Virtual Target Algorithm in Cooperative Control of Marine Vessels

Zoran Triska, Nikola Mišković, Đula Nađ and Zoran Vukić
Laboratory for Underwater Systems and Technologies
Faculty of Electrical Engineering and Computing
University of Zagreb
Unska 3, Zagreb, Croatia
E-mail: {zoran.triska, nikola.miskovic, dula.nad, zoran.vukic}@fer.hr

Abstract - Marine vessels (surface and underwater) present dynamic systems which are difficult to control due to their complexity, hydrodynamic effects and external forces. Moreover, cooperative control and guidance of these systems presents a task which still presents an intriguing research topic in the area of marine robotics. This paper presents a guidance method based on virtual targets (VT) applied to marine vehicles. The proposed algorithm is derived using a Lyapunov based approach which guarantees convergence and stability under external disturbances. Firstly, the VT algorithm is applied for path following of a single vehicle. It is demonstrated that this algorithm is convenient for following of conventional paths (line, circle arc, spline). Secondly, the VT algorithm is applied for cooperative control between two marine vehicles. The following formations of marine vessels will be described and analyzed: vehicle following – where one vehicle is the „leader“ followed by the „follower“ vehicle at a predefined distance; and the „wingman problem“ where two vehicles are required to follow a joint path at a constant predefined distance between them. Simulation results of the described algorithms will be given in the paper as well as the discussion on their quality.

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). Exploring the sea depths is one of the biggest tasks for the future. Thanks to development of advanced control theory and technological improvement, nowadays, the main interests of marine robotics are focused on cooperative control and guidance of marine vessels. Development of the multi-vehicle frameworks and thereby including more vehicles in cooperative missions, lead us to design more complex control systems.

This paper deals with virtual target algorithm in cooperative control of marine vessels. The work presented in this paper will be elaborated on an overactuated marine surface platform which development has been published at MIPRO'11 conference, [3]. The platform is developed at the Laboratory for Underwater Systems and Technologies (LABUST) by a group of students. This paper address simulation results of the described algorithms obtained in MATLAB, so only some important technical characteristics of the platform will be mentioned in following part. The marine platform which mathematical model is used in simulations is actuated with four thrusters in an X-shaped configuration which enable motion in surge, sway and yaw degree of freedom. This configuration is highly convenient for dynamic positioning as well as path following. Marine vehicles are often designed to be overactuated; they have more actuators than strictly necessary to maneuver. In this case, four thrusters are used to control three degree of freedom: surge, sway and yaw. This property guarantees reliability in the case of faults in the actuators. Platform development comprises driver electronics for the thrusters, a GPS unit, a compass, batteries and a single board computer used for sensor integration and control. These components enable manual control from the ground station as well as autonomous operation mode. The communication with the ground station is accomplished using a two-way wireless link. A schematic representation of the hardware infrastructure implemented inside the platform can be seen on Fig. 1. The control algorithm which enables autonomous movement is implemented on a single board computer. This systems configuration has proved to be convenient for laboratory use and testing of control and guidance 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.

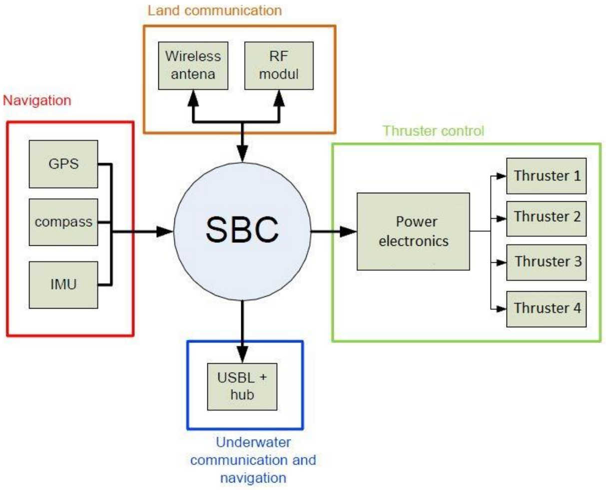


Fig 1: Schematic representation of the hardware infrastructure

This paper presents the next step in research activities regarding the guidance algorithms which include simulation results obtained using virtual target algorithm in order to achieve cooperative mission execution. It should be mentioned that the developed simulation model assumed that the dynamics of the platform were uncoupled.

