Tuning Marine Vehicles' Guidance Controllers through Self-Oscillation Experiments ⋆

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Abstract: This paper demonstrates the use of self-oscillation identification experiments for tuning heading and line following controllers for marine vehicles. The identification by use of self-oscillations (IS-O) has been developed for general LTI systems and for a class of nonlinear systems and it was used for tuning guidance controllers. The guidance controllers have been tuned using the results from IS-O experiments. Heading controller algorithm that gives smooth control output is presented. The line following controller generates reference heading as output. The described methodology is applied to autonomous catamaran Charlie and the experimental results are presented in the paper. It has been demonstrated that IS-O method gives good results in field conditions and that it is time conservative. All algorithms and results presented here are a result of joint work of researchers at the Consiglio Nazionale delle Ricerche, Genova and the University of Zagreb.

Keywords: Marine systems, Guidance systems, Line following, Self-oscillation

1. INTRODUCTION

Unmanned surface vehicles (USV) have recently become an ever-growing area of research around the world. Some examples of civil uses of USVs, which can be found in literature, are fishing trawler-like vehicle ARTEMIS, catamarans ACES and AutoCAT and kayak SCOUT (all developed at MIT), Measuring Dolphin, the catamaran Delfim, boat Caravela, autonomous catamarans Charlie and Springer, etc. Since the vehicles are unmanned, they all require different levels of control. The principle level of control is motion control and it usually implies the control of yaw and surge velocities. Mid control level, or guidance control, has the task to generate reference signals for the low level controllers. This level implies heading control and trajectory following (following a time-parametrized curve) and/or path following (following a planar path without temporal constraints). Finally, the upper level of control includes mission planning. This paper will address the problems of heading control and path following. These two controllers enable marine vehicles to either keep a desired heading or follow a desired line regardless of the external disturbances (sea currents which are always present).

In order to tune control parameters in all three levels of control, process' parameters have to be identified. This can be a very time-consuming process. Usually, identification of marine vehicles' mathematical model is performed in open-loop where a great number of experiments have to be performed. Identification procedure for autonomous catamaran Charlie can be found in Caccia et al. (2006), while similar techniques used on underwater vehicles are reported in Ridao et al. (2004), Stipanov et al. (2007). All these experiments are based on finding the vehicle's drag (from steady-state experiments) and inertia (from zig-zag manoeuvres or open-loop transients). The biggest advantage of these identification techniques is that the model parameters can be determined as precisely as necessary, given enough experimental data. The disadvantages are the effects of the omnipresent external disturbances on the identified parameters, and the fact that the procedure itself is time-consuming.

The identification method which has been proposed here is based on self-oscillations, Vukic et al. (2003). The main advantage of this method is that it is performed in closed loop which means that the influence of external disturbances is minimized, Miskovic et al. (2009). In addition to that, the algorithm itself is very time conservative. On the other hand, in order to use this method, exact mathematical model of the identified process has to be known. Also, due to assumptions on the higher harmonics, the identified parameters can slightly differ from the real values. The main goal is to define and identify an approximated model of the system dynamics sufficient to allow the synthesis

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Fig. 1. Unmanned surface vehicle Charlie.

and tuning of guidance controllers and with a degree of precision compatible with the sensors on-board the vehicle.

The paper is organized as follows. Section 2 describes a method called identification by use of self-oscillations (IS-O) which can be used on linear and nonlinear systems. The application of IS-O on steering equations and closed-loop heading equations of marine vehicles is described in this section. Section 3 describes the heading and line following controller for Charlie ASV. Section 4 gives experimental results and the paper is concluded with Section 5.

1.1 Charlie USV

The Charlie USV (see Fig. 1) is a small catamaran-like shape prototype vehicle originally developed by the CNR-ISSIA for the sampling of the sea surface microlayer and immediate subsurface for the study of the sea-air interaction Caccia et al. (2005). Charlie is 2.40 m long, 1.70 m wide and weighs about 300 kg in air. The propulsion system of the vehicle is composed by a couple of DC motors (300 W @ 48 V). The vehicle is equipped with a rudder-based steering system, where two rigidly connected rudders, positioned behind the thrusters, are actuated by a brushless DC motor. The navigation instrumentation set is constituted of a GPS Ashtech GG24C integrated with compass KVH Azimuth Gyrotrac able to compute the True North. Electrical power supply is provided by four 12 V @ 40 Ah lead batteries integrated with four 32 W triple junction flexible solar panels. The on-board real-time control system, developed in C++, is based on GNU/Linux and run on a Single Board Computer (SBC), which supports serial and Ethernet communications and PC-104 modules for digital and analog I/O.

