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ILOS Guidance - Experiments and Tuning

Marco Bibuli * Walter Caharija ** Kristin Y. Pettersen **
Gabriele Bruzzone * Massimo Caccia * Enrica Zereik *

* *CNR-ISSIA Via De Marini 6, 16149 Genova, Italy. e-mail: {marco.bibuli, gabriele.bruzzone, massimo.caccia, enrica.zereik}@ge.issia.cnr.it*
** *Dept. of Engineering Cybernetics, NTNU, NO-7491 Trondheim, Norway. e-mail: {walter.caharija, kristin.y.pettersen}@itk.ntnu.no*

Abstract: A recently proposed Integral Line-of-Sight (ILOS) guidance law is applied to an underactuated Unmanned Semi-Submersible Vehicle (USSV) for path following of straight lines. Derived from the popular Line-of-Sight guidance, the ILOS methods adds integral action to increase robustness with respect to environmental disturbances such as sea currents, wind and waves that unavoidably affect maritime operations. Integral action makes the vehicle side-slip and hence compensate for the disturbances acting in the underactuated sway direction. Furthermore, the integrator of the ILOS implemented in this paper has embodied, analytically derived, anti-windup properties. It is shown that even if an accurate model of the vessel dynamics is not available, a simple kinematic model and a few test runs give enough information to correctly choose the guidance law parameters. Data from sea trials are presented to verify the ILOS theory and give an experimentally based understanding of the behavior of the USSV when different look-ahead distances and integral gains are used.

Keywords: path following, ILOS guidance, underactuated vessel, experiments

1. INTRODUCTION

Automation of operations at sea is a technological driving factor in several aspects of the maritime industry and any development in this field can significantly improve safety, sustainability and effectiveness of such activities. Given the world's increasing demand for energy and food, the off-shore oil and gas industry has positioned itself at the fore-front of this trend (Nelson, 2010) but other activities, like sea shipping, offshore wind power production, fishing, fish-farming and coastal surveillance are following close. The joint use of Unmanned Surface and Aerial Vehicles (USVs and UAVs) and Autonomous Underwater Vehicles (AUVs) shows very promising results and tools to successfully run different integrated missions are available (Pinto et al., 2006). Furthermore, Bruzzone et al. (2013) demonstrated that cooperating USVs can perform emergency ship towing operations in the open sea or in a confined harbor.

Path following is a motion control scenario where a vehicle has to follow a predefined trajectory without any time constraints (Fossen, 2011). It is indeed a very wide concept and path following applications include wheeled mobile robots, marine vehicles and aerial vehicles (Sordalen and De Wit, 1993; Kaminer et al., 2006; Da Silva and Sousa, 2010). In particular, the field of marine control has delivered several linear as well as nonlinear control solutions for path following of fully actuated and underactuated ships. Nonlinear control techniques are applied in Indiveri et al. (2000) to control the yaw rate of an underactuated ship and hold a desired course. Inspired by Hauser and Hindman (1997), Encarnação and Pascoal (2001) propose a backstepping solution for trajectory tracking and path following of underactuated marine vehicles. Other relevant backstepping and Lyapunov-based approaches are found in Fossen and Berge (1997), Lapierre et al. (2003), Do et al. (2002) and Li et al. (2009). The Line-of-Sight (LOS) guidance is used in Papoulias (1991), Breivik and Fossen (2004), Fredriksen and Pettersen (2004) and Lekkas and Fossen (2012) to achieve path following of fully actuated as well as underactuated ships. Observers and adaptive techniques are introduced to compensate for ocean currents and hence achieve different path following and navigation tasks of marine vessels and underwater vehicles in Antonelli et al. (2003), Bibuli et al. (2008), Misković et al. (2009), Morgado et al. (2011) and Zereik et al. (2013). To render the popular LOS guidance robust with respect to ocean currents, Aguiar and Pascoal (1997) propose a modification based on measurements of the vehicle velocity, while integral action is added to the LOS reference generator in Børhaug et al. (2008), Breivik and Fossen (2009), Caharija et al. (2012a) and Caharija et al. (2012b).

In this paper the ILOS guidance developed in Caharija et al. (2012a) is applied to the underactuated CART USSV developed for emergency towing operations by CNR-ISSIA in Italy in cooperation with other international partners (Bruzzone et al., 2013). Since a model of the vehicle dynamics is not available, a short theoretical analysis of the ILOS method applied to a simple kinematic model is first presented. This analysis is based on previous work presented by the authors in Caharija et al. (2012c) and

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gives some simple but fundamental technical understanding of the ILOS guidance. The analytic guidance law is then discretized and converted into a suitable algorithm for the CART vehicle. Sea trials are performed where the vehicle is required to move along a desired straight-line path. Different combinations of the guidance law parameters are tested for different speeds/thrust levels. The results show that the vehicle converges and follows the desired course despite the environmental disturbances. As expected, side-slipping is performed by the guidance law in order to compensate for the drift and thus hold the vehicle on the path. The paper is organized as follows: Section 2 presents the ILOS guidance law applied to a kinematic model while Section 3 gives a brief description of the CART USSV. The experimental results are presented in Section 4. Conclusions are given in Section 5.