The paper is organized as follows. Section II describes the mathematical model of the basic motion of the marine platform used in simulation. In section III, a brief introduction to virtual target algorithm is given and in section IV this algoritm is expanded to path following approach and multi-network framework cooperative control. In section V, simulation results are presented and finally, in section VI some conlusions are made and guidelines for future work done.

II. MATHEMATICAL MODEL

A. The marine platform 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 surge (X) and sway (Y) force and yaw (N) moment.

The schematic representation of the mathematical model is given in Fig. 2.,[8]. 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 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, [7].

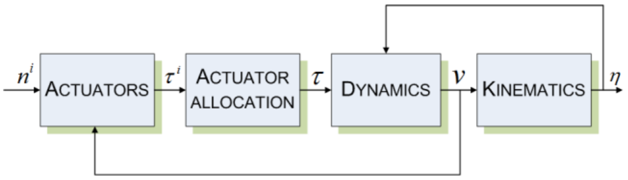


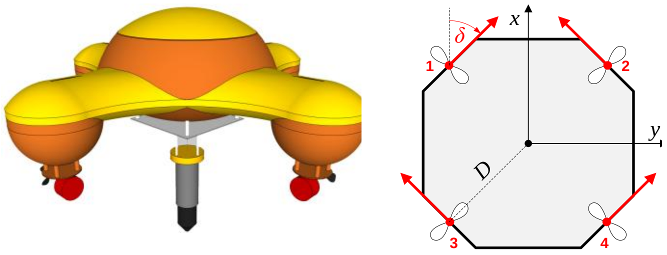
Fig. 2. Block-diagram of the mathematical model used to describe marine vessels.

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

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

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

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



a) b)

Fig. 3. a) Virtual model of the platform for dynamic positioning and b) x-shape actuator configuration.

The *actuator allocation* matrix gives relation between the forces exerted by thrusters (τ_1, τ_2, τ_3 and τ_4) and the forces that act on the rigid body (X , Y , N). For the case of the *Platform*, whose actuator configuration is given in Fig. 3b) and $\delta=45°$, the actuator matrix is given with (5) where D is shown in Fig.3.b).

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

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, [10].

The actuators can be simply modelled using an affine model given with (6) where n^i represents the individual thruster's control input (commanded rotation speed, input voltage, etc.), K_T is the thruster coefficient and τ^i is thrust exerted by the i -th thruster.

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

The nonlinear static thruster characteristic can easily be compensated within the control algorithm, [7], [11].

III. VIRTUAL TARGET ALGORITHM IN PATH-FOLLOWING

This section describes only fundamental concepts and problem formulation of the use of virtual target algorithm for single-vehicle guidance. For details and whole kinematic error modelling, interested reader can refer to [12], [13]. Before we deal with the essence of the problem, the kinematic model (1) is represented with

$$\begin{aligned} \dot{x} &= U\cos\psi_e \\ \dot{y} &= U\sin\psi_e \qquad (7) \\ \dot{\psi}_e &= r \end{aligned}$$

where

$$U = \sqrt{\dot{x}^2 + \dot{y}^2} \qquad \psi_e = arctg\,\frac{\dot{y}^2}{\dot{x}^2} \qquad (8)$$

With already defined Earth-fixed (inertial) frame {E}and a body-fixed coordinate system {B}, a *Serret- Frenet* frame $\{F\} := [s_1\ y_1\ 0]$ is defined,[15]. Virtual target attached to {F} moves along predefined path. Whole problem can be easily explained with reference to Fig.4.