Steering Equation Steering equation is often described in literature with (1) where r is yaw rate, ψ is heading, τ_N commanded yaw torque, and parameters to be identified are yaw inertia, I_r, and drag $k_{r|r|}$.

$$\begin{aligned} I_r\dot{r} &= -\tilde{k}_{r|r|}r|r| + \tau_N \\ \dot{\psi} &= r \end{aligned} . \quad (1)$$

For Charlie ASV, the yaw torque control is achieved by controlling the rudder angle δ while propeller revolution rate n is kept constant, i.e. $\tau_N = n^2\delta$. The dynamic parameters in (1) have been identified in Caccia et al. (2006). The identification experiments have also shown that the sway speed can be neglected.

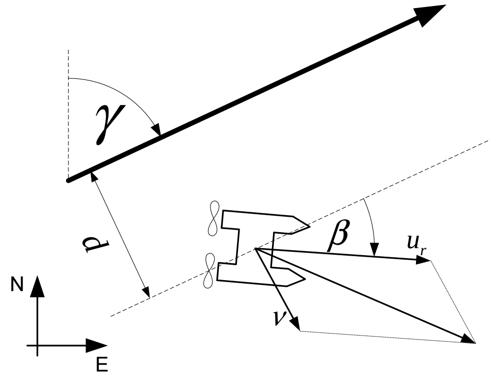

Fig. 2. Line following.

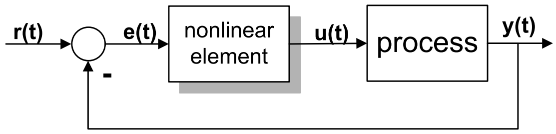

Fig. 3. Scheme for causing self-oscillations

Line Following Equations The line following approach is shown in Fig. 2. The aim is to steer the vehicle moving at surge speed u_r in such a way that its path converges to the desired line. If γ is orientation of the line that should be followed, a new parameter $\beta = \psi - \gamma$ (vehicle's orientation relative to the line) is defined. Having this in mind, the line following equations (2) - (5) can be written, where ν is drift due to sea current.

$$\dot{r} = -\frac{k_r|r|}{I_r}r|r| + \frac{1}{I_r}\tau_N \quad (2)$$

$$\dot{\psi} = r \quad (3)$$

$$\dot{\beta} = r \quad (4)$$

$$\dot{d} = u_r \sin\beta + \nu \quad (5)$$

The nonlinearities of the line-following model appear in (2) and (5). The first one can be eliminated by introducing a low level yaw rate or heading feedback. The second nonlinear equation can be linearized if angle β is assumed to be small. In this case (5) can be rewritten as $\dot{d} = u_r\beta + \nu$.

2. IDENTIFICATION BY USE OF SELF-OSCILLATIONS (IS-O)

The idea of using-self-oscillations to determine system parameters was introduced in Åstrom and Hagglund (1984) under the name "autotuning variation" method. Since then, relay-feedback systems proved to be a great tool for controller tuning in processes and for process identification, especially in pharmaceutical industry. Recent works on application of this methodology to marine vehicles (surface and underwater) can be found in Miskovic et al. (2007b), Miskovic et al. (2008) and Bibuli et al. (2008).

