A Sliding Mode Based Guidance System for Vehicle-Following Operations

Marco Bibuli * Gabriele Bruzzone * Massimo Caccia *
Andrea Caiti ** Nicola Di Lecce **

* *Consiglio Nazionale delle Ricerche, Istituto di Studi sui Sistemi Intelligenti per l'Automazione, Via De Marini 6, 16149 Genova, Italy, e-mail: {marco,max}@ge.issia.cnr.it*

** *Università di Pisa, Dipartimento di Sistemi Elettrici e Automazione, Largo L. Lazzarino, 56126 Pisa, Italy, e-mail: caiti@dsea.unipi.it*

Abstract: The purpose of this work is the development of a guidance and control system for the vehicle-following task, extendable to rigid formation maintenance, in the case of more than two vehicle within the framework. The novelty of a guidance system development based on a sliding mode control approach is described and validated by a number of experimental tests carried out with two Unmanned Surface Vehicles (USVs) during at-sea trials, and simulative tests extended to vehicle formation control.

Keywords: Coordinated Guidance, Vehicle Following, Unmanned Surface Vehicles, Mobile Robots.

1. INTRODUCTION

In recent years, several research efforts have been directed toward the control of group of Unmanned Marine Vehicles (UMVs). The interest in this field is well justified by the several advantages that such systems present respect to single autonomous vehicles and it is well supported by the improvements in technologies that allow the interaction and the integration among multiple systems. One of the main motivations is that multi-robot systems can be used to increase the system effectiveness; a platoon of UMVs can better perform a mission in terms of time and quality, can achieve tasks not executable by a single robot (moving a large object, search) or can take advantages of distributed sensing and actuation. Moreover, instead of building and using a single powerful marine vehicle, a multi-vehicle solution can be easier and cheaper, can provide flexibility to tasks execution and can make the system tolerant to possible robots' faults.

The idea of this development approach is highlighted, for instance, by the CADRE system, Vaganay et al. (2004) and Willcox et al. (2006), consisting of a network of AUVs (Autonomous Underwater Vehicles) and USVs (Unmanned Surface Vehicles) that cooperate to conduct wide area undersea mine countermeasures (MCM) surveys in an autonomous and concurrent way , while maintaining high-accuracy navigation and contact localization by a multi-modal communication architecture. The creation of a conceptual framework and middleware systems with the aim of coordinating a swarm of cooperating heterogeneous robotic vehicles to achieve a well defined practical goal in an optimized manner, is the object of the GREX project Aguiar et al. (2009). In Ghommam et al. (2009) the problem of steering a group of vehicles along a specified paths, while holding a desired inter-ship formation pattern, is addressed and solved through a passivity-based approach for both path-following and vehicles synchronization tasks. A path-following guidance system based on the virtual target approach and Lyapunov functions definition, integrated with a surge speed regulator, has been experimentally proven in Bibuli et al. (2009). An alternative method based on Cartesian coordinates and direct Lyapunov method for formation control of non-holonomic vehicles is presented in Li and Xiao (2005). Work Belkhouche et al. (2009) deals with the modeling and control of robot formation control through the use of a combination of classical guidance laws and kinematics rules, allowing a dynamic formation handling with a set of differential equations; moreover, the graph theory is used to store the relationship leader-follower and to plan the evolution of the formation. A leader-follower formation control of nonholonomic mobile vehicles is discussed in Mariottini et al. (2005); a sufficient condition for observability is proven and a recursive estimation enabling a leader-follower formation, if the leader is not trapped in an unobservable configuration, is shown. An Extended Kalman Filter is employed for the estimation of each follower position and orientation with respect to the leader, adopting a feedback linearizing control strategy to achieve a desired formation. An application of a sliding mode based technique has been developed in Zheng et al. (2008) to leaderless formation control for Unmanned Aerial Vehicles.

