Closed Loop Fuzzy/Lyapunov Control System for Planar Motion of Multiple Autonomous ROVs

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Abstract- **This paper deal with planar motion control of multiple underactuated Remotely Operated Vehicles (ROVs) based on merging of Fuzzy/Lyapunov and kinetic controllers. A cooperative algorithm based on a decentralized planning algorithm which considers the underwater vehicles in an initial open chain configuration is developed. All the planned trajectories are intersections-free, and each trajectory is planned independently of the others. The fuzzy controller generates the surge speeds and the yaw rates of each ROV, to achieve the objective of the planar motion planned by the decentralized algorithm, and it ensures robustness with respect to perturbations of the marine environment, forward surge speed control and saturation of the control signals, while the kinetic controller generates the thruster surge forces and the yaw torques of all the ROVs. The Lyapunov's stability of the equilibrium state of the closed loop motion control system is proved based on the properties of the Fuzzy maps for all the underwater vehicles, so that the stabilization of each vehicle in the planned trajectory is ensured. The validity of this control algorithm is supported by simulation experiments.**

Keywords- ***Autonomous ROVs; Decentralized Trajectory Planning; Fuzzy Control; Lyapunov's Stability; Motion Control***

I. INTRODUCTION

In recent years, there has been increasing interest in the use of underwater robotic vehicles to execute missions without direct supervisions of human operators [1]. The underwater robotic vehicles include the Remotely Operated Vehicles (ROVs). In this sense the priority of the ROV is to position itself, either tracking curves with autonomous navigation in the marine environment which has to be inspected, or near the structure of interest, against disturbances. Recently there has been a trend to use smaller autonomous underwater vehicles that use differential thrust for surge and yaw motion, with the advantage of increased maneuvrability in the yaw direction. In this case, the ROV moves in the horizontal plane, but the vehicles above have limited control for the motion along the sway direction, so that it is underactuated, because the dimension of the control vector is less than the number of independent directions of desired motion and in general, falls into category of so-called non-holonomic systems. However motion control strategies for non-holonomic Unmanned Aerial Vehicles (UAV) [2] and ground cars [3] cannot be directly applicable to the case of underwater ROVs, because they are subjected to complex hydrodynamic factors [4], they present unactuated dynamics and have a minimum surge control speed constraint that is greater than zero. Generally the ROV propulsion system has to be divided into two independent subsystems responsible for movement in the horizontal and vertical planes respectively [5], [6]. Hierarchical architecture for the motion control of underwater vehicles, which encompasses strategic, tactical and execution levels of control has been proposed [7]. Planar motion control strategies have been developed adopting a dual-loop hierarchical guidance control schemes [8], [9]. An approach of planar motion steering of underwater vehicles equipped with longitudinal control surfaces which allow the drag coefficient modulation in the sway direction has been developed in [10]. Recently there has been widespread interest in the problem of cooperative motion control of multiple Autonomous Marine Vehicles (AMVs). An important scenario that motivates the cooperative motion control is the automatic ocean exploration, where there is inefficiency due to the fact a single underwater vehicle may need to wander significantly to collect data over a large spatial domain [11]. Cooperative group of ROVs can solve the problem above. The problem of multiple underwater vehicle control in the presence of severe communications constraints has been developed [12], [13]. Intelligent control has not been addressed in any of the papers above. About Fuzzy control strategies, a fuzzy like proportional derivative controller for ROV to control the yaw and the dept has been developed in [14]. A fuzzy hierarchical motion control for single ROV has been developed in [15], where a continuous time model for single underactuated ROV and hierarchical architecture which merge a low level kinetic controller with an high level fuzzy inference system have been presented for a single underwater vehicle.

In this paper we elaborate on the method developed in [15] with new results applied to multiple autonomous ROVs. The following contributions are given:

1) A continuous time model for planar motion of platoon of underactuated ROVs, developed using polar coordinates, to consider the unactuated sway direction of each vehicle.

2) A cooperation based on a new algorithm of decentralized trajectory planning, where planar circular trajectories are planned. Each trajectory is planned independently of the others, so that the main advantages of this method are the absence of collisions and communication less between the ROVs.

3) A new closed loop control system for multiple ROVs, where the fuzzy controller generates the guidance laws in terms of surge speeds and yaw rates of all the cooperative ROVs, needed to achieve the reference trajectories planned by the decentralized algorithm of the previous point. In this sense, Lyapunov's theory provides conditions on the fuzzy control surfaces under which the errors between the actual motion of each ROV and the reference motion converge to zero, as regards the longitudinal and lateral positions and the orientations of each vehicle. The main advantages of the

fuzzy approach are the robustness with respect to disturbance of the marine environment, the generation of forward surge speeds for all the cooperative ROVs, and the saturation of all the control signals.

4) A kinetic controller which gives the surge forces and the yaw torques for each ROV, to ensure the convergence of the actual speeds of all the underwater vehicles to the guidance commands given by the fuzzy controller of the previous point.

This paper is organized as it follows. In Section II continuous time kinematic and dynamic models are presented for planar motion of a platoon of underactuated ROVs. The mathematical models above are necessary to apply the fuzzy and the kinetic control laws. Section III presents a new algorithm of decentralized trajectory planning, where circular trajectories without intersections are planned. Section IV presents the closed loop fuzzy/Luapunov's control with the kinetic control system. The Fuzzy controller generates the guidance commands for all the cooperative underwater vehicles, where the Lyapunov's theorem is used in order to investigate the asymptotical stability of the motion errors, while the kinetic controller generates the surge forces and the yaw torques of all the ROVs, where convergence of the actual speeds of the ROVs to the fuzzy guidance commands is ensured. In Section V simulation experiments are developed in a Matlab environment to show the validity of the control system, where kinematic and dynamic parameters of real small ROVs are employed.

II. MULTIPLE UNDERACTUATED ROVS KYNEMATICS AND DYNAMICS

Consider a platoon of r underactuated ROVs. Fig. 1 shows the assumed platoon configuration in open chain.

Fig. 1 Platoon of ROVs in open chain configuration

Let (X, Y) be the Earth Fixed Reference System (ERF) and $(x_{bi}, y_{bi}), i = 1...r$ be the fixed body frames of each ROV (cf. Fig. 2).