The self-oscillation experiment is performed in closed loop which consists of the process itself and a nonlinear element (see 3). The method is based upon forcing the system into self-oscillations. The magnitude X_m and frequency ω of the obtained self-oscillations can be used to determine process' parameters. The link between the space of process' parameters and the space of magnitudes and frequencies of self-oscillations is the Goldfarb principle given with (6), (see Vukic et al. (2003)).

$$G_P(j\omega) = -\frac{1}{G_N(X_m)} = -\frac{1}{P_N(X_m) + jQ_N(X_m)} \quad (6)$$

where $G_N(X_m) = P_N(X_m) + jQ_N(X_m)$ is the describing function of the nonlinear element, and $G_P(j\omega)$ is the process frequency characteristic. The most commonly used nonlinear element is relay with hysteresis whose describing function parameters are $P(X_m) = \frac{4C}{\pi X_m}\sqrt{1-\left(\frac{x_a}{X_m}\right)^2}$ and $Q(X_m) = -\frac{4C}{\pi X_m^2}x_a$, where C is relay output and x_a is hysteresis width. Detailed derivation of the general algorithm for determining parameters of LTI processes can be found in Miskovic et al. (2007a). The same paper includes modifications for astatic systems and systems with delays. In the following subsections only final results of the algorithm for linear systems and methodology for using the proposed method on nonlinear systems are given.

2.1 Identifying Linear Systems

Let a linear time invariant process be described by a transfer function (7) where n is the number of non-zero poles, m the number of finite zeros and $n \geq m$.

$$G_P(s) = \frac{\sum_{i=0}^{m} b_i s^i}{\sum_{i=0}^{n} a_i s^i}. \quad (7)$$

Let us suppose that the closed loop system is as in Fig. 3. Using (6), a general equation in the frequency domain that gives relation between oscillation parameters (magnitude X_m and frequency ω) and process' parameters can be constructed. In order to obtain a unique solution, we fix the value $a_0 = 1$. If all other parameters are unknown, the number of the experiments that need to be run is $\varepsilon = \left\lceil \frac{n+m+1}{2} \right\rceil$. Let us define three vectors of measurements $\omega = \left[\, \omega_1 \cdots \omega_\varepsilon \,\right]^T$, $\mathbf{P} = \left[\, P_1 \cdots P_\varepsilon \,\right]^T$ and $\mathbf{Q} = \left[\, Q_1 \cdots Q_\varepsilon \,\right]^T$ where elements P_i and Q_i are real and imaginary parts of the nonlinear element, respectively, and ω_i frequency of the self-oscillations obtained in the i_{th} experiment. The vector of unknown parameters is defined as $\mathbf{\Theta} = \left[\, \mathbf{\Theta}_a \; \mathbf{\Theta}_b \,\right]^T = \left[\, a_1 \cdots a_n \; b_0 \cdots b_m \,\right]^T$. From the above mentioned we can write (8) where $\mathbf{\Omega}_a$ and $\mathbf{\Omega}_b$ are given with (9) and (10), respectively, where $\mathbf{I}_\varepsilon = \mathbf{I}_{\varepsilon\times\varepsilon}$, $\mathbf{0}_\varepsilon = \mathbf{0}_{\varepsilon\times\varepsilon}$, $\underline{0} = \mathbf{0}_{\varepsilon\times 1}$, $\underline{I} = \mathbf{I}_{\varepsilon\times 1}$.

$$\underbrace{\left[\, \mathbf{\Omega}_a \; \mathbf{\Omega}_b \,\right]}_{\mathbf{\Omega}} \mathbf{\Theta} = \underbrace{\begin{bmatrix} -\underline{I} \\ \underline{0} \end{bmatrix}}_{\mathbf{Y}} \quad (8)$$

$$\mathbf{\Omega}_a = \begin{bmatrix} \mathbf{0}_\varepsilon & -\mathbf{I}_\varepsilon & \mathbf{0}_\varepsilon & \mathbf{I}_\varepsilon \\ \mathbf{I}_\varepsilon & \mathbf{0}_\varepsilon & -\mathbf{I}_\varepsilon & \mathbf{0}_\varepsilon \end{bmatrix} \underbrace{\begin{bmatrix} \omega.^1 & \underline{0} & \underline{0} & \underline{0} & \omega.^5 & \underline{0} & \cdots \\ \underline{0} & \omega.^2 & \underline{0} & \underline{0} & \underline{0} & \omega.^6 & \cdots \\ \underline{0} & \underline{0} & \omega.^3 & \underline{0} & \underline{0} & \underline{0} & \cdots \\ \underline{0} & \underline{0} & \underline{0} & \omega.^4 & \underline{0} & \underline{0} & \cdots \end{bmatrix}}_{n} \quad (9)$$

