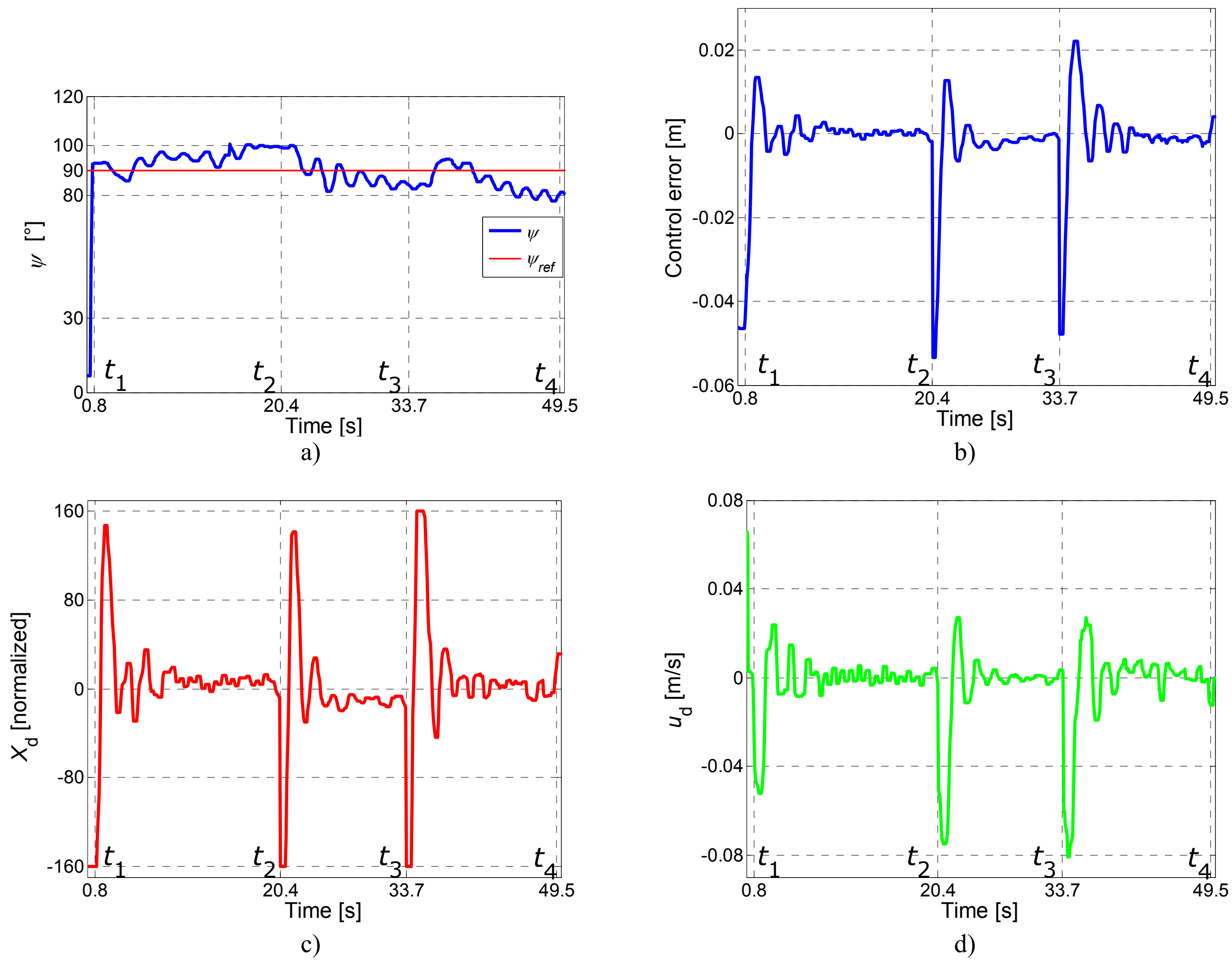


Fig. 8. Responses during the experiment: a) heading, c) control error, d) force in the direction perpendicular to the line, e) approach speed to the line

which occurs 5cm before reaching the following line, as it was mentioned before.

The line following controller output, i.e. force X_d which is perpendicular to the line, is shown in Fig. 8. c). Note in same figure that controller at some switching points generates thrust greater than the allowed thrust. The absolute maximum normalized thrust is set to 160 and for generated thrust above maximum the antiwindup algorithm is initiated, resulting in satisfactory dynamic behaviour. Fig. 8.d) shows the speed u_d in the direction perpendicular to the line, which is a consequence of the applied force X_d .

V. Conclusion and Future Work

This paper describes the continuation of the work on laboratory marine platforms. After having previously presented results obtained on a simulation model, this paper focuses on implementation of the proposed control and guidance algorithms on the real vehicle. The experiments were carried out in the Laboratory for Underwater Systems and Technologies (LABUST) at the University of Zagreb. The greatest contribution of the paper is in proving the concept of simultaneous heading control and guidance. The main task of the experiments was to simultaneously keep a predefined heading of the platform while guidance control is performed.

In the paper the authors have shown the equivalence between heading control and the proposed guidance controller. The experiments prove the functionality of the proposed controllers: fast convergence, zero steady state error and satisfactory behaviour of the antiwindup algorithm. Additional experiments showing the platform behaviour can be found online.

The future work will include implementing the developed strategies on a vehicle to be used in field conditions. The final goal of this project is to achieve cooperation between marine robotics and human divers where the proposed platform will serve as an aiding system in diver navigation.

Acknowledgment

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