2. THE ILOS GUIDANCE

In this section the ILOS guidance is presented and applied to a kinematic model. The relative velocity approach from Caharija et al. (2012a) is used while the theoretical analysis is derived from Caharija et al. (2012c).

2.1 The Environmental Disturbance Model

The effect of environmental disturbances is incorporated into a kinematic ocean current model:

Assumption 1. The ocean current $\boldsymbol{V}_c \triangleq [V_x, V_y]^T$ is defined in the inertial frame i and is assumed constant, irrotational and bounded, i.e. $\exists V_{\max} > 0 \mid V_{\max} \geq \sqrt{V_x^2 + V_y^2}$.

2.2 The Kinematic Model and the Control Objectives

The control system is required to make the vehicle follow a given straight line $\mathcal{P}$ in the presence of unknown and constant ocean currents. In addition, it should also maintain a desired constant surge relative velocity $U_{rd} > 0$. Notice that the relative surge velocity U_{rd} is the velocity of the USV with respect to the water in the surge direction of the body-fixed frame b. The state of the USV is given by the vector $\boldsymbol{\eta} \triangleq [x, y]$ and represents the coordinates of the vehicle in the inertial frame i. Following Caharija et al. (2012c), where the underactuated and actuated dynamics are neglected, the kinematic model becomes:

$$\dot{x} = U_{rd}\cos(\psi_d) + V_x, \tag{1}$$

$$\dot{y} = U_{rd}\sin(\psi_d) + V_y. \tag{2}$$

The term ψ_d is the control input and is the yaw angle provided by the aft rudders. Notice that (1-2) does not consider the kinetics since a model of the CART USSV is not available, and hence the dynamics of the speed and yaw controllers are neglected. Therefore, the vehicle described in (1-2) is assumed to hold a desired relative surge velocity U_{rd} as well as a desired heading ψ_d (Caharija et al., 2012c). The general underactuated case with a full dynamic model is presented in Caharija et al. (2012a) and Caharija et al. (2012b).

Remark 1. A detailed explanation of why it is possible to neglect both the actuated and underactuated dynamics as a first approximation is found in Caharija et al. (2012c). This method is very valuable when designing new guidance laws or when the model of the vessel is not available.

The following assumption is necessary to achieve path following in presence of currents acting in any direction:

Assumption 2. The propulsion system is capable of delivering enough thrust so that U_{rd} satisfies $U_{rd} > V_{\max}$.

Remark 2. For most vehicles Assumption 2 is easy to meet since currents have usually intensities of less than 1 [m/s].

To simplify the analysis without any loss of generality, the inertial reference frame i is placed such that its x-axis is aligned with the desired path, giving $\mathcal{P} \triangleq \{(x, y) \in \mathbb{R}^2 : y = 0\}$. The vessel y coordinate then corresponds to the cross-track error and the control objective is:

$$\lim_{t\to\infty} y(t) = 0. \tag{3}$$

2.3 The ILOS Reference Generator

The ILOS guidance presented in Børhaug et al. (2008) and Caharija et al. (2012a) is used to set the desired heading angle and make the vehicle follow the x-axis:

$$\psi_{ILOS} \triangleq -\tan^{-1}\left(\frac{y + \sigma y_{\text{int}}}{\Delta}\right), \quad \Delta,\ \sigma > 0, \tag{4a}$$

$$\dot{y}_{\text{int}} = \frac{\Delta y}{(y + \sigma y_{\text{int}})^2 + \Delta^2}, \tag{4b}$$

where Δ is the look-ahead distance and σ is the integral gain. Both are constant design parameters. The integral effect is meant to give a nonzero angle (4a) at equilibrium, since the vehicle is underactuated and hence it cannot compensate for disturbances in the sway direction. This allows the vessel to side-slip while staying on the desired course. Therefore, it is possible to write $\psi_d(t) \to \psi_{ss} \in (-\pi/2, \pi/2)$. The value of ψ_{ss} will be specified later. Notice that the law (4b) gives less integral action when the vehicle is far from $\mathcal{P}$, reducing the risk of wind-up effects.

2.4 Stability of the Closed Loop Kinematic System

Theorem 1. Given a USV whose kinematics are defined by (1-2), if Assumptions 1-2 hold and if the gain σ satisfies:

$$0 < \sigma < U_{rd} - V_{\max}, \tag{5}$$

then the guidance law (4) achieves (3). The reference signal ψ_d is defined by (4a) and $\psi_{ss} \triangleq -\tan^{-1}(V_y/\sqrt{U_{rd}^2 - V_y^2})$.