$$\mathbf{\Omega_b} = \begin{bmatrix} \mathbf{P}^T & \mathbf{Q}^T \\ \mathbf{Q}^T & -\mathbf{P}^T \end{bmatrix} \begin{bmatrix} \mathbf{I}_\varepsilon & \mathbf{0}_\varepsilon & -\mathbf{I}_\varepsilon & \mathbf{0}_\varepsilon \\ \mathbf{0}_\varepsilon & -\mathbf{I}_\varepsilon & \mathbf{0}_\varepsilon & \mathbf{I}_\varepsilon \end{bmatrix} \cdot \cdot \underbrace{\begin{bmatrix} \omega.^0 & \underline{0} & \underline{0} & \underline{0} & \omega.^4 & \underline{0} & \cdots \\ \underline{0} & \omega.^1 & \underline{0} & \underline{0} & \underline{0} & \omega.^5 & \cdots \\ \underline{0} & \underline{0} & \omega.^2 & \underline{0} & \underline{0} & \underline{0} & \cdots \\ \underline{0} & \underline{0} & \underline{0} & \omega.^3 & \underline{0} & \underline{0} & \cdots \end{bmatrix}}_{m+1} \quad (10)$$

The dot symbol $(.^k)$ denotes the element-wise exponent. The parameter vector $\mathbf{\Theta}$ can be found by using the formula $\mathbf{\Theta} = \mathbf{\Omega}^{-1}\mathbf{Y}$ only if there is an even number of unknown parameters. If there is an odd number of parameters, matrix $\mathbf{\Omega}$ will have one row more than there are parameters. In this case, the last row can simply be omitted, or the pseudo-inversion $\mathbf{\Theta} = \left\{\mathbf{\Omega^T\Omega}\right\}^{-1}\mathbf{\Omega^T Y}$ can be used to determine the solution. The robustness of the procedure is ensured by choosing experiments so that a set of suitable data is obtained, unlike classical identification procedures where higher dimension of the regressor guarantees greater robustness.

2.2 Identifying Nonlinear Systems

The algorithm used for nonlinear systems cannot be generalized in the same manner as for linear systems. However, let us describe the nonlinear process with

$$f(a_i, y^{(n)}, y^{(n-1)}, ..., y, u^{(m)}, u^{(m-1)}, ..., u) = 0 \quad (11)$$

where a_i are process' parameters, y is output and u input to the system. If the system is in oscillatory regime (due to the presence of the nonlinear element as in Fig. 3), the following equations can be written, under the assumption that the oscillations are symmetric $y = X_m \sin(\omega t)$, $\dot{y} = X_m j\omega \sin(\omega t), \ldots, y^{(k)} = X_m(j\omega)^k \sin(\omega t)$. Unity feedback implies that $u(t) = -G_N(X_m)y(t)$. This procedure is in fact development of the closed loop equation into Fourier series. The main assumption in the describing function method is that higher harmonics are negligible (see Vukic et al. (2003)) - this simplifies (11) and (12) is obtained.

$$f_R(a_i, X_m, \omega) + jf_I(a_i, X_m, \omega) = 0 \quad (12)$$

From here, if sufficient number of experiments is performed, unknown parameters can be determined.

2.3 Application to Yaw Degree of Freedom

Using the procedure described in 2.2, the following equation is obtained.

$$-X_m\omega^2 \sin(\omega t) I_r + X_m^2\omega^2 \cos(\omega t)|\cos(\omega t)| k_{r|r|} = G_N X_m \sin(\omega t)$$

By developing the nonlinear term into a Fourier series where only the first harmonic is retained, i.e. $\cos(\omega t)\,|\cos(\omega t)| \approx \frac{8}{3\pi}\cos(\omega t) = j\frac{8}{3\pi}\sin(\omega t)$, (13) and (14) can be derived.