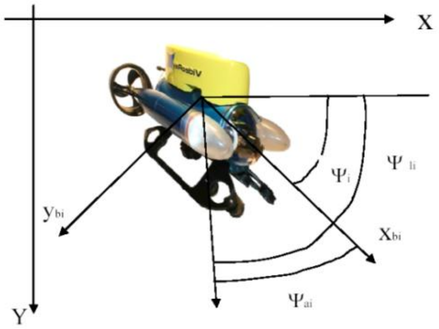

Fig.2 i-ROV with reference systems

Now the principal results of the mathematical model developed in [15] are extended for a platoon of r ROVs below. In the horizontal plane the following vectors have to be considered:

$$\boldsymbol{\eta}_i(t) = [x_i(t) \; y_i(t) \; \psi_i(t)]^{\mathrm{T}}, \quad \boldsymbol{\upsilon}_i(t) = [u_i(t) \; v_i(t) \; r_i(t)]^{\mathrm{T}} \quad i = 1...r, \tag{1}$$

where:

$x_i(t),\ y_i(t)$ represent the position coordinates with reference to the ERF of the i-ROV;

$\psi_i(t)$ represents the yaw, i.e. the orientation of the i-ROV;

$u_i(t),\ v_i(t)$ represent the surge and sway speeds respectively, i.e. the linear velocities along longitudinal and transversal axes evaluated in relation to the fixed body frame of the i-ROV ;

$r_i(t)$ represents the yaw rate, i.e. the angular velocity about the axis perpendicular to the plane (X,Y) of the i-ROV.

It results:

$$\begin{aligned} &\dot{x}_i(t) = u_i(t)\cos\psi_i(t) - v_i(t)\sin\psi_i(t), \\ &\dot{y}_i(t) = u_i(t) sen\psi_i(t) + v_i(t)\cos\psi_i(t), \\ &\dot{\psi}_i(t) = r_i(t) \\ &\mathrm{i} = 1...\mathrm{r}. \end{aligned} \tag{2}$$

The presence of the sway speed is evident. It is responsible for translational motion with respect to the vehicle's longitudinal axis, so that Equation (2) require integration of the unactuated dynamics to obtain the planar trajectory from the surge and angular velocities. Indicate the thruster surge force of the i-ROV with $\tau_{ui}(t)$ and the yaw torque of the i-ROV with $\tau_{ri}(t)$. Indicate the mass of the i-ROV with m_i , the inertial moment about the axis perpendicular to the plane (x_{bi}, y_{bi}) with I_{zi} and the hydrodynamic masses with $X_{\dot{u}}, Y_{\dot{v}}$ and $N_{\dot{r}}$. The dynamic model of the platoon of ROVs results as it follows:

$$\begin{aligned} &m_{ui}\dot{u}_i(t) - m_{vi}v_i(t)r_i(t) = \tau_{ui}(t), \\ &m_{vi}\dot{v}_i(t) + m_{ui}r_i(t)u_i(t) = 0, \\ &m_{ri}\dot{r}_i(t) = \tau_{ri}(t), \\ &\mathrm{i} = 1...\mathrm{r}, \end{aligned} \tag{3}$$

where:

$$\begin{aligned} &m_{ui} = m_i - X_{\dot{u}}, \\ &m_{vi} = m_i - Y_{\dot{v}}, \\ &m_{ri} = I_{zi} - N_{\dot{r}}, \\ &\mathrm{i} = 1...\mathrm{r}. \end{aligned} \tag{4}$$

Note that the sway force is unavailable, so that, to deal with this problem, the following polar coordinates transformation is defined (see Fig. 2):

$$\begin{aligned} &u_{li}(t) = \sqrt{u_i^2(t) + v_i^2(t)}, \\ &\psi_{li}(t) = \psi_i(t) + \psi_{ai}(t), \\ &i = 1...r, \end{aligned} \tag{5}$$

where:

$$\psi_{ai}(t) = \arctan[v_i(t)/u_i(t)] \quad (6)$$
$$i = 1...r$$

are the sideslip angles of the vehicles.

Since the surge velocity is positive, it gives:

$$-0.5\pi \le \psi_{ai}(t) \le 0.5\pi, \quad (7)$$
$$i = 1...r.$$

The dynamical equations of the platoon of ROVs result as it follows:

$$\begin{aligned} &\dot{x}_i(t) = u_{li}(t)\cos\psi_{li}(t), \\ &\dot{y}_i(t) = u_{li}(t)\sin\psi_{li}(t), \\ &\dot{\psi}_{li}(t) = r_i(t) + \dot{\psi}_{ai}(t) = r_{li}(t), \\ &\tau_{ui}(t) = m_{ui}\dot{u}_{li}(t)/\cos\psi_{ai}(t) - m_{vi}v_i(t)r_i(t) + \\ &\quad + \frac{m_{ui}}{m_{vi}} r_i(t)u_i(t)\tan\psi_{ai}(t), \\ &\tau_{ri}(t) = m_{ri}\dot{r}_i(t), \\ &i = 1...r. \end{aligned} \quad (8)$$

The accelerations of the i-ROV with respect to the body reference system may be written as it follows:

$$\begin{bmatrix} \ddot{x}_{Bi}(t) \\ \ddot{y}_{Bi}(t) \end{bmatrix} = \begin{bmatrix} \cos(\psi_{li}(t) - \psi_{ai}(t)) & \sin(\psi_{li}(t) - \psi_{ai}(t)) \\ -\sin(\psi_{li}(t) - \psi_{ai}(t)) & \cos(\psi_{li}(t) - \psi_{ai}(t)) \end{bmatrix} \begin{bmatrix} \ddot{x}_i(t) \\ \ddot{y}_i(t) \end{bmatrix} \quad (9)$$
$$i = 1...r$$

Practically each vehicle of the open chain configuration of Fig. 1 is equipped with an inertial navigation system which calculates the positions, velocities and accelerations of all the ROVs from an Inertial Measurement Unit (IMU). In the IMU there are accelerometers measuring specific force and gyros measuring angular rate. The output of the accelerometers gives data on the Accelerations (9). Therefore the longitudinal and lateral positions may be evaluated by applying the inverse of (9) and then double integration, once the orientation of the ROV has been calculated from the data of the gyros.

The mathematical model given by (8) will not be used to plan the trajectories. In Section III, only geometrical considerations will be made in order to plan circular trajectories. They will be used in Section IV to design the high level fuzzy system and the low level kinetic control.

III. DECENTRALIZED MOTION PLANNING FOR MUTIPLE ROVS

In this section a new decentralized motion planning algorithm generating the reference trajectories of all the underwater vehicles is presented. A circular reference motion is considered for the cooperative ROVs. From Equation (8) it is evident that an autonomous ROV moving with constant linear and angular velocities, tracks a circular trajectory. Note that the velocities above include the motion along the sway direction. Therefore a reference motion may be planned along a circumference that includes the initial coordinates above and the position of the target. From the observation of the Fig. 3, the following geometrical considerations can be developed.