Proof. A brief presentation of the proof is presented here. For more details see Caharija et al. (2012c). The dynamics of the cross track error y are obtained from (2) and (4b), where $\psi_d \triangleq \psi_{ILOS}$:

$$\dot{y} = -U_{rd}\frac{y + \sigma y_{\text{int}}}{\sqrt{(y + \sigma y_{\text{int}})^2 + \Delta^2}} + V_y, \tag{6}$$

$$\dot{y}_{\text{int}} = \frac{\Delta y}{(y + \sigma y_{\text{int}})^2 + \Delta^2}. \tag{7}$$

The equilibrium point of the system (6-7) is $y_{\text{int}}^{\text{eq}} = (\Delta V_y)/(\sigma\sqrt{U_{rd}^2 - V_y^2})$, $y^{\text{eq}} = 0$ and the error variables $e_1 \triangleq y_{\text{int}} - y_{\text{int}}^{\text{eq}}$, $e_2 \triangleq y + \sigma e_1$ are introduced:

$$\dot{e}_1 = -\frac{\Delta\sigma e_1}{D(e_2)^2} + \frac{\Delta e_2}{D(e_2)^2}, \tag{8}$$

$$\dot{e}_2 = -\frac{\Delta\sigma^2 e_1}{D(e_2)^2} - \frac{(U_{rd}D(e_2) - \sigma\Delta)e_2}{D(e_2)^2} + V_y f(e_2), \tag{9}$$

where $D(e_2) \triangleq \sqrt{(e_2 + y_{\text{int}}^{\text{eq}})^2 + \Delta^2}$ while $f(e_2)$ is given in Caharija et al. (2012c) and satisfies the bound $|f(e_2)| \leq |e_2|/\sqrt{(e_2 + \sigma y_{\text{int}}^{\text{eq}})^2 + \Delta^2}$. Given the quadratic Lyapunov function candidate $V \triangleq 1/2\sigma^2 e_1^2 + 1/2 e_2^2$, it is shown in Caharija et al. (2012c) that its time-derivative $\dot{V}$ satisfies:

$$\dot{V} \leq -\sigma^2 \Delta |\bar{e}_1|^2 - \Delta_z (U_{rd} - V_{\max} - \sigma)|\bar{e}_2|^2 \triangleq -W, \quad (10)$$

where the notation $\bar{e}_1 \triangleq e_1/\sqrt{(e_2 + \sigma y_{\text{int}}^{\text{eq}})^2 + \Delta^2}$ and $\bar{e}_2 \triangleq e_2/\sqrt{(e_2 + \sigma y_{\text{int}}^{\text{eq}})^2 + \Delta^2}$ is used. It is straightforward to show that Assumptions 1-2 and (5) guarantee positive definiteness of W. Hence, according to the same Lyapunov arguments of Caharija et al. (2012c), the system (6-7) is uniformly globally asymptotically stable (UGAS) and uniformly locally exponentially stable (ULES). □

Remark 3. Notice that the analysis above gives well defined bounds upon the integral gain σ but it does not provide any criteria for how to choose the look ahead distance Δ. The tuning of Δ is therefore made at the experimental stage. As a rule of thumb, the USV length is set as a lower bound for Δ (Caharija et al., 2012c).

Remark 4. The control system on the CART USSV does not provide the option to directly control its relative velocity. However, the thrust level (RPMs) can be set. This is the closest available option to relative velocity control.

3. VEHICLE DESCRIPTION

The CART USSV, developed by CNR-ISSIA and shown in Figure 1, is a 0.9 m long and 0.75 m wide robotic platform. Thrust is provided by four DC brushless motors coupled to 4-bladed propellers, capable to deliver a maximum bollard pull of about 15 Kg. A central cylindric canister contains all the electronics and sensors. In particular, the USSV is equipped with a single board computer running a GNU/Linux based real-time control application, a GPS system providing absolute position measurements and an Attitude and Heading Reference System (AHRS). Another cylinder contains a set of lithium ions batteries. At full charge the vehicle can operate continuously for 5 − 6 hours. The communication between the vehicle and the remote control station is provided by a 2.4 Ghz WiFi link.