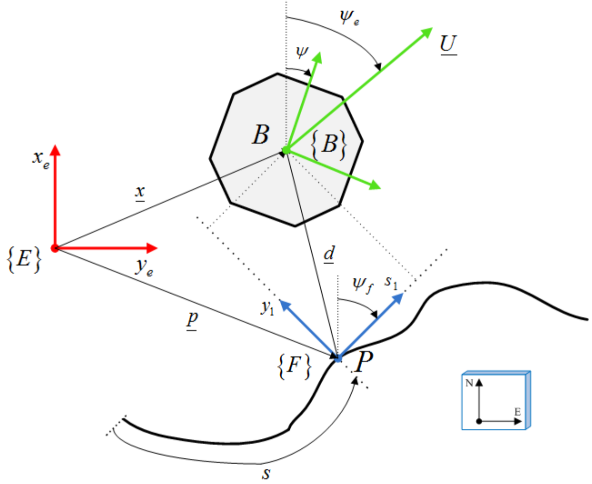


Fig.4. Vehicle parameters and frame definitions

After some mathematical calculations, the following kinematic error model is obtained and expressed with respect to the frame {F}

$$\begin{cases} \dot{s}_1 = -\dot{s}(1 - c_c y_1) + U\cos\beta \\ \dot{y}_1 = -c_c \dot{s} s_1 + U\sin\beta \\ \dot{\beta} = r - c_c s \end{cases} \qquad (9)$$

where $\dot{s}$ is speed of virtual target, attached to the frame {F}, c_c is path curvature, U is vehicle's total velocity and β is difference between vehicle's direction of motion and orientation of virtual target which is the same as local path tangent at point P. Control demands can be formulated as follows. After some transient time, platform must be in origin of {F} frame, which means that s_1 and $y_1$converge to zero. Second task is to reduce β towards zero. When these requirements are fulfilled, path following is achieved. In order to design control law which ensure convergences both the vehicle and virtual target, one of the possible Lyapunov's function candidate is chosen.

$$V_E = \frac{1}{2}\left(s_1^2 + y_1^2\right) \qquad (10)$$

Computing its time derivative and after substitutions are made, with proper choice of $\dot{s}$, $\dot{V}_E$ becomes negative – definite. Choosing

$$\dot{s}^* = U\cos\beta + k_2 s_1 \qquad (11)$$

as control signal which guarantees that $\dot{V}_E < 0$, a new additional degree of freedom is introduced in the control structure. The speed of virtual target later takes a part in defining yaw rate reference. Considering the candidate Lyapunov function:

$$V = \frac{1}{2}(\beta - \varphi)^2 \qquad (12)$$

and choosing control law:

$$r^* = \dot{\varphi} - k_1(\beta - \varphi) + c_c(s)\dot{s} \qquad (13)$$

$V \leq 0$ is secured where $k_1$is nonnegative controller gain and φ is angle of approach which is modelled as function of lateral y_1 coordinate. The approach angle is instrumental in shaping transient maneuvers during the path approach phase. The following hyperbolic tangent shaped function, parameterized by $k_\varphi > 0$ and $0 < \psi_a < \frac{\pi}{2}$ has desirable properties due to inherent saturation.

$$\varphi(y_1) = -\psi_a \tanh(k_\varphi y_1) \qquad (14)$$

The advantages of proposed kinematic control laws are in following. Asymptotically convergence to zero of the variables β, s_1 and y_1 is achieved, classic singularity of the path following problem is removed and vehicle can perform following of various kinds of the paths.

The above kinematic control law applies to the kinematic model of marine vehicles only. Using the backstepping techniques, this control law can be extended to deal with the vehicle dynamics. However, after that yaw rate reference is determined, a classic I-P controller is designed for yaw rate control,[9]. Backstepping technique supposes that process parameters are very accurately determined. If we have some uncertainty in mathematical model control signal can experienced chattering which is not acceptable behaviour, [12]. The complete control structure used for simulation can be seen on Fig. 5. Low level control is an I-P controller designed according to second order binomial model transfer function as desired behaviour. High level control is based on the virtual target algorithm.

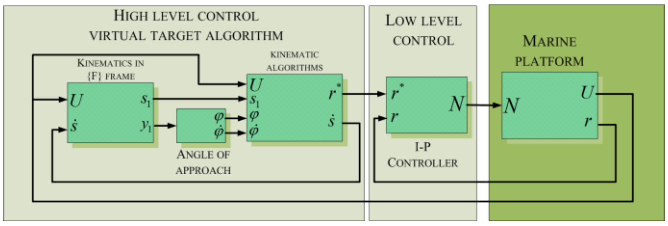


Fig.5. Virtual target based control structure

IV. COOPERATIVE CONTROL OF MARINE VESSELS

In this section, intention is to expand control algorithm and show have to efficiently use them to control several vehicles in order to achieve cooperation between them. Guidance and control of cooperative missions is demanding task and still presents a challenge in the area of marine robotics. Two or more marine vehicles operating together form a multi-vehicle framework, [1], [2]. Usually, one vehicle is the leader which executes some mission objectives and the rest of the vehicles (followers) follow his movements in some way. In the continuing part of this section, two coordinative tasks will be described. Each of them use single vehicle path following algorithm based on virtual target. With the virtual target based approach, coordination task is completely uncoupled from single - vehicle path following task.