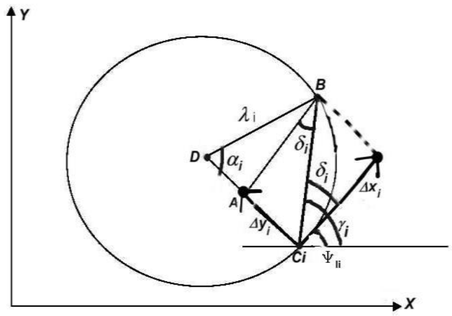

Fig. 3 Trajectory planning

Let $C_i(x_i(0), y_i(0), \psi_{li}(0))$ be the initial position of the i-ROV of the open chain configuration, where ψ_{li} is given by the second equation of (5) and considers the sidelslip angle due to the motion of the ROV along the sway direction. Consider the position B with generalized coordinates $[x_T \ \ y_T \ \ \psi_T]$, as the position and orientation of the target. Let Δx_i and Δy_i be the shiftings along the tangent and radial directions respectively of the i-vehicle. Let BC_i be the distance from the position of the target to the initial position of the i-ROV. Indicate with λ_i the radius of the circumference. It yields:

$$\begin{aligned} &BC_i = \tilde{d}_i = \sqrt{(x_T - x_i(0))^2 + (y_T - y_i(0))^2}, \\ &\gamma_i = \arctan\left[(y_T - y_i(0))/(x_T - x_i(0))\right], \\ &i = 1...r, \end{aligned} \quad (10)$$

where γ_i is the angle between BC_i and the x axis. Consider the following angular relation (see Fig. 3):

$$\begin{aligned} &\delta_i = \gamma_i - \psi_{li}(0) = \\ &= \arctan\left[(y_T - y_i(0))/(x_T - x_i(0))\right] - \psi_{li}(0). \\ &i = 1...r \end{aligned} \quad (11)$$

The length of the line BA is equal to the distance Δx_i. Therefore, if we consider the triangle C_iAB, then:

$$\Delta x_i = \tilde{d}_i \cos\delta_i; \ \Delta y_i = \tilde{d}_i \sin\delta_i$$
$$i = 1...r. \quad (12)$$

From the observation of Fig. 3, the angular shifting α_i between C_i and B may be calculated. It yields:

$$\Delta x_i = \lambda_i \sin\alpha_i \quad (13)$$
$$i = 1...r.$$

From observation of the triangle DAB, it results:

$$\lambda_i^2 = (\lambda_i - \Delta y_i)^2 + \Delta^2 x_i \quad (14)$$
$$i = 1...r.$$

The solution of the Equation (14) with respect to λ_i is:

$$\lambda_i = (\Delta^2 x_i + \Delta^2 y_i)/2\Delta y_i. \quad (15)$$
$$i = 1...r$$

The values of the reference angular (r_{lir}) and linear (u_{lir}) velocities of each cooperative vehicle may be calculated as follows:

$$r_{lir} = \frac{\alpha_i}{\Delta T};\; u_{lir} = r_{lir}\lambda_i; \quad i = 1...r, \tag{16}$$

where ΔT is a fixed look-ahead time interval chosen by the designer. Now consider multiple underwater vehicles in an initial open chain configuration (cf. Fig. 1), i.e. collinear and with the same orientations given by Δx_i *(i=1, 2)*. Note that the direction above includes the motion along the sway direction so that it considers the sideslip angle given by (6). The algorithm allows circular trajectories without intersections to be planned, so that the ROVs will avoid collisions while moving. Each trajectory is planned independently of the others. The main advantage of this approach is the communication less between the vehicles. Fig. 4 shows an example, where two underwater vehicles are considered in open chain configuration $C_1 - C_2$. One observes that the first vehicle of the open chain follows a circular trajectory from C_1 to the target *B* along Δx_1, while the second vehicle follows a circular trajectory from C_2 to the target one along Δx_2. The distance between C_1 and *B* is smaller than the distance between C_2 and *B*, so that, based on the Equation (10), it is $\tilde{d}_1 < \tilde{d}_2$. Consequently, based on the Equations (12) and (15), the radius of the circumference tracked by the first ROV (i.e. λ_1) is smaller than the radius of the circumference tracked by the second ROV (i.e. λ_2). Since the vehicles are initially collinear and have the same orientations, and the circumferences must be include both the initial positions of the vehicles and the target position, the trajectories are without intersections and the vehicles can reach the target without collisions. The method can be used for *r* cooperative underwater vehicles in initial open chain $C_1 - C_2 - ... - C_r$, so that each ROV can reach the target without coming into collision with other ROVs.

The ROVs have to be in open chain configuration initially, i.e. collinear. If there is an underwater vehicle which is not mutually collinear, it must reach a collinear position. On this subject, some studies have focused on modelling formations of non-holonomic vehicles [17].

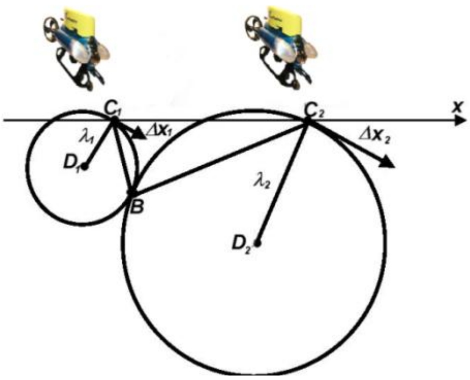

Fig. 4 Cooperative motion of two ROVs

IV. FUZZY/LYAPUNOV CONTROL AND KINETIC SYSTEM FOR PLANAR MOTION OF MULTIPLE ROVS

A. *Planar Motion Control Problem for Multiple ROVs*

Consider the reference surge velocities and the reference yaw rates given by (16) in presence of a certain sideslip angle. Indicate the reference signals of each underwater vehicle with $u_{ri}(t)$ and $r_{ri}(t)$. They are without sideslip angle. Let the time varying coordinates of the reference trajectories evaluated in relation to the ERF be $x_{ri}(t), y_{ri}(t)$ and $\psi_{lir}(t)$. From Equation (8) it is evident that the equations of the reference planar trajectories are the following:

$$\begin{aligned} &\dot{x}_{ri}(t) = u_{lir}(t)\cos\psi_{lir}(t), \\ &\dot{y}_{ri}(t) = u_{lir}(t) sen\psi_{lir}(t), \\ &\dot{\psi}_{lir}(t) = r_{ri}(t) + \dot{\psi}_{ai}(t) = r_{lir}(t), \\ &\mathrm{i} = 1...\mathrm{r} \end{aligned} \tag{17}$$

where:

$$u_{ri}(t) = u_{lir}(t)\cos\psi_{ai}(t), \quad i = 1...r. \tag{18}$$

Indicate with $u_{ci}(t)$ and $r_{ci}(t)$ the surge velocities and yaw rates controls of each ROV respectively, while indicate with $u_{lic}(t)$ and $r_{lic}(t)$ the guidance control laws in the presence of sideslip angle. It yields:

$$\begin{aligned} &\boldsymbol{\alpha}^T_{ci}(t) = [u_{ci}(t) \quad r_{ci}(t)], \\ &0 < \sigma_{1i} \le u_{ci}(t) \le \sigma_{2i}, \\ &\sigma_{i1}, \sigma_{2i} \in R^+ \\ &i = 1...r \end{aligned} \tag{19}$$

and:

$$\boldsymbol{\beta}_{ci}(t) = \begin{bmatrix} u_{ci}(t)/\cos\psi_{ai}(t) \\ r_{ci}(t) + \dot{\psi}_{ai}(t) \end{bmatrix} = \begin{bmatrix} u_{lic}(t) \\ r_{lic}(t) \end{bmatrix} \quad \mathrm{i} = 1...\mathrm{r}, \tag{20}$$