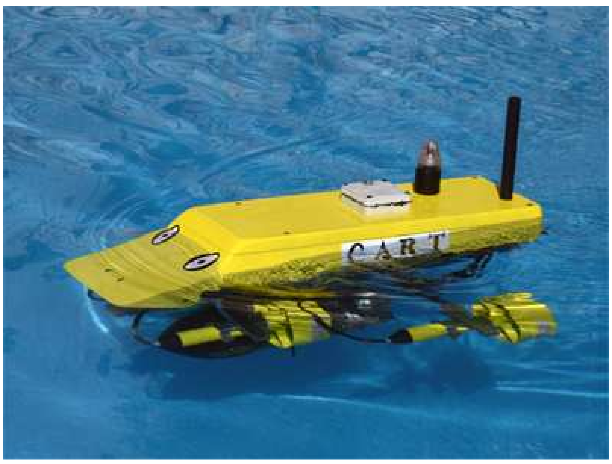

Fig. 1. The CART USSV during operations.

For the purpose of exploiting the CART vehicle as a platform for the development of advanced navigation, guidance and control techniques, as well as payload carrier in different experimental campaigns, the software control architecture has been upgraded and an extensively tested and well known software system has been ported. In particular the control architecture of the CNR-ISSIA Charlie USV (Bibuli et al., 2008) has been customized and transferred on the CART USSV as well. The porting operation involved the development of a new *driver* layer, thus creating the connection between the hardware and the software architecture. No rearrangement of the architecture higher levels was required, due to the complete decoupling from hardware-related issues.

The CART USSV has a very high level of maneuverability. This, together with its high power-to-weight ratio and the smart placement of the motors, allows to choose the thrust/torque mapping in such a way that all the engines deliver thrust, but only the two rear ones contribute to torque generation. This makes the motion of the vehicle smoother and less subjected to yaw jerks. Since a validated dynamic model of the employed vehicle is not yet available, a simple Proportional-Derivative (PD) control scheme has been implemented to provide the basic auto-heading feature. The controller parameters have been set through on the field tests, obtaining an overshoot-free response in normal sea conditions.

4. EXPERIMENTAL RESULTS

With the aim of evaluating the performance of the proposed guidance technique, an extensive set of sea trials has been carried out. In these experiments the vehicle is required to move along two geo-referenced parallel straight lines in order to exhibit the transient response and the steady-state behavior of the guidance system. At the beginning, the first reference line is fed to the ILOS. After a while, a command is sent to make the vehicle turn back and converge to the second line. The procedure is repeated for different parameter settings and speeds. In particular, path following of the reference lines is executed at different speed regimes, to highlight the response dependency on the speed profile. The guidance module has been also tested for different values of Δ and σ, to separately analyze the response as function of the two parameters. This allows precise tuning and selection of the best setting for the practical exploitation of the proposed guidance. The reference paths are the two parallel straight lines l_1 and l_2 defined by a point and an angular orientation on the local horizontal Cartesian plane:

l_1: point (60m ; -50m) , orientation $-130°$
l_2: point (70m ; -50m) , orientation $50°$

The first set of experiments focuses on the evaluation of the ILOS for different speeds held by the vehicle in motion. Figure 2 shows the comparison between different tests where the guidance system, characterized by the same parameter setting ($\Delta = 5.0$ and $\sigma = 0.1$), is commanded to track the two reference lines at different surge thrust regimes. The commanded surge thrust values are 20%, 30%, 40% and 50% of the total available thrust provided by the motors. These values correspond to average steady state speeds of 0.6, 0.8, 0.9 and 1.0 m/s, respectively. Notice that the values $\Delta = 5.0$ and $\sigma = 0.1$ are selected since they provide satisfactory path following performance.