The purpose of this work is the development of a guidance and control system for the vehicle-following task, extendable to rigid formation maintenance, in the case of more than two vehicle within the framework. The novelty of a guidance system development based on a sliding mode control approach has been inspired by the work proposed in Orlando et al. (2007), with the aim of bridging the gap between the theory of sliding mode base control and

practical application to real robot formation management. The design and implementation of an accurate and reliable navigation, guidance and control system, able to operate with only linear and angular position measurements, is fundamental for the development of relatively cheap remotely controlled vehicles for civil applications. Every *follower* vehicle locally reconstruct the trajectory that has to be tracked, on the basis of a reduced set of information sent by the *leader* of the formation.
This work is focused on cooperative guidance system development for Unmanned Surface Vehicles (USVs); the validity of the proposed technique is however extendable to any kind of UMVs.
Initially the vehicle-following problem is solved for the case of a two vehicles framework, then the developed algorithm is extended to a generic vehicle formation control. The implementation and experimental validation of the proposed technique are focused on the Charlie and ALANIS USVs of the CNR-ISSIA, described in the following. The ALANIS USV, driven in manual mode, acts as *leader* vehicle defining an on-line trajectory reference that the *follower* vehicle Charlie has to track.

In section 2 the modeling of the system and theoretical vehicle-following problem resolution, by means of a sliding mode based guidance system, are reported. Section 3 describes the vehicles involved in the at-field experimentation, detailing the network architecture developed. Simulative and experimental results are presented in section 4, while conclusions of the work are given in section 5.

2. THEORETICAL APPROACH

2.1 Kinematic Modeling

Assuming that the vessel motion is restricted to the horizontal plane, i.e. neglecting pitch, roll and heave, two reference frames are considered: an inertial, earth-fixed frame $< e >$, where position and orientation $[x\ y\ \psi]$ of the vessel are usually expressed, and a body-fixed frame $< b >$, where surge and sway velocities ($[u\ v]$ absolute, $[u_r\ v_r]$ with respect to the water), yaw rate r, and force and moments $[X\ Y\ N]$, are represented. See Figure 1 for a pictorial representation of the Charlie USV, including reference frames, absolute and relative speed, actuator location and rudder angles. Denoting with $[\dot{x}_C\ \dot{y}_C]^T$ the sea current, the body-fixed absolute velocity and velocity with respect to the water are related by:

$$\begin{aligned} u &= u_r + \dot{x}_C \cos\psi + \dot{y}_C \sin\psi \\ v &= v_r - \dot{x}_C \sin\psi + \dot{y}_C \cos\psi \end{aligned} \tag{1}$$

and the vehicle kinematics is usually expressed in the earth-fixed frame $< e >$ (with x-axis pointing in the North direction and y-axis pointing in the East direction) as:

$$\begin{aligned} \dot{x} &= u_r\ \cos\psi - v_r\ \sin\psi + \dot{x}_C \\ \dot{y} &= u_r\ \sin\psi + v_r\ \cos\psi + \dot{y}_C \\ \dot{\psi} &= r \end{aligned} \tag{2}$$

relating vehicle speed in the earth-fixed and body-fixed frames.

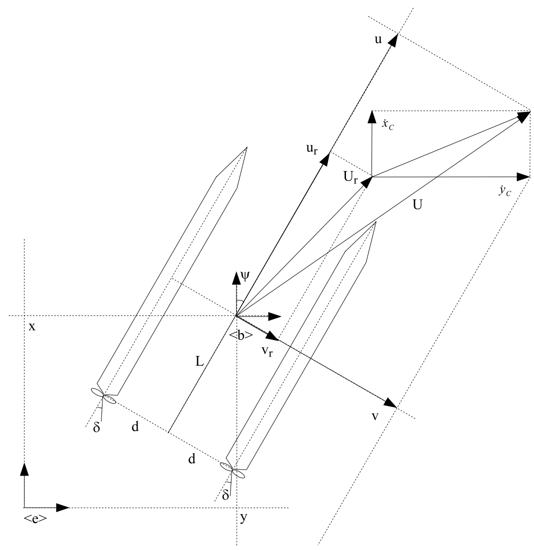

Fig. 1. Charlie USV basic nomenclature

2.2 Sliding Mode Based Coordinated Guidance

The issue is to find a guidance law that ensures a trajectory tracking and a bounded position error, given a trajectory. The speed or dynamic behavior along the path may be of secondary interest. The references are yielded by the leader GPS measurements and are computed by the intelligence on follower board for making a decentralized architecture. Thus, the programmed task into the *follower* vehicle is, further to track the reference trajectory, to keep a safety distance from the *leader* vehicle and a fixed angle with respect to the leader heading. The *follower* reference is computed as