Note that, once (7) has been verified, the control signals $u_{lic}(t)$ are positive every time if and only if the surge velocities $u_{ci}(t)$ are positive. If the speed of each ROV reaches the control velocity instantaneously, then the position and orientation of each vehicle may be obtained as it follows:

$$\begin{aligned} &\dot{x}_i(t) = u_{lc}(t)\cos\psi_l(t), \\ &\dot{y}_i(t) = u_{lc}(t) sen\psi_{li}(t), \\ &\dot{\psi}_{li}(t) = r_{ci}(t) + \dot{\psi}_{ai}(t) = r_{lic}(t) \\ &i = 1...\mathrm{r}.. \end{aligned} \tag{21}$$

In any case the dynamical effects causes the impossibility of instantaneous reachability of the control velocities, so that indicate the surge force and the yaw torque control signals of each ROV with $\tau_{uic}(t)$ and $\tau_{ric}(t)$ and with $\boldsymbol{\alpha}_i(t)$ the following vectors :

$$\boldsymbol{\alpha}_i^{\mathbf{T}}(t) = [u_i(t) \;\; r_i(t)] \quad \mathrm{i} = 1...\mathrm{r}, \tag{22}$$

where $u_i(t)$ and $r_i(t)$ are the actual surge speeds and yaw rates of the multiple ROVs. Let $u_{li}(t)$ and $r_{li}(t)$ be the same functions in the presence of sideslip angle.

The fuzzy controller proposed in this paper gives the Guidance Commands (20) for all the vehicles, and ensures the boundedness and convergence to zero of motion errors in relation to the body frame given by:

$$\mathbf{e}_i(t)=\begin{bmatrix} e_{xi}(t)\\ e_{yi}(t)\\ e_{\psi li}(t)\end{bmatrix}=\begin{bmatrix}\cos\psi_{li}(t) & \sin\psi_{li}(t) & 0\\ -\sin\psi_{li}(t) & \cos\psi_{li}(t) & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix} x_{ri}(t)-x_i(t)\\ y_{ri}(t)-y_i(t)\\ \psi_{lir}(t)-\psi_{li}(t)\end{bmatrix}$$
$$i=1...r. \tag{23}$$

However the Fuzzy controller does not consider the dynamical effects. In particular the dynamics of the ROVs are given by the fourth and fifth equations in (8); therefore it is necessary to consider a dynamical controller which gives the functions $\tau_{uic}(t)$ and $\tau_{ric}(t)$ to ensure convergence to zero of the errors given by the difference between the actual speeds and the fuzzy guidance control laws:

$$\bar{\mathbf{e}}_i(t)=\boldsymbol{\alpha}_{ci}(t)-\boldsymbol{\alpha}_i(t)=\begin{bmatrix} e_{ui}(t)\\ e_{ri}(t)\end{bmatrix}=\begin{bmatrix} u_{ci}(t)-u_i(t)\\ r_{ci}(t)-r_i(t)\end{bmatrix}=$$
$$=\begin{bmatrix}(u_{lic}(t)-u_{li}(t))\cos\psi_{ai}(t)\\ (r_{lic}(t)-r_{li}(t))\end{bmatrix} \tag{24}$$
$$\mathrm{i}=1...\mathrm{r}.$$

B. Fuzzy Control Laws with Lyapunov's Stability

The fuzzy system generates the guidance laws given by (19) and (20), where $u_{lc}(t)$ has to be saturated and must be a forward velocity, so that the Lyapunov's asymptotical stability of the tracking errors given by (23) is ensured. The fuzzy control laws for the multiple ROVs are the following:

$$\begin{aligned}
&u_{ci}(t)=f_i(\mathbf{e}_i(t))*\cos\psi_{ai}(t)+u_{ri}(t),\\
&r_{ci}(t)=[r_{ri}(t)+\dot{\psi}_{ai}(t)]+[u_{ri}(t)/\cos\psi_{ai}(t)]\times\\
&\quad\times[g_i(\mathbf{e}_i(t))+h_i(\mathbf{e}_i(t))\sin e_{\psi li}(t)],\\
&u_{ci\max}\ge u_{ci}(t)\ge 0,\\
&u_{ri}(t)>0\quad\forall t,\\
&\mathrm{i}=1...\mathrm{r}
\end{aligned}\tag{25}$$

where the nonlinear functions $f_i(\mathbf{e}_i(t))$, $g_i(\mathbf{e}_i(t))$ and $h_i(\mathbf{e}_i(t))$ are continuous and differentiable. The functions (20) are explicated as it follows:

$$\begin{aligned}
&u_{lic}(t)=f_i(\mathbf{e}_i(t))+u_{lir}(t),\\
&r_{lic}(t)=r_{lir}(t)+u_{lir}(t)[g_i(\mathbf{e}(t))+h_i(\mathbf{e}(t))\sin e_{\psi li}(t)],\\
&u_{lic\max}\ge u_{lic}(t)\ge 0,\\
&u_{lir}(t)>0\quad\forall t\\
&i=1...r.
\end{aligned}\tag{26}$$

The functions $f_i(\mathbf{e}_i(t)), g_i(\mathbf{e}_i(t))$ and $h_i(\mathbf{e}_i(t))$ are associated to a single ROV of the open chain of Fig. 1 and they are the crisp outputs of fuzzy controllers. The Fuzzy inference systems are explained below. The following linguistic labels are defined:

S=Small;

M=Medium;

H=High;

Opp=Opposite.

The input and output Fuzzy memberships are generalized bell functions and they are shown in Figs. 5 and 6.