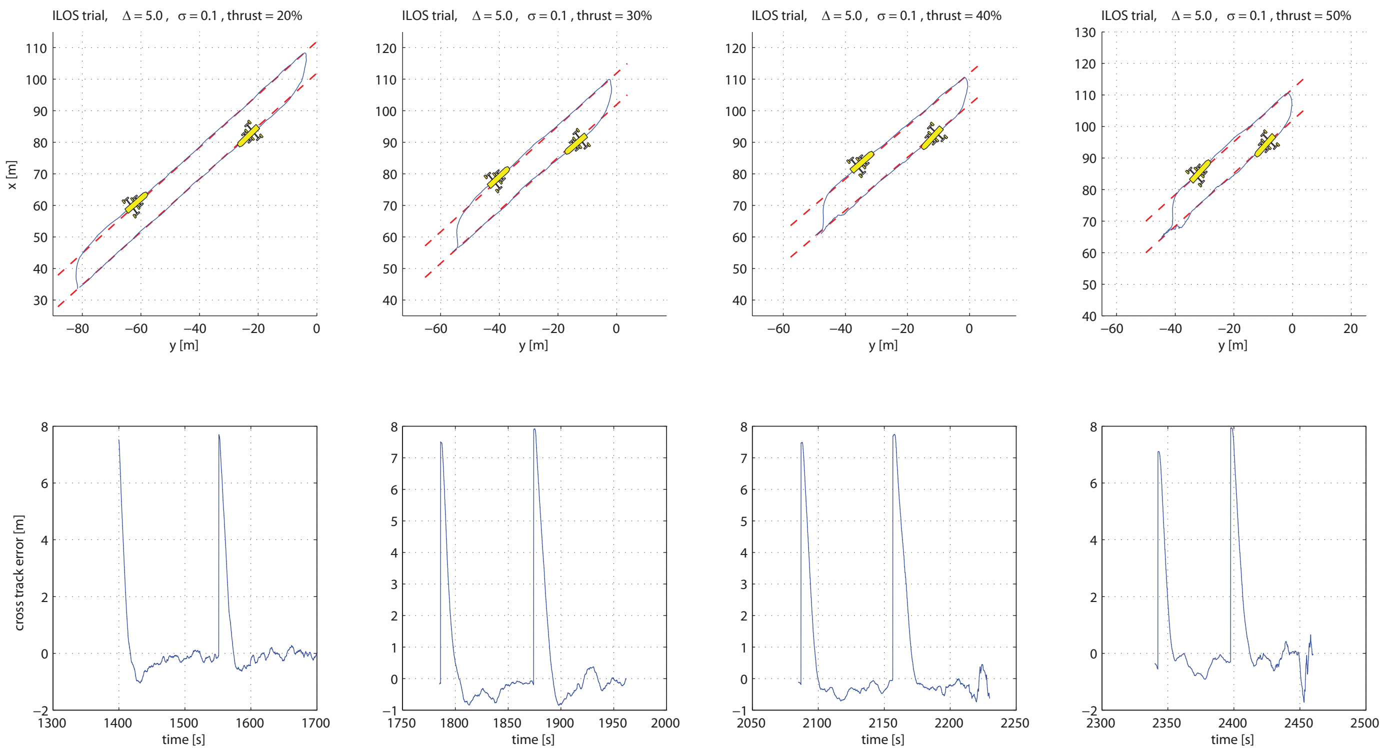

Fig. 2. Speed dependency evaluation - the upper plots show the motion of the vehicle (blue) along the reference lines (red); the lower plots show the cross track error variation in time.

As shown in the plots of Figure 2, the vehicle converges and tracks the reference lines. Notice how every change of the reference line is followed by a peak in the cross track error. The ILOS guidance quickly reacts and takes the vehicle onto the new line. In particular, in the error plots of Figure 2 it can be noticed that during steady-state the cross-track error is always less than 1 m, with no significant difference with respect to the actual surge thrust setting. The statistical analysis reported in Table 1 supports this argument, indicating comparable standard deviation values during steady-state response. The steady-state mean values are in the order of $0.2 \div 0.3$, m thus indicating a practical rejection to constant external disturbances. It should be mentioned that during the experiments the environmental conditions were characterized by a light breeze and small waves. In

Table 1. Speed dependency evaluation statistics

thrust [%]	mean value [m]	standard deviation [m]
20	-0.1709	0.2762
30	-0.2193	0.3242
40	-0.2131	0.2546
50	-0.1847	0.3148

particular, a careful post mission analysis of the telemetry data reveals a difference of about 5° between the reference line orientation and the desired vehicle heading, generated by the guidance system, when the vehicle is on path. This side-slip is due to the integral part of the guidance (4) that compensates for the drift caused by sea currents, wind and waves. This is in accordance with the theoretical analysis presented in Caharija et al. (2012a) and Caharija et al. (2012b).

The second and third experiments analyze the sensitivity of the guidance system with respect to the Δ and σ parameters. Figure 3 shows the motion of the vehicle where the parameter Δ is set to 2.0 m, 5.0 m and 10.0 m. Interpreting the parameter Δ as the look-ahead distance, the effect of increasing such value induces a slower convergence onto the reference line, while Δ values approaching the size of the vehicle indeed reduce the convergence time, but introduce small oscillations during the on-path motion, caused by overshooting. This oscillating behavior at short Δ is simulated in Caharija et al. (2012c) and is foreseen by the more detailed Lyapunov analysis of the complete kinematic-dynamic system in Caharija et al. (2012a) where a lower bound for Δ is analytically derived.

The results of the third experiment are shown in Figure 4. In Figure 4 the vehicle behavior is assessed with respect to different values of the integral gain σ. The guidance law is tested for the following values of σ: 0.05, 0.1 and 0.5. As it can be observed, with lower integral gains the guidance system loses its efficiency to reject constant disturbances, i.e. the side-slipping of the vehicle is not enough to completely compensate for the drift, while increasing the value of σ leads to overshoots in the transient response during the convergence phase. Notice that the condition (5), derived from the Lyapunov analysis of Section 2, gives an upper bound upon the choice of σ. The experimental results confirm what the theoretical analysis predicted: a high σ gain causes unstable behaviors.