$$I_r = \frac{P_N}{\omega^2} \quad (13)$$

$$k_{r|r|} = -\frac{3\pi}{8}\frac{Q_N}{X_m\omega^2} \quad (14)$$

2.4 Application to Heading Closed Loop

There are cases when heading closed loop already exists in the system and it is not possible to identify the open loop dynamics. Moreover, the only control signal which can be commanded to the system is the reference heading value. Let us suppose that heading closed loop transfer function can be written as in (15).

$$\frac{\psi}{\psi_{ref}} = \frac{b_{1\psi}s + 1}{a_{3\psi}s^3 + a_{2\psi}s^2 + a_{1\psi}s + 1} \tag{15}$$

Using the procedure presented in 2.1 with $n = 3$ and $m = 1$. Under the assumption that the heading control loop is set properly (the closed loop gain should be 1, i.e. $b_0 = 1$), two equations (obtained from the same experiment, e.g. the last one) can be omitted which results in final algorithm shown with (16). From this follows that two experiments have to be performed in order to determine unknown parameters from (15).

$$\begin{bmatrix} 0 & -\omega_1^2 & 0 & -\omega_1 Q_1 \\ 0 & -\omega_2^2 & 0 & -\omega_2 Q_2 \\ \omega_1 & 0 & \omega_1^3 & \omega_1 P_1 \\ \omega_2 & 0 & \omega_2^3 & \omega_2 P_2 \end{bmatrix} \begin{bmatrix} a_{1\psi} \\ a_{2\psi} \\ a_{3\psi} \\ b_{1\psi} \end{bmatrix} = \begin{bmatrix} -1 - P_1 \\ -1 - P_2 \\ -Q_1 \\ -Q_2 \end{bmatrix} \tag{16}$$

3. HEADING AND LINE-FOLLOWING CONTROLLER DESIGN

3.1 Heading Controller for Charlie ASV

The controller that is used is given with (17) where $\tilde{k}_{r|r|}$ is drag identified using the self-oscillation algorithm (14) and $e_\psi = \psi_{ref} - \psi$. This is an I-PD controller modified so that it would compensate for the nonlinearity which appears in the steering equation (1), Vukic and Kuljaca (2005). This controller is appropriate for control because controller output is smooth even when abrupt reference heading changes are commanded.

$$\tau_N = K_{I\psi} \int_0^t e_\psi dt - K_{P\psi}\psi - K_{D\psi}\dot{\psi} + \tilde{k}_{r|r|}\dot{\psi}\left|\dot{\psi}\right| \tag{17}$$

Using control algorithm (17), the closed loop equation is

$$\frac{\psi}{\psi_{ref}} = \frac{1}{\underbrace{\frac{I_r}{K_{I\psi}}}_{a_{3\psi}} s^3 + \underbrace{\frac{K_{D\psi}}{K_{I\psi}}}_{a_{2\psi}} s^2 + \underbrace{\frac{K_{P\psi}I_r}{K_{I\psi}}}_{a_{1\psi}} s + 1} \tag{18}$$

where $\tilde{I}_r$ is yaw inertia identified using the self-oscillation algorithm (13). The controller parameters are set so that the closed-loop transfer function is equal to the model function $G_{m\psi}(s) = \frac{1}{a_{3\psi}s^3 + a_{2\psi}s^2 + a_{1\psi}s + 1}$ which is stable. In that case, the controller parameters are given with (19).

$$K_{I\psi} = \frac{\tilde{I}_r}{a_{3\psi}}, K_{P\psi} = \frac{a_{1\psi}}{a_{3\psi}}, K_{D\psi} = \frac{a_{2\psi}}{a_{3\psi}}\tilde{I}_r \tag{19}$$

Stability of this closed loop system can be compromised if unknown process parameters are falsely identified. Having this in mind, in Miskovic et al. (2008) it is shown how saturating the derivation channel of the controller can ensure closed loop stability. To sum up, the algorithm for controller tuning is as follows:

- I Perform one self-oscillation experiment on open loop steering system (1) and determine magnitude X_m and frequency ω of self-oscillations.
- II Calculate $\tilde{I}_r$ and $\tilde{k}_{r|r|}$ using (13) and (14).
- III Define desired closed loop dynamics ($a_{3\psi}$, $a_{2\psi}$ and $a_{1\psi}$).
- IV Calculate controller parameters using (19) and implement the controller using (17).