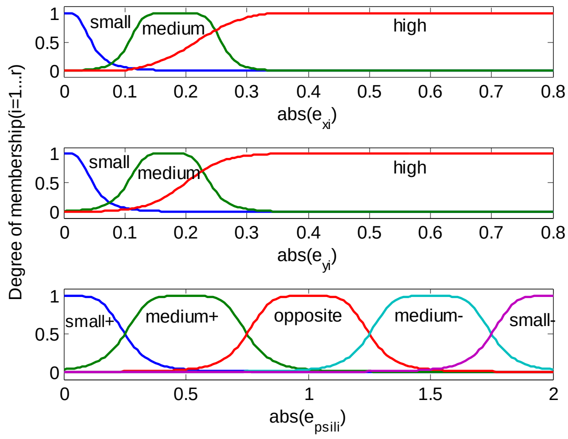

Fig. 5 Input membership functions for multiple ROVs

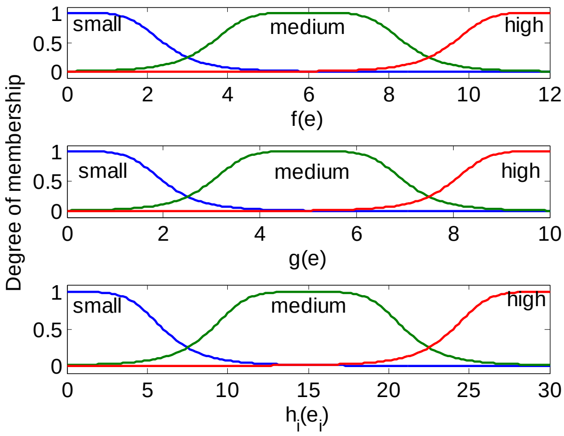

Fig. 6 Output membership functions for multiple ROVs

The fuzzy rules are shown in Table 1.

TABLE I FUZZY RULES

	abs $(e_{xi}(t))$	abs $(e_{yi}(t))$	abs $(e_{\psi li}(t))$	f_i	g_i	h_i
1	S	S	S+	S	S	S
2	S	M	S+	S	M	S
3	S	H	S+	M	H	S
4	M	S	S+	M	S	S
5	M	M	S+	M	M	S
6	M	H	S+	M	H	S
7	H	S	S+	H	M	S
8	H	M	S+	H	M	S
9	H	H	S+	H	H	S
10	S	S	M+	M	M	M

11	S	M	M+	M	M	M
12	S	H	M+	M	H	M
13	M	S	M+	M	M	M
14	M	M	M+	M	M	M
15	M	H	M+	M	H	M
16	H	S	M+	H	M	M
17	H	M	M+	H	M	M
18	H	H	M+	H	H	M
19	S	S	OPP	M	M	H
20	S	M	OPP	M	M	H
21	S	H	OPP	M	H	H
22	M	S	OPP	M	M	H
23	M	M	OPP	M	M	H
24	M	H	OPP	M	H	H
25	H	S	OPP	H	M	H
26	H	M	OPP	H	M	H
27	H	H	OPP	H	H	H
28	S	S	M-	M	M	M
29	S	M	M-	M	M	M
30	S	H	M-	M	H	M
31	M	S	M-	M	M	M
32	M	M	M-	M	M	M
33	M	H	M-	M	H	M
34	H	S	M-	H	M	M
35	H	M	M-	H	M	M
36	H	H	M-	H	H	M
37	S	S	S-	S	S	S
38	S	M	S-	S	M	S
39	S	H	S-	M	H	S
40	M	S	S-	M	S	S
41	M	M	S-	M	M	S
42	M	H	S-	M	H	S
43	H	S	S-	H	M	S
44	H	H	S-	H	H	S
45	H	H	S-	H	H	S

Remark 1: The inputs of the fuzzy inference system are the absolute values of the motion errors. The selected values of the input memberships may be different for each underwater vehicle. However, if all the ROVs have the same kinematic and dynamic characteristics, it is desiderable that the values above are the same. This is also valid for the values of the functions $f_i(\mathbf{e}_i(t))$, $g_i(\mathbf{e}_i(t))$ and $h_i(\mathbf{e}_i(t))$ that appear in the fuzzy output memberships. In any case the input and output ranges may be subjected to changes manually to optimize the performance of the motion of all the underwater vehicles with respect to uncertainties of the marine environment which perturb the nominal motion of the ROVs, so that the advantage of the fuzzy control is the robustness with respect to the disturbances above.

The fuzzy rules are "if…then" types. The method for the logical "and" and for the implication are the minimum and the 'minimum' and the 'fuzzy minimum'. The consequents of each rule have been recombined using a maximum method. The defuzzyfication method is the 'centroid'.

The choice of the form of the membership functions is not accidental, but it is essential to obtain the Lyapunov's stability of the motion errors given by (23).

Assumption 1. The membership functions have to be chosen in order to satisfy the following properties:

Property 1:

$$f_i(\mathbf{e}_i(t)) = 0 \Leftrightarrow \mathbf{e}_i(t) = \mathbf{0},\quad g_i(\mathbf{e}_i(t)) = 0 \Leftrightarrow \mathbf{e}_i(t) = \mathbf{0},\quad h_i(\mathbf{e}_i(t)) = 0 \Leftrightarrow \mathbf{e}_i(t) = \mathbf{0},\quad \mathrm{i} = 1...\mathrm{r}. \tag{27}$$

Property 2:

$$0 \le f_i(\mathbf{e}_i(t)) \le f_{i\max} \quad \mathrm{i} = 1...\mathrm{r} \tag{28}$$

Property 3:

$$0 \le g_i(\mathbf{e}(t)) \le g_{i\max} \quad \mathrm{i} = 1...\mathrm{r}. \tag{29}$$

Property 4:

$$0 \le h_i(\mathbf{e}_i(t)) \le h_{i\max} \quad \mathrm{i} = 1...\mathrm{r}. \tag{30}$$

Property 5:

$$\sum_{j=0}^{M-1}\left[\int_{j}^{j+1} g_i(\mathbf{e}_i(t))dt\right] > 0,\quad j \in N, M > 0,\quad i = 1...r. \tag{31}$$

Property 6:

$$\begin{gathered}\frac{\partial f_i(\mathbf{e}_i(t))}{\partial e_{xi}} > 0; \frac{\partial f_i(\mathbf{e}_i(t))}{\partial e_{yi}} \cong 0; \frac{\partial f_i(\mathbf{e}_i(t))}{\partial e_{\psi\, li}} \cong 0,\\ \frac{\partial g_i(\mathbf{e}_i(t))}{\partial e_{xi}} \cong 0; \frac{\partial g_i(\mathbf{e}_i(t))}{\partial e_{yi}} > 0; \frac{\partial g_i(\mathbf{e}_i(t))}{\partial e_{\psi\, li}} \cong 0,\\ \frac{\partial h_i(\mathbf{e}_i(t))}{\partial e_{xi}} \cong 0; \frac{\partial h_i(\mathbf{e}_i(t))}{\partial e_{yi}} \cong 0; \frac{\partial h_i(\mathbf{e}_i(t))}{\partial e_{\psi\, li}} > 0,\\ i = 1...r\end{gathered} \tag{32}$$

Remark 2: From the Property (27) and from the first equation in (26), it yields:

$$u_{lir}(t) = \rho_{1i} \le u_{lic}(t) \le \rho_{2i} = f_{i\max} + u_{lir}(t)\ ,\quad \mathrm{i} = 1...\mathrm{r}, \tag{33}$$

where $f_{i\max}$ is the maximum value of the fuzzy function $f_i(\mathbf{e}_i(t))$ associated to the i-ROV. Note that the saturation value of the linear speed control of each underwater vehicle depends on the numerical value of $f_{i\max}$, so that the maximum values of each control signals may be regulated by varying the maximum value of each fuzzy function. Since the reference surge speed is positive, the linear control speed of the i-ROV is bounded and it is a forward command.