5. CONCLUSIONS

In this paper the experimental validation of the ILOS guidance law has been carried out, proving its reliability in real applications at sea. The performance of the proposed guidance technique has been analyzed at different speed regimes and parameter settings, to observe the response of the system. The results are in accordance with the theory developed by the authors. Future developments include the introduction of a dynamic model of the USSV and the comparison of the ILOS with other guidance methods.

REFERENCES

Aguiar, A. and Pascoal, A.M. (1997). Modeling and control of an autonomous underwater shuttle for the transport of benthic laboratories. In *Proc. of MTS/IEEE Conference OCEANS '97*, 888–895.

Antonelli, G., Caccavale, F., Chiaverini, S., and Fusco, G. (2003). A novel adaptive control law for underwater vehicles. *IEEE Transactions on Control Systems Technology*, 11(2), 221–232.

Bibuli, M., Bruzzone, G., Caccia, M., Indiveri, G., and Zizzari, A. (2008). Line following guidance control: Application to the charlie unmanned surface vehicle. In *Proc. of IEEE/RSJ International Conference on Intelligent Robots and Systems*, 3641–3646.

Breivik, M. and Fossen, T.I. (2004). Path following of straight lines and circles for marine surface vessels. In *Proc. of the 6th IFAC Conference on Control Applications in Marine Systems*, 65–70.

Breivik, M. and Fossen, T.I. (2009). *Guidance Laws for Autonomous Underwater Vehicles*, chapter 4, 51–76. A. V. Inzartsev, IN-TECH Education and Publishing.

Bruzzone, G., Bibuli, M., Caccia, M., and Zereik, E. (2013). Cooperative robotic maneuvers for emergency ship towing operations. In *Proc. of MTS/IEEE Conference OCEANS '13 - Bergen*, 1–7.

Børhaug, E., Pavlov, A., and Pettersen, K.Y. (2008). Integral LOS control for path following of underactuated marine surface vessels in the presence of constant ocean currents. In *Proc. of the 47th IEEE Conference on Decision and Control*, 4984–4991.

Caharija, W., Candeloro, M., Pettersen, K.Y., and Sørensen, A.J. (2012a). Relative velocity control and integral LOS for path following of underactuated surface vessels. In *Proc. of the 9th IFAC Conference on Manoeuvring and Control of Marine Craft.*

Caharija, W., Pettersen, K.Y., Gravdahl, J.T., and Børhaug, E. (2012b). Path following of underactuated autonomous underwater vehicles in the presence of ocean currents. In *Proc. of the 51st IEEE Conference on Decision and Control*, 528–535.

Caharija, W., Pettersen, K.Y., Gravdahl, J.T., and Sørensen, A.J. (2012c). Topics on current compensation for path following applications of underactuated underwater vehicles. In *Proc. of IFAC Workshop on Navigation, Guidance and Control of Underwater Vehicles*, 184–191.

Da Silva, J. and Sousa, J.B. (2010). A dynamic programming approach for the motion control of autonomous vehicles. In *Proc. of the 49th IEEE Conference on Decision and Control*, 6660–6665.

Do, K., Jiang, Z., and Pan, J. (2002). Universal controllers for stabilization and tracking of underactuated ships. *Systems & Control Letters*, 47(4), 299 – 317.

Encarnação, P. and Pascoal, A.M. (2001). Combined trajectory tracking and path following: an application to the coordinated control of autonomous marine craft. In *Proc. of the 40th IEEE Conference on Decision and Control*, 964–969.

Fossen, T.I. (2011). *Handbook of Marine Craft Hydrodynamics and Motion Control.* John Wiley & Sons, Inc., Hoboken, NJ.

Fossen, T. and Berge, S. (1997). Nonlinear vectorial backstepping design for global exponential tracking of marine vessels in the presence of actuator dynamics. In *Proc. of the 36th IEEE Conference on Decision and Control*, 4237–4242.

Fredriksen, E. and Pettersen, K.Y. (2004). Global κ-exponential way-point manoeuvering of ships. In *Proc. of the 43rd IEEE Conference on Decision and Control*, 5360–5367.

Hauser, J. and Hindman, R. (1997). Aggressive flight maneuvers. In *Proc. of the 36th IEEE Conference on Decision and Control*, volume 5, 4186–4191.

Indiveri, G., Aicardi, M., and Casalino, G. (2000). Robust global stabilization of an underactuated marine vehicle on a linear course by smooth time-invariant feedback. In *Proc. of the 39th IEEE Conference on Decision and Control*, 2156–2161.

Kaminer, I., Yakimenko, O., Pascoal, A., and Ghabcheloo, R. (2006). Path generation, path following and coordinated control for timecritical missions of multiple uavs. In *Proc. of American Control Conference*, 4906–4913.