A. Vehicle following

In vehicle following scenario, the Leader has to perform some motion. Through the communication link, the Leader sends basic navigation information to the Follower and then Follower vehicle reconstructs online the path to be followed. For instance, Leader follows a predefined path and Follower has to follow a Leader, maintaining a desired distance between them. Also, Leader vehicle can be open-loop controlled by human operator, [14]. As already mentioned, Follower vehicle follows the path shaped by Leader vehicle at fixed or variable distance, measured in curvilinear abscissa of the reconstructed path. Further on, if we add more vehicles in multi-framework system, a relation Leader – Follower can be generalized. One vehicle will be ultimate leader which only executes its own mission. Next in the Leader hierarchy will be second vehicle which is at same time the Follower of ultimate Leader and also a Leader to the vehicle below in hierarchy system. At the bottom is simple Follower as a tail of such a formation system. Whole framework act as a giant snake and some collision avoidance algorithm must be applied in order to prevent ultimate leader crashing with the followers while performing sharp manoeuvres. Collision avoidance is beyond the scope of this paper and an assumption of smooth path with small curvature is made. The vehicle following approach proposed in this work is based on the single vehicle path – following guidance technique for each vehicle. In addition, to achieve desired distance between formation members, the vehicle's surge speed must be controlled according to the error from desired distance from local Leader. So, the curvilinear distances between the Leaders and Followers are defined as the difference between respective curvilinear abscissas $\Delta s_i = s_{Li} - s_{Fi}$.

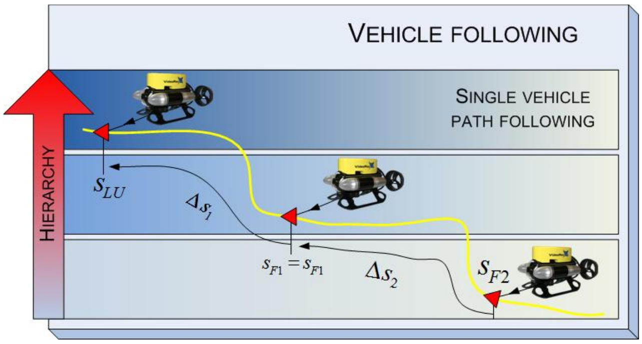


Fig.6. Hierarchy system and defined curvilinear distances

Thus, the task is to design a control law in order to reach a desired distance D^*. Defining the distance error as $e_s = \Delta s - D^*$, the implemented solution to make $e_s \to 0$ is in the form of tangent hyperbolic function added with feed-forward Leader surge force signal. The final form of the surge control law is

$$X^* = X_L + k_u \tanh(k_e e_s) \qquad (15)$$

where k_u and k_e are tunable controller gains. With the properly calculated surge force Follower vehicle produces required surge speed to maintain desired distance.

B. Wingman problem

One of the most common formation tasks is holding parallel formation while vehicles move along different paths. As in vehicle-following, Leader executes manoeuvres while Wingmen vehicles must maintain parallel formation with respect to the Leader vehicle.

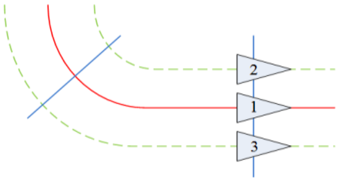


Fig.7. Example of parallel vehicle formation

Obviously, speed of the wingmen vehicles must be controlled to accomplish parallel formation. To achieve cooperation, each vehicle is controlled with virtual target based approach. Their virtual targets are used for the cooperation purpose.