Now a reformulation of the theorem presented in [15] for single ROV, is presented in this paper for multiple ROVs.

Theorem 1. Consider the mathematical model of the system constituted by *r* ROVs as given by (21), in closed loop with the fuzzy control signals given by (26). Under the assumption 1, the equilibrium state of the closed loop system is the origin of the state space and it is asymptotically stable.

Proof. After some computations, the state space representation of the closed loop motion control system assumes the following form:

$$\dot{\mathbf{e}}_i(t) = \begin{bmatrix} (r_{lir}(t) + u_{lir}(t)g_i(\mathbf{e}_i(t)) + h_i(\mathbf{e}_i(t))\sin e_{\psi\, li}(t))e_{yi}(t) + \\ + (f_i(\mathbf{e}_i(t)) + u_{lir}(t)(1-\cos e_{\psi\, li}(t))) \\ -(r_{lir}(t) + u_{lir}(t)(g_i(\mathbf{e}_i(t)) + h_i(\mathbf{e}_i(t))\sin e_{\psi\, li}(t))e_{xi} + \\ + u_{lir}(t)\sqrt{1-\cos^2 e_{\psi\, li}(t)} \\ -u_{lir}(t)(g_i(\mathbf{e}_i(t)) + h_i(\mathbf{e}_i(t))\sin e_{\psi\, li}(t)) \end{bmatrix} \tag{34}$$

$\mathrm{i} = 1...\mathrm{r}.$

The equilibrium state of the Representation (34) is the origin of the state space, once the property of the fuzzy functions given by (27) is verified. The following Lyapunov's function is chosen:

$$V_0 = \sum_{i=1}^{r} (f_i(\mathbf{e}_i) + g_i(\mathbf{e}_i)) + \sum_{i=1}^{r} \left[(1-\cos e_{\psi li}) \sum_{j=0}^{M-1} \left(\int_j^{j+1} g_i(\mathbf{e}_i(t))dt \right) \right] \tag{35}$$

Differentiating the Function (35) and considering the properties given by (32), after some computations it yields:

$$\begin{aligned}\dot{V}_0 = &-\sum_{i=1}^{r} \frac{\partial f_i(\mathbf{e}_i(t))}{\partial e_{xi}} (f_i(\mathbf{e}_i(t) + u_{lir}(1-\cos e_{\psi li})) + \\ &+\sum_{i=1}^{r} \left(u_{lir}\sqrt{1-\cos^2 e_{\psi li}} \frac{\partial g_i(\mathbf{e}_i(t))}{\partial e_{yi}} \right) + \\ &-\sum_{i=1}^{r} \left[\sqrt{1-\cos^2 e_{\psi li}} u_{lir} g_i(\mathbf{e}_i(t)) \sum_{j=0}^{M-1} \left(\int_j^{j+1} g_i(\mathbf{e}_i(t))dt \right) \right] + \\ &-\sum_{i=1}^{r} \left[u_{lir} h_i(\mathbf{e}_i(t)) \sin^2 e_{\psi li} \sum_{j=0}^{M-1} \left(\int_j^{j+1} g_i(\mathbf{e}_i(t))dt \right) \right] \\ &+\sum_{i=1}^{r} \left[(1-\cos e_{\psi li}) \sum_{j=0}^{M-1} g_i(\mathbf{e}_i(j)) \right]\end{aligned} \tag{36}$$

Based on the Properties (27)-(31), one may observe that the Function (35) is definite positive. Assuming the reference linear velocities of all the ROVs ($u_{lir,} i = 1...r$) are positive and considering the Assumption 1, lead to the following mathematical relations:

$$\begin{aligned}&0 \le \sum_{i=1}^{r} \left(\sqrt{1-\cos^2 e_{\psi li}} u_{lir} \frac{\partial g_i(\mathbf{e}_i(t))}{\partial e_{yi}} \right) < \\ &< \sum_{i=1}^{r} \left[\sqrt{1-\cos^2 e_{\psi li}} u_{lir} g_i(\mathbf{e}_i(t)) \sum_{j=0}^{M-1} \left(\int_j^{j+1} g_i(\mathbf{e}_i(t))dt \right) \right] \\ &\sum_{i=1}^{r} \left[u_{ri} h_i(\mathbf{e}_i(t))(1-\cos^2 e_{\psi i}) \sum_{j=0}^{M-1} \left(\int_j^{j+1} g_i(\mathbf{e}_i(t))dt \right) \right] > \\ &> \sum_{i=1}^{q} \left[(1-\cos e_{\psi i}) \sum_{j=0}^{M-1} g_i(\mathbf{e}_i(j)) \right] \ge 0\end{aligned} \tag{37}$$

Therefore Function (36) is definite negative and the equilibrium point of Model (34) is asymptotically stable.

C. Kinetic Control for Motion Control of Multiple ROVs

The kinetic control generates the thruster surge force and the yaw torque control for the underactuated system of multiple underwater vehicles given by (8). The dynamics of the ROVs implies the velocity errors given by (24), so that it is necessary to generate the dynamical control laws to ensure the convergence to zero of the errors above.

The following theorem may be formulated.

Theorem 2. Consider the underactuated system of the multiple ROVs given by (8) in closed loop with the fuzzy guidance commands given by (26) and with the following dynamical control laws:

$$\begin{aligned}&\tau_{ric}(t) = m_{ri}[\dot{r}_{lic}(t) - \ddot{\psi}_{ai}(t)] + \bar{K}_i m_{ri}[r_{lic}(t) - \dot{\psi}_{ai}(t) - r_i(t)], \\ &\tau_{uic}(t) = \frac{m_{ui}\dot{u}_{lic}(t)}{\cos\psi_{ai}(t)} + m_{ui}[r_{lic}(t) - \dot{\psi}_{ai}(t)] \times \\ &\quad \times \int_0^t [r_{lic}(t) - \dot{\psi}_{ai}(t)] u_{lic}(t) \cos\psi_{ai}(t)dt + \\ &\quad + \frac{m_{ui}}{m_{vi}} [(r_{li}(t) - \dot{\psi}_{ai}(t)) u_{li}(t) \sin\psi_{ai}(t)] + \\ &\quad + \frac{K_i m_{ui}}{\cos\psi_{ai}(t)} (u_{lic}(t) - u_{li}(t)), \\ &\bar{K}_i, K_i \in R^+ \\ &i = 1...r.\end{aligned} \tag{38}$$

where $\tau_{uic}(t)$ and $\tau_{ric}(t)$ are the surge force and the yaw torque controls of each ROV respectively, m_{ui}, m_{vi} and m_{ri} are given by (4), $u_{lic}(t)$ and $r_{lic}(t)$ are the fuzzy guidance commands given by (26), $u_{li}(t)$ and $r_{li}(t)$ are the actual velocities of each vehicle including the sideslip angle $\psi_{ai}(t)$ given by (6). Then the velocity errors given by (24) converge asymptotically to zero.