Lapierre, L., Soetanto, D., and Pascoal, A.M. (2003). Nonlinear path following with applications to the control of autonomous underwater vehicles. In *Proc. of the 42nd IEEE Conference on Decision and Control*, 1256–1261.

Lekkas, A.M. and Fossen, T.I. (2012). A time-varying lookahead distance guidance law for path following. In *Proc. of the 9th IFAC Conference on Manoeuvring and Control of Marine Crafts.*

Li, Z., Sun, J., and Oh, S. (2009). Design, analysis and experimental validation of a robust nonlinear path following controller for marine surface vessels. *Automatica*, 45(7), 1649–1658.

Misković, N., Vukić, Z., Bibuli, M., Caccia, M., and Bruzzone, G. (2009). Marine vehicles' line following controller tuning through self-oscillation experiments. In *Proc. of the 17th Mediterranean Conference on the Control and Automation*, 916–921.

Morgado, M., Batista, P., Oliveira, P., and Silvestre, C. (2011). Position USBL/DVL sensor-based navigation filter in the presence of unknown ocean currents. *Automatica*, 47(12), 2604–2614.

Nelson, S.G. (2010). AKPO: The subsea production system. In *Proc. of Offshore Technology Conference.*

Papoulias, F.A. (1991). Bifurcation analysis of line of sight vehicle guidance using sliding modes. *International Journal of Bifurcation and Chaos*, 1(4), 849–865.

Pinto, J., Dias, P.S., Gonçalves, R., Marques, E., Sousa, J.B., and Pereira, F. (2006). Neptus-a framework to support a mission life cycle. In *Proc. of the 7th IFAC Conf. on Manoeuvring and Control of Marine Craft.*

Sordalen, O. and De Wit, C. (1993). Exponential control law for a mobile robot: extension to path following. *IEEE Transactions on Robotics and Automation*, 9(6), 837–842.

Zereik, E., Bibuli, M., Bruzzone, G., and Caccia, M. (2013). Jacobian task priority-based approach for path following of unmanned surface vehicles. In *Proc. of the 9th IFAC Conference on Control Applications in Marine Systems.*