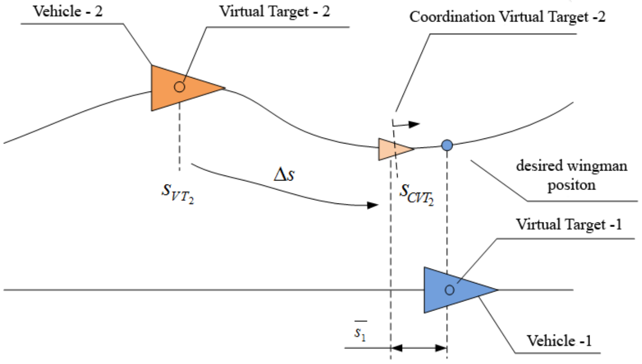


Fig.8. General wingman problem network

The key idea is to add a new virtual target, Coordination Virtual Target (CVT) for each wingmen vehicle. Controlling the speed of CVT, desired position of CVT is determined. Control law which ensures proper CVT curvilinear speed is

$$\dot{s}^*_{CVT_2} = U_1 \cos \bar{\beta} - \bar{k}_2 \bar{s}_1 \qquad (16)$$

where U_1 is total velocity of Vehicle-1, $\bar{\beta}$ is the difference between the local path tangent given by position of the CVT and the virtual target of Vehicle-1, $\bar{s}_1$ is projected longitudinal error, and $\bar{k}_2$ is a tunable gain. CVT behaves like the virtual target for Leader, moving on the path of Wingman vehicle. When CVT is set on the path of wingman vehicle, curvilinear distance can be calculated. With reference to Fig. 8., Vehicle -2 is a wingman vehicle and formation position error is $\Delta s = s_{CVT} - s_{VT2}$. To obtain completely parallel formation D^* is set to zero.

V. SIMULATION RESULTS

In this section, simulation results are presented in order to illustrate the performance of the previously proposed guidance algorithm. The simulation case study which is presented here consists of two cooperation scenarios and this paper is focused only on them. Video and results of all other scenarios with different mission paths can be found online at http://labust.fer.hr/media/virtual.

A. Vehicle-following simulation results

The first scenario includes vehicle following for three vehicles where path to be followed is a circle with $R = 1m$ and constant path curvature which is in this case $c_c = 1\ m^{-1}$. At the moment $t = 0s$ the Leader is positioned at the origin of the NE coordinate frame and it is commanded to follow the circle. The first Follower is positioned at point $P_1 = [1.25\ m, 0\ m]$ and the second at point $P_2 = [1\ m, -0.5\ m]$. Throughout the whole simulation reference distance between vehicles was kept at $0.4\ m$. Recorded responses of vehicle distances in the term of curvilinear abscissa can be seen in Fig. 10. Follower-1 generates path for Follower-2, so distance error must be observed relative to the vehicle- 1 which is in front of him. Fig.9. gives the path for all three vessels during the simulated mission. The control errors are shown in Fig. 11. and it is clear that after initial overshoots the vessels reach zero steady state error. An overshoot is direct consequence of efforts to get closer to the vessel as soon as possible.