Proof. From the first equation of (38) and fourth and fifth equations of (8) it follows the following system of differential equations:

$$m_{ri}[\dot{r}_{lic}(t) - \ddot{\psi}_{ai}(t) - \dot{r}_i(t)] + \bar{K}_i m_{ri}[r_{lic}(t) - \dot{\psi}_{ai}(t) - r_i(t)] = 0 \quad i = 1...r. \tag{39}$$

Indicate whit $\theta_i(t)$ the following functions:

$$\theta_i(t) = r_{lic}(t) - \dot{\psi}_{ai}(t) - r_i(t) \quad i = 1...r, \tag{40}$$

The Equations System (39) can be rewritten as it follows:

$$\dot{\theta}_i(t) + \bar{K}_i\theta_i(t) = 0 \quad i = 1...r. \tag{41}$$

Note that the functions $\theta_i(t)$ converge to zero rapidly if the constant $\bar{K}_i$ are sufficiently large. It yields:

$$\lim_{t\to\infty}[r_{ci}(t) - r_i(t)] = 0 \quad i = 1...r, \tag{42}$$

therefore the second component of the Vector (24) converges asymptotically to zero. From the second equation of (3) the sway velocity of each vehicle results as it follows:

$$v_i(t) = -\frac{m_{ui}}{m_{vi}} \int_0^t r_i(t)u_i(t)dt = -\frac{m_{ui}}{m_{vi}} \int_0^t r_i(t)u_{li}(t)\cos\psi_{ai}(t)dt \quad \text{i = 1...r,} \tag{43}$$

Replacing (43) in the fourth equation of (8), and by choosing the surge force control that results from the second equation of (38), after some computations, it follows:

$$\begin{aligned}&\frac{m_{ui}(\dot{u}_{lic}(t) - \dot{u}_{li}(t))}{\cos\psi_{ai}(t)} + \frac{K_i m_{ui}}{\cos\psi_{ai}(t)}[u_{lic}(t) - u_{li}(t)] + \\ &m_{ui}[r_{lic}(t) - \dot{\psi}_{ai}(t)] \int_0^t [r_{lic}(t) - \dot{\psi}_{ai}(t)] u_{lic}(t)\cos\psi_{ai}(t)dt + \\ &- m_{ui}[r_{li}(t) - \dot{\psi}_{ai}(t)] \int_0^t [r_{li}(t) - \dot{\psi}_{ai}(t)] u_{li}(t)\cos\psi_{ai}(t)dt = 0, \\ &i = 1...r.\end{aligned} \tag{44}$$

Considering that the actual orientation of each ROV converges to the fuzzy guidance law (cf. eq. 42), in a steady state the Equations (44) may be rewritten as it follows:

$$m_{ui}[\dot{u}_{ci}(t)-\dot{u}_i(t)]+K_i m_{ui}[u_{ci}(t)-u_i(t)]+ \\ +m_{ui}r_i(t)\cos^2\psi_{ai}(t)\int_0^t r_i(t)[u_{ci}(t)-u_i(t)]dt=0 \\ \mathrm{i}=1...\mathrm{r}. \quad (45)$$

Now, the planned trajectories are circumferences, so that the steady state value of the actual yaw rates of all the vehicles are constant numbers. Indicate the values above with ρ_i (i=1...r). Equation (45) may be rewritten in function of the velocity errors given by the first component of (24) as it follows:

$$\ddot{e}_{ui}(t)+K_i\dot{e}_{ui}(t)+[\rho_i\cos\psi_{ai}(t)]^2 e_{ui}(t)=0, \\ \mathrm{i}=1...\mathrm{r}. \quad (46)$$

The eigenvalues associated to the differential equations (46) are given by the following equations:

$$\mu_i^{\,2}+K_i\mu_i+[\rho_i\cos\psi_{ai}(t)]^2=0, \\ i=1...r \quad (47)$$

The eigenvalues μ_i of each differential equation have to be real and negative, so the following constraints must be satisfied:

$$K_i>2\rho_i\sqrt{0.5\pi}, \\ \mathrm{i}=1...\mathrm{r}. \quad (48)$$

Once the constraints given by (48) are satisfied, the solutions of the Equations System (47), i.e. the first component of the Vector (24), converge asymptotically to zero.

To clarify how the fuzzy and the kinetic controllers (cf. Eqs. 26 and 38) work together, Fig. 7 shows a block diagram of the closed loop control system of the i-ROV.

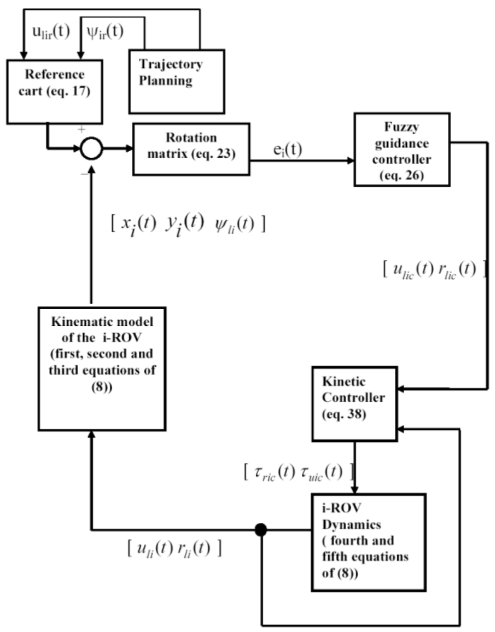

Fig. 7 Block diagram of the motion control system of the i-ROV

V. SIMULATION EXPERIMENTS

In this section simulation in Matlab environment has been performed, where the efficiency of the motion controls system and the effectiveness of the planning algorithm are shown in case of two identical ROVs.