$$\begin{aligned} x^* &= x_l - L\cos(\psi_l + \varphi) \\ y^* &= y_l - L\sin(\psi_l + \varphi) \\ \psi^* &= \psi_l \end{aligned} \tag{3}$$

where the index "l" denotes the *leader* measurements and the term L fixes the desired distance from the target. Instead, the variable φ allows to carry out the vehicle-following task to any angle with respect to the *leader* heading, so that the result control algorithm can be easily fitted and extended to USVs platoon to perform a rigid formation task. Thus, computing into every vehicles the suitable reference trajectory by handling the values of φ and L the fleet formation is built.
The proposed solution for UMVs coordinated guidance relies on the development of a discrete-time *Sliding Mode Control* (SMC); such kind of controllers are characterized by a discontinuous control action which dynamically changes structure upon reaching a set of predetermined switching surfaces. This kind of control may result in a very robust system and thus provides a possibility to achieve the goals of high-precision and fast response.
First, the discrete-time model of the system is considered:

$$\begin{aligned} x_{k+1} &= x_k + \Delta T\ u_k \cos(\psi_k) \\ y_{k+1} &= y_k + \Delta T\ u_k \sin(\psi_k) \\ \psi_{k+1} &= \psi_k + \Delta T\ r_k \end{aligned} \tag{4}$$

where ΔT is the sample time of the system, that for the Charlie USV is 0.125 s. In this last equation, for the basic analysis of the technique, the sea currents have been neglected, as well as the sway speed component that cannot be identified from practical measurements with the onboard sensors (details can be found in Caccia et al. (2008)). Then the following quantities have to be introduced:

$$\begin{aligned} \Delta x_k^* &= x_{k+1}^* - x_k^* \\ \Delta y_k^* &= y_{k+1}^* - y_k^* \\ \Delta \psi_k^* &= \psi_{k+1}^* - \psi_k^* \end{aligned} \tag{5}$$

The tracking error is defined as:

$$\begin{aligned} e_k^x &= x_k - x_k^* \\ e_k^y &= y_k - y_k^* \\ e_k^\psi &= \psi_k - \psi_k^* \end{aligned} \tag{6}$$

The dynamics of tracking errors is expressed by the following equations:

$$\begin{aligned} e_{k+1}^x &= e_k^x - \Delta x_k^* + \Delta T\, u_k \cos(\psi_k) \\ e_{k+1}^y &= e_k^y - \Delta y_k^* + \Delta T\, u_k \sin(\psi_k) \\ e_{k+1}^\psi &= e_k^\psi - \Delta \psi_k^* + \Delta T\, r_k \end{aligned} \tag{7}$$

Defining the following sliding surfaces:

$$\begin{aligned} \sigma_x &= e_{k+1}^x - e_k^x + \gamma_x e_{k-1}^x \\ \sigma_y &= e_{k+1}^y - e_k^y + \gamma_y e_{k-1}^y \end{aligned} \tag{8}$$

position error tracking is asymptotically bounded thanks to quasi-sliding motion on surface. Asymptotic boundedness of e_k^x and e_k^y is obtained through a suitable choice of γ_x and γ_y, such that the root of the associated equations

$$\begin{aligned} z^2 - z + \gamma_x &= 0 \\ z^2 - z + \gamma_y &= 0 \end{aligned} \tag{9}$$

are positive real and inside the unit circle. Moreover, posing $u_k^x = u_k \cos(\psi_k)$ and $u_k^y = u_y \sin(\psi_k)$, the following condition must also be satisfied:

$$\psi_k = \arctan\left(\frac{u_k^y}{u_k^x}\right) \tag{10}$$

To impose the fulfilment of (10), another sliding surface has to be defined:

$$\sigma_{psi} = \arctan\left(\frac{u_k^y}{u_k^x}\right) - \psi_k \tag{11}$$

so the angular tracking error e_k^ψ is bounded thanks to a proper choice of u_k^x and u_k^y.