3.2 Line-Following Controller

Here we present a line following approach which is suitable if heading control has already been achieved or open-loop steering equation cannot be identified and only closed-loop heading equation parameters can be determined. In other words, heading controller parameters cannot be tuned, but have already been set. This means that only one tunable controller exists, and that is the line-following controller which gives reference heading, ψ_{ref}, as output. The overall control scheme using this approach is shown in Fig. 4.

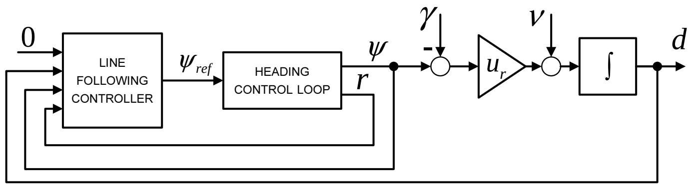

Fig. 4. Line following control structure.

If heading control loop is closed using a P-D controller than it has two poles and no finite zeros. If I-PD controller is used than the closed loop has three poles without finite zeros. Now let's assume that the heading controller is of unknown structure. For the sake of generality, an assumption is made that the closed loop heading control can be approximated with three poles and one finite zero giving the transfer function in a form (20).

$$\frac{\psi}{\psi_{ref}} = \frac{b_{1\psi}s + 1}{a_{3\psi}s^3 + a_{2\psi}s^2 + a_{1\psi}s + 1} \tag{20}$$

The parameters of this transfer function are not known so two self-oscillation experiments have to be carried out as described in 2.4. Using (16), unknown parameters can be identified. For the purpose of controller tuning, we can simplify this transfer function with two poles and a zero. In short, first it is necessary to find the real pole and than the following approximation can be made

$$\frac{\psi}{\psi_{ref}} = \frac{b_{1\psi}s + 1}{(-\frac{1}{p}s + 1)(\frac{1}{\omega^2}s^2 + \frac{2\zeta}{\omega}s + 1)} \approx \frac{\bar{b}_{1\psi}s + 1}{\bar{a}_{2\psi}s^2 + \bar{a}_{1\psi}s + 1}$$

where $\bar{b}_{1\psi} = b_{1\psi} + \frac{1}{p}$, $\bar{a}_{2\psi} = \frac{1}{\omega^2}$ and $\bar{a}_{1\psi} = \frac{2\zeta}{\omega}$.

The line-following controller is than given with (21).

$$\psi_{ref} = -K_\psi\psi - K_r r - K_d d + K_{Id}\int_0^t (d_{ref} - d)\, dt \tag{21}$$

According to Fig. 4, open loop transfer function is given with $\frac{d}{\psi_{ref}} = \frac{u_r}{s}\frac{\psi}{\psi_{ref}}$ which yields the closed loop transfer function given with (22) with $a_0 = \frac{u_r K_{Id}}{\bar{a}_{2\psi}+\bar{b}_{1\psi}K_r}$, $a_1 = \frac{u_r K_d+\bar{b}_{1\psi}K_{Id}u_r}{\bar{a}_{2\psi}+\bar{b}_{1\psi}K_r}$, $a_2 = \frac{1+K_\psi+\bar{b}_{1\psi}K_d u_r}{\bar{a}_{2\psi}+\bar{b}_{1\psi}K_r}$ and $a_3 = \frac{\bar{a}_{1\psi}+K_r+\bar{b}_{1\psi}K_\psi}{\bar{a}_{2\psi}+\bar{b}_{1\psi}K_r}$.

$$\frac{d}{d_{ref}} = \frac{\left(\bar{b}_{1\psi}s+1\right)a_0}{s^4+a_3s^3+a_2s^2+a_1s+a_0} \quad (22)$$

From here, the controller parameters can be calculated using matrix equation (23).