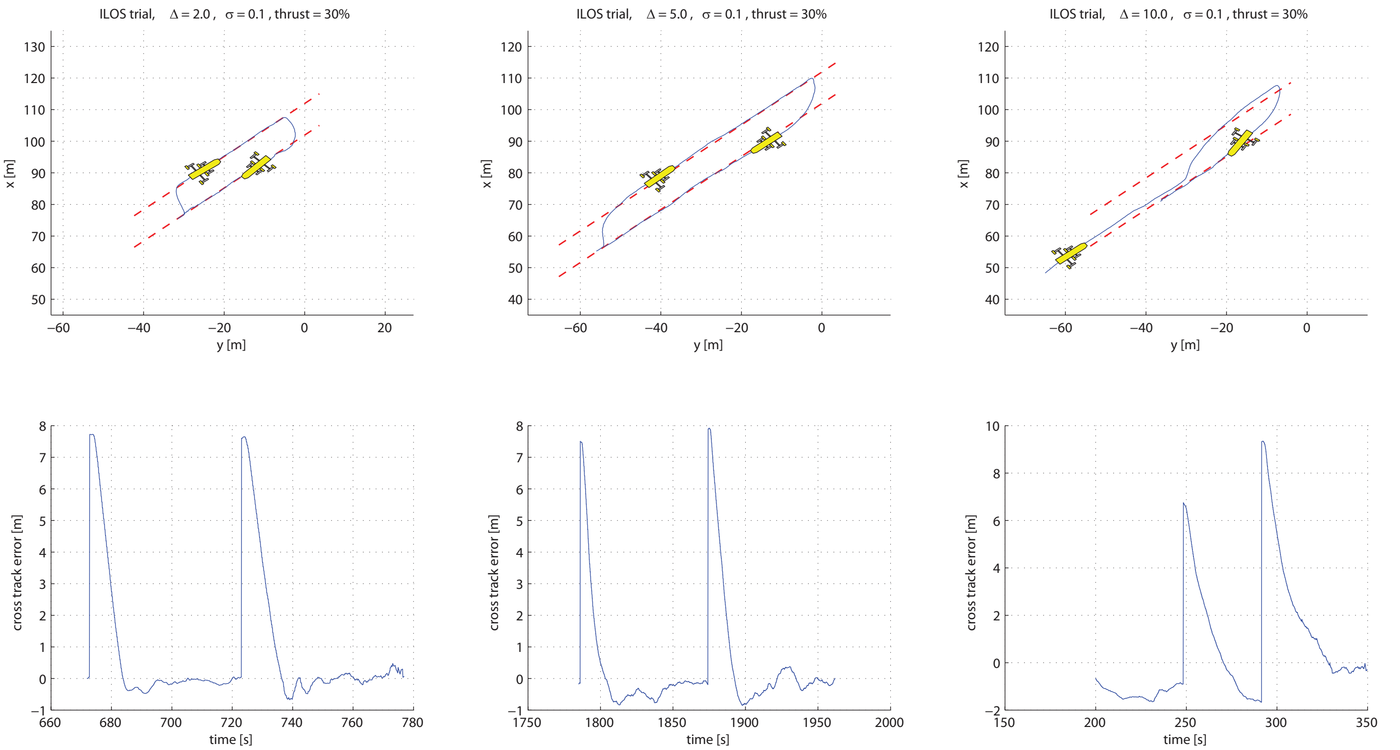

Fig. 3. Sensitivity of the ILOS guidance with respect to the look ahead distance Δ - the upper plots show the motion of the vehicle (blue) along the reference lines (red); the lower plots show the cross track error variation in time.

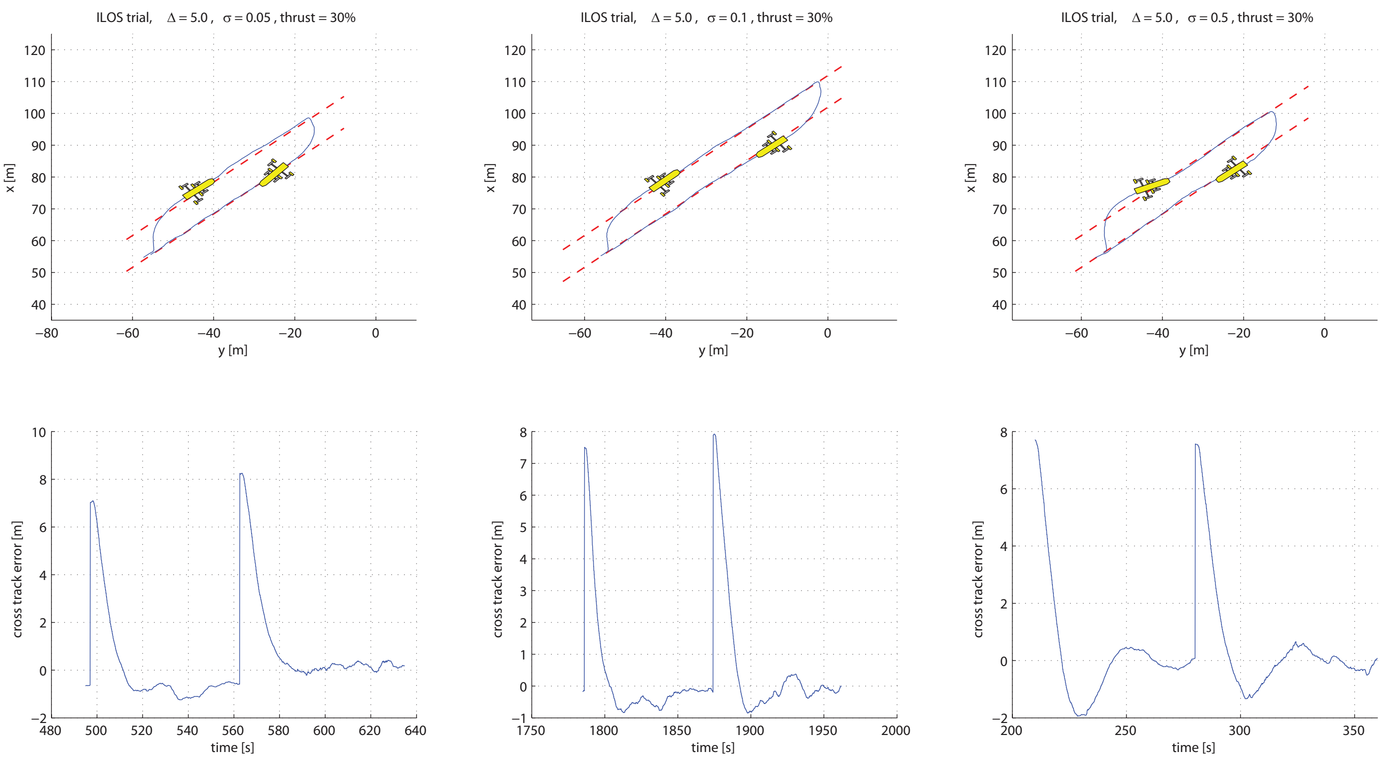

Fig. 4. Sensitivity of the ILOS guidance with respect to the integral gain σ - the upper plots show the motion of the vehicle (blue) along the reference lines (red); the lower plots show the cross track error variation in time.