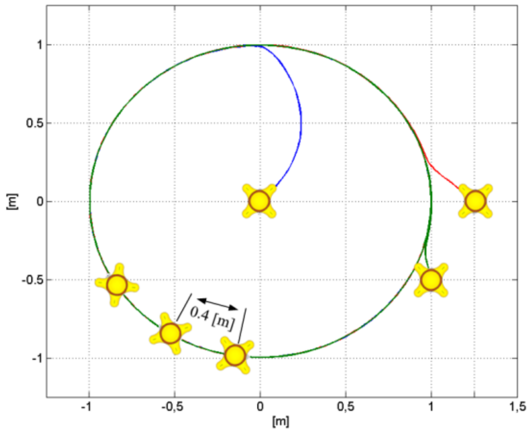


Fig.9.The paths of the vessels during simulation

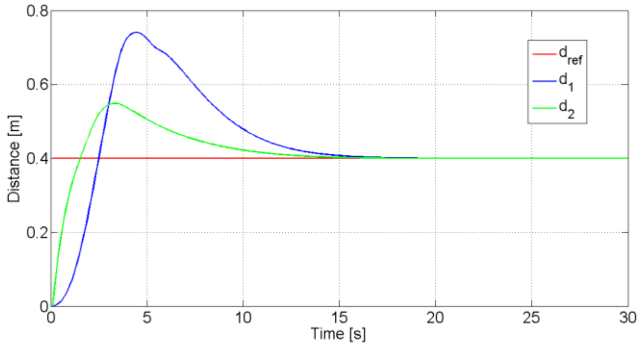


Fig.10.Distance between the vehicles

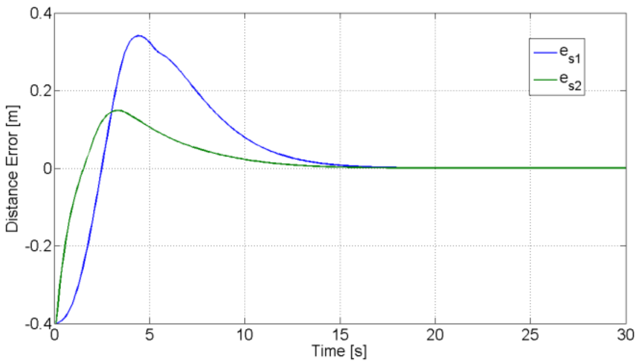


Fig.11. Response of distance error

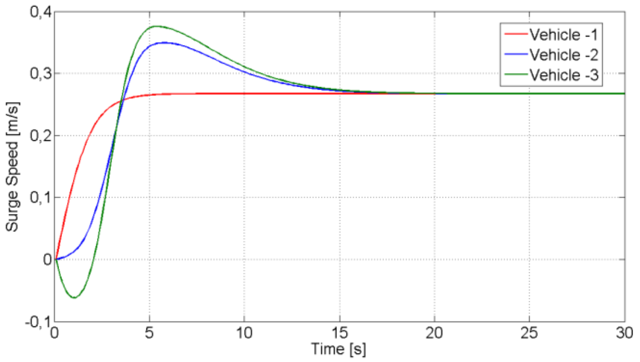


Fig.12. Surge speeds of the vehicles

B.Wingman Problem Simulative Results

For the Wingman framework simulation, a motion coordination task between three vehicles is presented. Leader vehicle executes same path following as in vehicle following (circle with $R = 1\ m$) while other two vehicles have to follow concentric circles with $R = 0.5\ m$ and $R = 1.5\ m$, respectively. During the whole simulation, desired parallel formation position is successfully achieved. Fig. 13. shows the convergence and maintenance of the desired formation while performing the path following tasks. It is obvious that vehicle which has to cross the longest path must have the largest surge speed. In Fig. 14. surge speeds of the formation members can be seen. Leader speed has smooth asymptotically response while Follower speeds are results of controlling surge forces in order to achieve the coordination task.

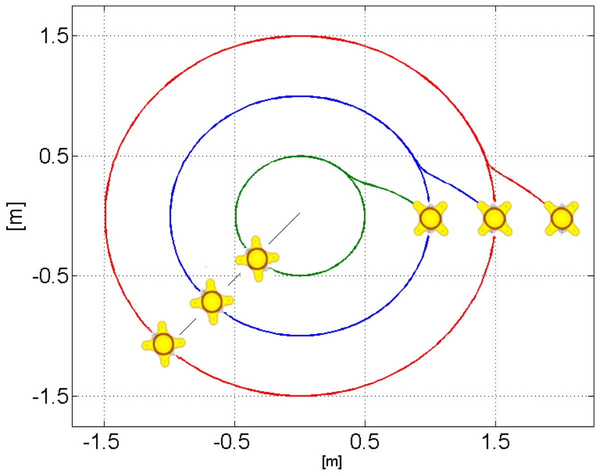


Fig.13. The paths of the vessels – The wingman problem

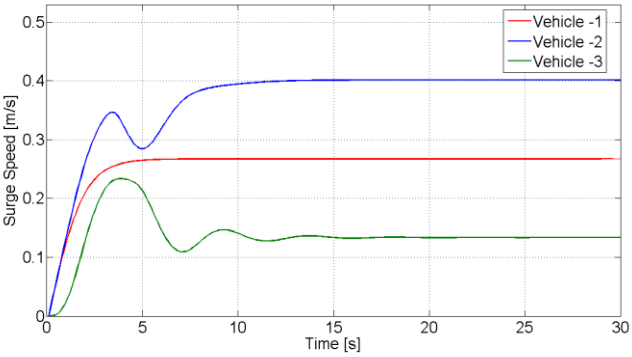


Fig.14. Surge speeds of the vehicles

It should be noticed, the Leader commanded surge force was kept constant throughout the whole simulation which resulted in a constant steady-state cruising speed. The Wingman vehicle surge forces are calculated according to (15). After transient time, even surge speeds of the Wingman vehicles are in steady-state. Considering that circles are concentric and differences in a radius between Leader vehicle and Wingman vehicles are same, the absolute difference between surge speeds would also be same.