$$\begin{bmatrix} 1-a_3\bar{b}_{1\psi} & \bar{b}_{1\psi} & 0 & 0 \\ -a_2\bar{b}_{1\psi} & 1 & \bar{b}_{1\psi}u_r & 0 \\ -a_1\bar{b}_{1\psi} & 0 & u_r & u_r b_{1\psi} \\ -a_0\bar{b}_{1\psi} & 0 & 0 & u_r \end{bmatrix} \begin{bmatrix} K_r \\ K_\psi \\ K_d \\ K_{Id} \end{bmatrix} = \begin{bmatrix} a_3\bar{a}_{2\psi}-\bar{a}_{1\psi} \\ a_2\bar{a}_{2\psi} \\ a_1\bar{a}_{2\psi} \\ a_0\bar{a}_{2\psi} \end{bmatrix} \quad (23)$$

This procedure can also be used when heading controller structure and parameters are known and tunable. Nevertheless, this approach enables tuning the line-following controller without changing the heading controller parameters. The algorithm can be summarized as follows:

I Perform two self-oscillation experiments on a closed loop steering system (15) and determine magnitudes X_{m1}, X_{m2} and frequencies ω_1, ω_2 of self-oscillations.
II Calculate $a_{3\psi}$, $a_{2\psi}$, $a_{1\psi}$ and $b_{1\psi}$ using (16).
III Calculate approximated parameters $\bar{a}_{2\psi}$, $\bar{a}_{1\psi}$ and $\bar{b}_{1\psi}$.
IV Define desired line following closed loop dynamics (a_3, a_2, a_1 and a_0).
V Calculate line-following controller parameters using (23) and the identified parameters.
VI Implement line following controller using (21).

4. EXPERIMENTAL RESULTS

The following section will give experimental results for closed loop heading response and line following responses. All results are obtained using the IS-O method. For the line following controller, we present results when inner control loop (heading controller) has two different structures: Case 1 is achieved by a P-D controller and Case 2 by a I-PD heading controller. These experiments were performed to demonstrate that the proposed methodology works for various inner loop control structures.

4.1 Heading Controller

The identification experiments was run so that the relay output (rudder angle δ) was $C = 25°$ and hysteresis width was $x_a = 10°$. The experiment is shown in Fig. 5. The complete identification experiment finished after 5 oscillations which took about $80s$. The I-PD controller given with (17) was tuned so that the desired closed loop function is Bessel filter with characteristic frequency $0.45s^{-1}$. Heading responses are shown in Fig. 6. Heading response has little overshoot and steady-state error does not exist. Rudder activity in steady-state is low, which is one of the strongest specifications while designing the control system in order to minimize energy consumption and mechanical stress.

4.2 Line-following Controllers

In these identification experiments, relay output C is commanded heading angle ψ_{REF}. Two experiments with

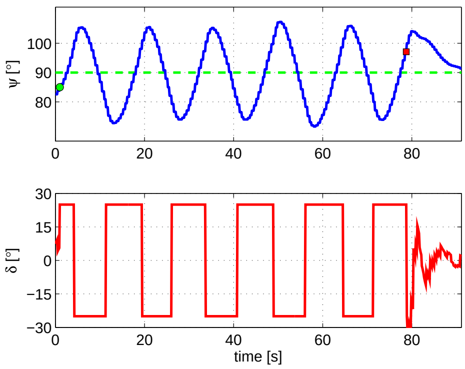

Fig. 5. I-SO applied to yaw steering.

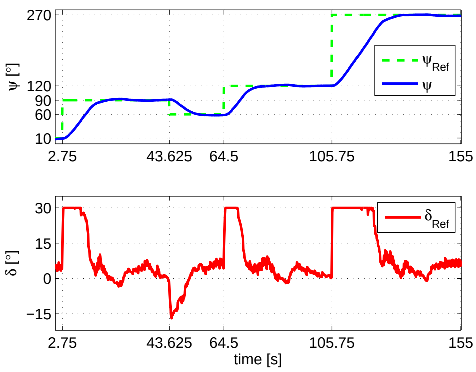

Fig. 6. Heading and rudder angle response.

Table 1. Relay parameters for cases 1 & 2.