Finally, the control laws that assure the quasi-sliding motion on $\sigma_x = 0$, $\sigma_y = 0$ and $\sigma_\psi = 0$ can be defined; given the tracking error system (6), the achievement of quasi-sliding motions on surfaces (8) and (11) is guaranteed by the following control laws:

$$\begin{aligned} u_k &= \frac{1}{\Delta T}\left(\sqrt{(p_k^x)^2 + (p_k^y)^2}\right) \\ r_k &= \frac{1}{\Delta T}\left[\arctan\left(\frac{p_k^y}{p_k^y}\right) - \psi_k - \nu_k^\psi\right] \end{aligned} \tag{12}$$

with

$$\begin{aligned} p_k^x &= \Delta x_k^* - \gamma_x e_{k-1}^x - k_D^x e_{k+1}^x - \nu_k^x \\ p_k^y &= \Delta y_k^* - \gamma_y e_{k-1}^y - k_D^y e_{k+1}^y - \nu_k^y \end{aligned} \tag{13}$$

where the terms $k_D^x e_{k+1}^x$ and $k_D^y e_{k+1}^y$ are the position tracking error dynamics used to anticipate the steering action and to counteract possible sea currents. k_D^x and k_D^y are the constant values, while the terms ν_k^x, ν_k^y and ν_k^ψ are defined as:

$$\begin{aligned} \nu_k^x &= k_x \tanh\left(\frac{\sigma_x}{\phi}\right) \\ \nu_k^y &= k_y \tanh\left(\frac{\sigma_y}{\phi}\right) \\ \nu_k^\psi &= k_\psi \tanh\left(\frac{\sigma_\psi}{\phi}\right) \end{aligned} \tag{14}$$

where k_x, k_y and k_ψ are their amplitudes and the factor ϕ is the positive scalar which determines the boundary layer thickness close to the sliding surfaces. From them, the *switch control* parts are obtained, while the remaining parts of control laws (12) are usually known as *equivalent control*.

The $\tanh(\cdot)$ functions appear with the aim of attenuating the effect of the so called *chattering phenomenon*. The *chattering phenomenon* is generally perceived as illegitimate motion, which oscillates about the sliding surface $\sigma = 0$. It can also cause resonance in high frequency unmodeled dynamics. High frequency unmodeled dynamics degrade the system performance and can produce instability too. In the ideal sliding mode controller, the trajectory should converge as soon as it reaches the desired one. In reality, delay will occur between the instant in which the σ sign changes and the time in which the control switches. In order to overcome (to weaken) this drawback, a research activity aimed to find a continuous control action that is robust against uncertainties, guaranteeing the attainment of the same control objective of the standard sliding mode approach, has been carried out in recent years. The resulted algorithms, turn out to belong to the two classes of *soft variable control structure* (in particular, *boundary layer sliding mode control*) and of the most recent second order sliding mode control algorithms Salgado-Jimnez and Jouvencel (2003).

3. VEHICLES' FRAMEWORK

3.1 Charlie USV

The Charlie USV is a small autonomous catamaran prototype which is 2.40 m long, 1.70 m wide and weighs about 300 Kg in air. The vessel, designed and developed by CNR-ISSIA Genova for sampling sea surface microlayer and collecting data on the air-sea interface in Antarctica, is propelled by two DC thrusters whose revolution rate is controlled by a couple of servo-amplifiers, closing a hardware speed control loop with time constant negligible with respect to the system. With respect to the original model, the vehicle has been upgraded with a rudder-based steering system, constituted by two rigidly connected rudders, positioned behind the propellers, and actuated by a

Fig. 2. Charlie USV

brushless motor. The vessel navigation package is constituted by a GPS Ashtech GG24C integrated with a KVH Azimuth Gyrotrac, providing 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.