VI. CONCLUSION AND FUTURE WORK

In this paper, a relatively new control approach in marine applications has been described. Firstly, single vehicle path algorithm is developed with the aim of expanding on cooperative tasks. Use of virtual target as control technique provides highly decoupling between the coordination system and each individual vehicles control system. The system stability and the performance of control system are shown in simulation results. The simulations prove the functionality of the proposed control law.

The future work will include implementing the developed virtual target algorithm on a real vessel to be used in field conditions. After successfully applied single vehicle path following algorithm, our final goal would be to achieve cooperation between two or more vehicles in field conditions.

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REFERENCES

[1] M. Breivik and T.I. Fossen. Guidance Laws for Planar Motion Control. *Proc. of 47th IEEE Conference on Decision and Control*, pages 570-577, Cancun, Mexico, 2008.

[2] M. Breivik and T.I. Fossen. Path following for marine surface vessels. *Proc. of Oceans 2004*, pages 2282-2289, Kobe, Japan, 2004.

[3] N. Miskovic, Z. Triska, D. Nad and Z. Vukic. Guidance of Small – Scale Overactuated Marine Platform – Experimental Results. *Proceedings of the 34rd International convention on information and communication technology, electronics ad mircroelectronics MIPRO 2011, CTS*, 2011.

[4] T.I. Fossen. *Guidance and Control of Ocean Vehicles*. John Wiley & Sons, New York, NY, USA, 1994.

[5] L. Moreira and T. I. Fossen and C. Guedes Soares. Path following control system for a tanker ship model. *Ocean Engineering*, 34:2074--2085, 2007.

[6] E. Omerdic. *Thruster fault diagnosis and accommodation for overactuated open--frame underwater vehicles*. PhD thesis, University of Wales College, Newport, United Kingdom, 2002.

[7] N. Miskovic and Z. Vukic and M. Barisic and P.P. Soucacos. AUV identification by use of self--oscillations. *Proc. of the CAMS'07 Conference*, 2007.

[8] N. Mišković and M. Bibuli and G. Bruzzone and M. Caccia and Z. Vukić. Tuning Marine Vehicles' Guidance Controllers through Self--Oscillation Experiments. *Proceedings of the MCMC'09 Conference*, 2009.

[9] Jong-Woo Choi and Sang-Cheol Lee. Antiwindup Strategy for PI-Type Speed Controller. *Industrial Electronics, IEEE Transactions on*, 56(6):2039-2046, 2009.

[10] N. Miskovic. *Use of self-oscillations in guidance and control of marine vessels*. PhD thesis, University of Zagreb, Faculty of Electrical Engineering and Computing, Zagreb, Croatia, 2010.

[11] Z. Vukic and Lj. Kuljaca. *Automatic Control -- Analysis of Linear Systems*. Kigen, Zagreb, 2005. (in Croatian).

[12] M. Bibuli. *Advanced Guidance Techniques and mission control architecture development towards marine robotic systems enhancement*. PhD thesis, University of Genova, Faculty of Engineering, Genova, Italy, 2010.

[13] M. Bibuli, G. Bruzzone, M. Caccia and L. Lapierre.*Path-Following Algorithms and Experiments for an Unmanned Surface Vehicle*. Journal of Field Robotics 1-20(2009), Wiley Periodicals,Inc,2009.

[14] M. Bibuli, M.Caccia and L. Lapierre.*Virtual target Based Coordinated Path-following for Multi-Vehicle Systems*. Proceedings of the.....

[15] L.Lapierre, D.Soetanto and A.Pascoal. *Nonlinear Path Following with Applications to the Control of Autonomous Underwater*. Proceedings of the 42nd IEEE conference on Decision and Control, Hawaii USA, December,2003.