Case	IS-O Experiment #1	IS-O Experiment #2
1	$C = (-90 \pm 20)°$, $x_a = 5°$	$C = (90 \pm 15)°$, $x_a = 5°$
2	$C = (-90 \pm 10)°$, $x_a = 5°$	$C = (90 \pm 30)°$, $x_a = 10°$

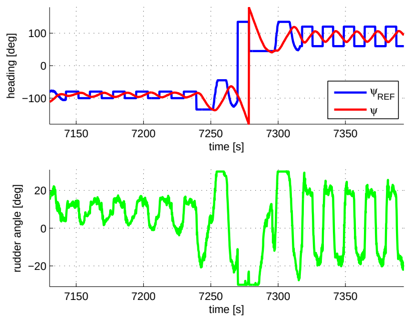

Fig. 7. I-SO applied to heading closed loop - Case 2.

relay parameters have to be run in order to identify the inner closed loop transfer function. These parameters are shown in Table 1. The relay parameters were chosen in such a way that the rudder during the experiments never saturates. This is very important because only in that case true inner loop dynamics can be identified. The experiment is shown in Fig. 7. Here we give responses only for IS-O experiment for Case 2 for brevity. Each identification experiment takes about $1.5min$.

The line following controller given with (21) was tuned so that the desired closed loop function is Bessel filter. For both cases the characteristic frequency of the fourth

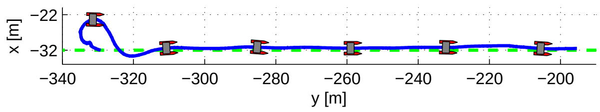

Fig. 8. U-turn and path following - Case 1.

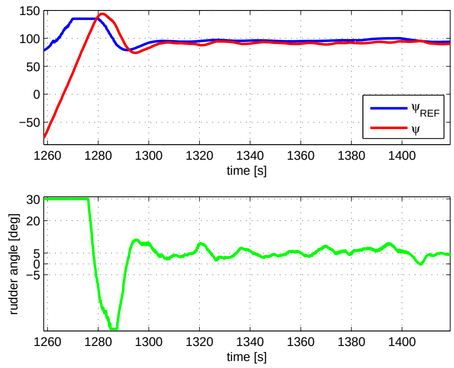

Fig. 9. Responses during path in Fig. 8 (Case 1).

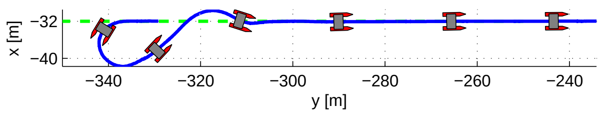

Fig. 10. U-turn and path following - Case 2.

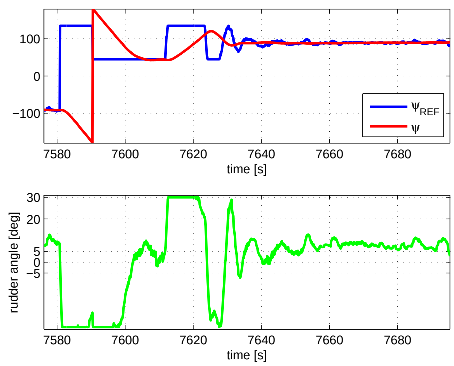

Fig. 11. Responses during path in Fig. 10 (Case 2).

order Bessel filter was chosen so that the rudder activity in steady-state is low. For Case 1, the U-turn path of the vehicle is shown in Fig. 8 while the commanded heading ψ_{REF}, heading ψ and rudder angle δ are shown in Fig. 9. For Case 2, the U-turn path of the vehicle is shown in Fig. 10 while ψ_{REF}, ψ and δ are shown in Fig. 11. It is clear that, for both cases, rudder activity in steady-state is minimal, and that the line following is without error.

5. CONCLUSION

The paper presents the use of IS-O method applied to designing guidance controllers - heading and path following. The proposed method was applied to autonomous catamaran Charlie and has proved to be simple and feasible in field conditions. During the IS-O experiments it was shown that rudder must not saturate in order to obtain properly identified model. The methodology was used to tune path following controller which outputs reference heading. Two different, pre-tuned, inner control loop dynamics were identified using the proposed method and the designed controller demonstrated satisfactory performance.

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