3.2 ALANIS USV

The ALANIS USV is a 4.50 long, 2.20 m wide, rubber dinghy shaped aluminum vessel with a 40 HP Honda outboard motor (see Fig. 3). It weighs 600 Kg for a load capacity of 800 Kg and has an autonomy of about 12 hours guaranteed by a fuel capacity of 65 l. A motorised winch

Fig. 3. ALANIS USV

can be mounted on board for automatic deployment and recovery of scientific instrumentation through a stern hole of 0.20 m of diameter. The basic navigation package is constituted by a Garmin GPS 152 with 12 parallel channels, a Navicontrol Smart Compass SC1G, and a dual-axis Applied Geomechanics IRIS MD900-TW Wide-Angle clinometer providing accurate pitch and roll measurements. A manually (dis)connectible electro-mechanical system for servo-actuating the vessel steering and throttle allows the *dual* use of the vehicle as a manned and unmanned platform. Indeed, the possibility of having a crew onboard and fast switching control to a human pilot has been motivated by the lack of rules for operating unmanned vehicles at sea. The basic navigation, guidance and control system, implemented on a Single Board Computer based architecture running GNU/Linux OS, consists of PD auto-heading and LOS way-point guidance.

3.3 ALANIS-Charlie Connection

Preliminary field trials have been carried out in the Genova Prà harbour, with the Charlie USV (*Follower*) following the ALANIS USV (*Leader*). In the first experiments the *Leader* USV sends to the *Follower* vehicle its fundamental navigation data (position, course and speed).
The ALANIS navigation data are sent to the Charlie USV through a radio link, which is seen by its control system as an additional sensor providing the measurements required by the vehicle-following guidance module. Due to safety reasons, i.e. to have both the vehicles under strict visual control by the human operator when executing automatic coordinated manoeuvres in an area with recreational traffic, the basic Charlie operator station, consisting of a laptop and a wireless communication link, has been mounted onboard the ALANIS USV to perform the experiments. Charlie and ALANIS control systems and the related HCIs are connected by means of three communication links. Two links (a wireless channel working at 2.4 GHz with a maximum data transfer rate of 3 Mbps and a radiomodem channel working at 169 MHz with a transfer rate of 2400 bps) are devoted to the communication between Charlie HCI and Charlie control system. The radiomodem link acts as a backup channel, due to the frequent and unpredictable main wireless link disconnections, allowing to send a basic command set to drive or recover the vehicle. The third link, a radiomodem channel working at 436 MHz with a transfer rate of 2400 bps, is used to transmit telemetry data (GPS position, course and speed) from ALANIS to Charlie. The complete communication scheme is depicted in Fig. 4.

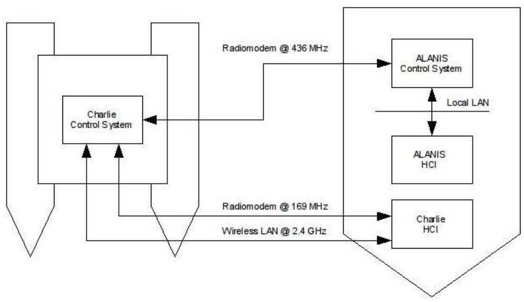

Fig. 4. Charlie-ALANIS network configuration

4. RESULTS

Simulated and experimental results are presented in this section. The trials have been carried out combining in a nested-loop architecture the *sliding mode* guidance system for coordinated motion, with an already existing *gain-scheduling PI*-type controller for low-level dynamics regulation.In order to design linear and angular velocity controllers, the dynamical characteristics of surge and yaw motions is modeled with the following generic 1-dof model:

$$\tilde{m}_\xi \dot{\xi} = \tilde{k}_\xi \xi + \tilde{k}_{\xi|\xi|} \xi |\xi| + \tau \qquad (15)$$

where $\tilde{m}_\xi$, $\tilde{k}_\xi$ and $\tilde{k}_{\xi|\xi|}$, τ represent inertia, linear and quadratic drag coefficients, and control action respectively. On this basis, a *PI* (Proportional Integral) gain scheduling controller can be adopted, considering (15) as a generic nonlinear model:

$$\tilde{m}_\xi \dot{\xi} = f(\xi) + \tau \tag{16}$$

according to Khalil (1996), it is possible to design a parameterized family of *PI* linear controllers at each constant operating point ξ, obtaining a desired characteristic equation for the closed-loop linearized system of the form:

$$s^2 + 2\sigma s + \sigma^2 + \omega_n^2 = 0 \quad , \quad \sigma > 0 \tag{17}$$

which does not depends on the particular constant operating point.
All the details on the synthesis of the *PI* gain scheduling controller for linear and angular velocities regulation for the Charlie USV, can be found in Caccia et al. (2008).

A first experimental results is reported in Figure 5, where the Charlie vehicle is required to follow the ALANIS USV, manually driven at the speed of 1 m/s, maintaining a distance of $L = 20$ m at an angle of $\varphi = 0$ deg., i.e. on the tail of the *leader* vehicle. The trajectory generated by the *leader* motion is followed with good performance; it is worth noticing that the Charlie USV has a slower dynamics' characteristic with respect to ALANIS, thus narrow or tricky manoeuvres performed by the *leader* might lead to local divergences of the Charlie USV from the reference trajectory. Figure 6 reports the absolute value of the position error (in the upper part of the figure) and the orientation error (lower part). As introduced before, it can be noticed the difficulty of reducing the error to zero, that however is maintained within a limited value, due to the slower Charlie dynamics with respect to the ALANIS one, and also to external disturbances (wind and sea current) always present in the testbed site. The same effect appears in the orientation error where the oscillatory behavior is due to the steering action to correct the overall error. Although vehicle following capabilities are proven to be satisfactory with a reasonable precision level, a well known drawback of the sliding mode control application is the presence of the chattering effect. This can be easily noticed in Figure 7 that highlights the mechanical stress induced by the actuation signals of thrust motors and rudder, generated by the sliding mode based guidance system.
A simulative result, depicted in Figure 8, reports the behavior of the proposed *sliding mode* based guidance technique performing the coordination of a USV formation, where two simulated Charlie vehicles follow the trajectory defined by the motion of a simulated ALANIS USV. In this trials, the *follower* USVs are required to maintain a $L = 5$ m distance at the angles of $\varphi_1 = 90$ and $\varphi_2 = -90$ deg. respectively, i.e. on the sides of the *leader*. Figure 9 shows the complete correction of position and orientation errors, proving the effectiveness of the approach presented.

5. CONCLUSIONS

A *sliding mode* based guidance for coordinated motion control of UMVs has been investigated for his properties of robustness with respect to measurement and environmental noises, achieving the goals of high-precision and fast

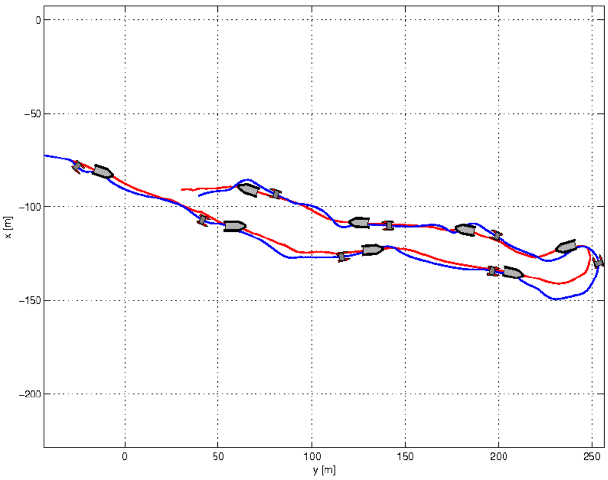

Fig. 5. Experimental vehicle-following trial. ALANIS (red line) as *leader* vehicle, Charlie (blue line) as *follower* vehicle.

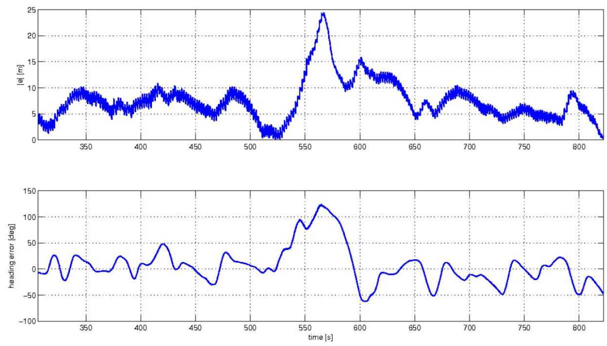

Fig. 6. Experimental vehicle-following trial. Absolute value of the position error (upper plot) and orientation error (lower plot).

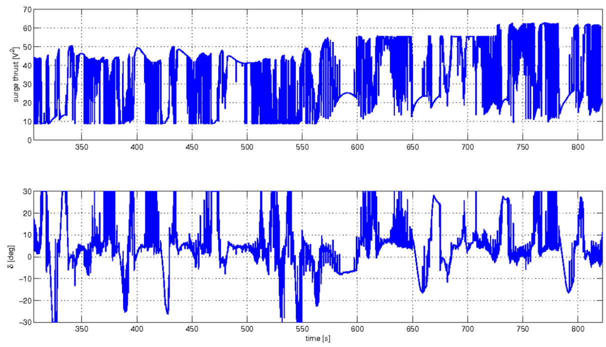

Fig. 7. Commanded signal on thrust motors (upper plot) and rudder (lower plot).

response navigation.
Simulated and experimental at-sea trials have been reported, highlighting the performances of the proposed technique in the formation control of cooperative vehicles. With the aim of reducing the chattering effect, typical of the sliding mode based control, also reported in the experimental results, ongoing researches are under investigation as, for instance, the integration of the robot dynamics through the backstepping technique, in order to improve the overall performances and to reduce actuation stress.

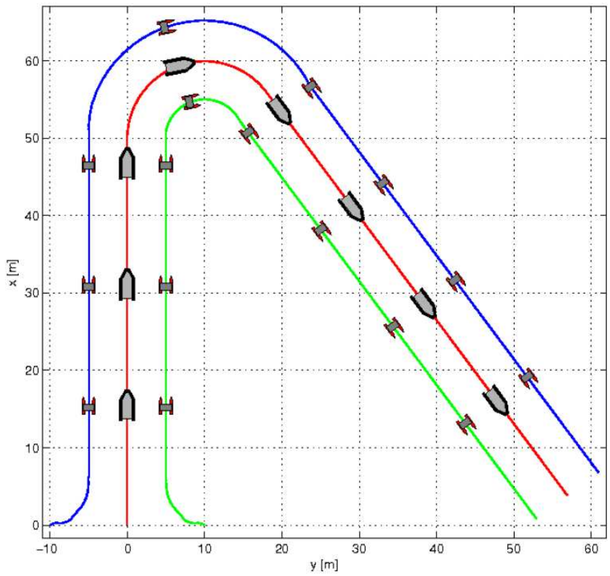

Fig. 8. Simulated vehicle formation trial. One simulated ALANIS (red line) as *leader* vehicle, two simulated Charlie (blue and green lines) as *follower* vehicles.

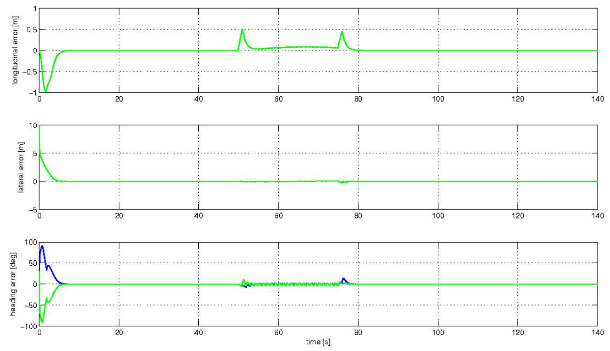

Fig. 9. Simulated vehicle formation trial. Lateral, longitudinal and orientation errors, green line - *follower-1*, blue line - *follower-2*

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