The parameters of the underwater vehicles have been chosen based on existing underwater vehicles [16]. The nominal parameters of the ROVs are as follows:

$$m_i=30kg, \\ X_{\dot{u}i}=Y_{\dot{v}i}=29.4462\,kg, \\ N_{\dot{r}i}=1.5423\,kg\cdot m^2, \\ I_{zi}=0.27\,kg\cdot m^2, \\ i=1,2. \quad (49)$$

The numerical values of the fuzzy memberships are shown in Figs. 5 and 6, while Fig.8 shows the fuzzy surfaces $f_i(\mathbf{e}_i(t)), i=1,2$. The fuzzy surfaces $g_i(\mathbf{e}_i(t))$ and $h_i(\mathbf{e}_i(t))$ have the same symmetry of $f_i(\mathbf{e}_i(t))$.

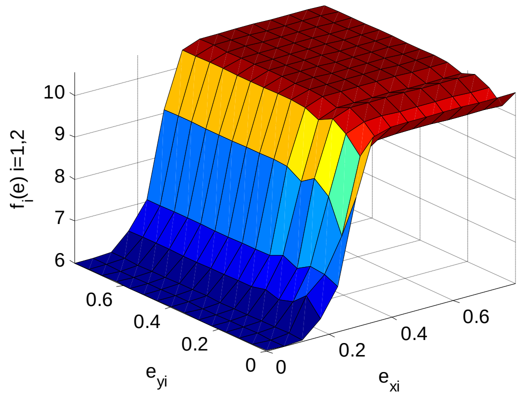

Fig. 8 Fuzzy control surface of the ROVs

The reference trajectories of each vehicle were generated using the algorithm developed in Section III. Initially the ROVs are in open chain configuration along x-direction. All the generalized coordinates of the motion of the ROVs are shown in Fig. 9.

The initial positions of the two vehicles are as follows:

$$x_1(t=0)=40m; \\ x_2(t=0)=80m; \\ y_1(t=0)=20m; \\ y_2(t=0)=20m; \\ \psi_{l1}(t=0)=1{,}74rad; \\ \psi_{l2}(t=0)=1.74rad. \quad (50)$$

The position coordinates of the target are:

$$x_T=30.7m; \\ y_T=-40m. \quad (51)$$

In the planar motion the depth of all the vehicles is constant and it is assumed as it follows:

$$z_i=-15m, \\ i=1,2. \quad (52)$$

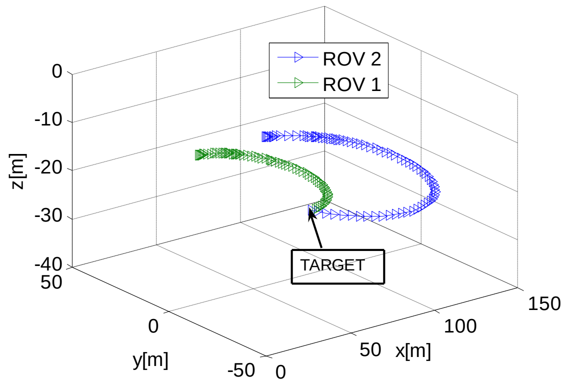

Fig. 9 Planar motion of the ROVs

Remark 3: Note that there are not intersections between the trajectories, so that there are not collisions between the vehicles during the motion.

Figures 10 and 11 show the motion errors given by (23) and the sideslip angles given by (6).

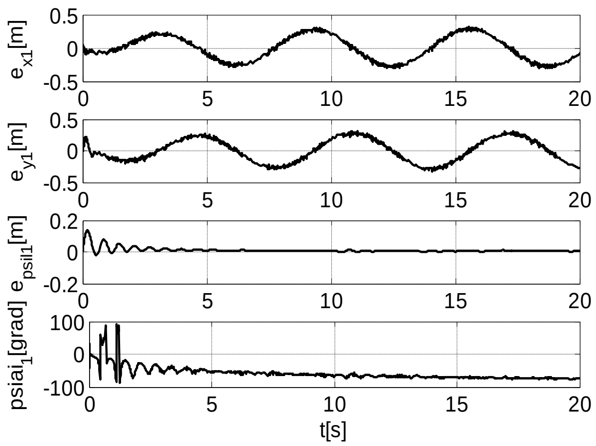

Fig. 10 Motion errors and sideslip angle of the ROV 1

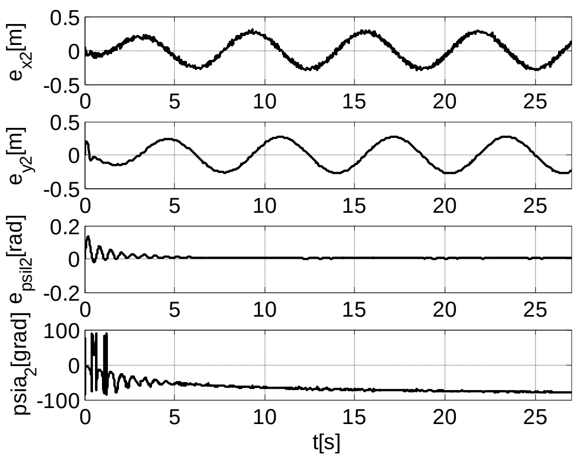

Fig. 11 Motion errors and sideslip error of the ROV 2

Remark 4: Observing Figs. 10 and 11, it is evident that the ranges of the errors of the fuzzy memberships shown in Figs 5, 6 and 8 cover the values of the motion errors of each vehicle. The motion errors are equal to zero initially. Due to the dynamics of the underwater vehicles, there is a certain delay time before reaching the steady state. Therefore, after just a short time, the longitudinal and lateral motion errors are subjected to very small oscillations around the equilibrium state, while the orientation errors converge to zero. The values of the sideslip angles are in the range shown in (7).

In Figs. 12 and 13, the fuzzy guidance commands given by (26) and the velocity errors of the two vehicles given by the first and second components of the Vector (24) are plotted.

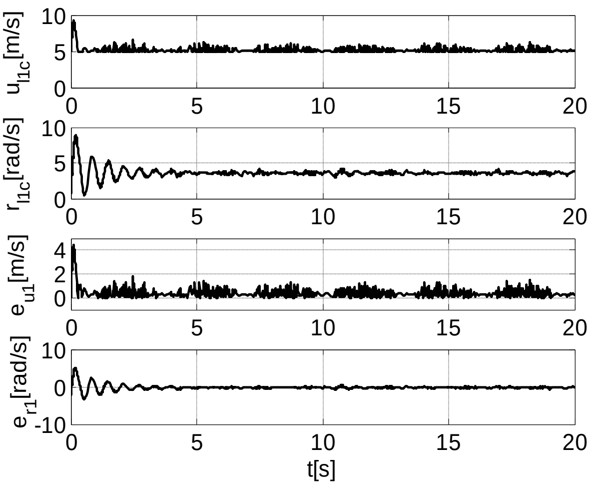

Fig. 12 Fuzzy guidance commands and velocity errors of ROV 1

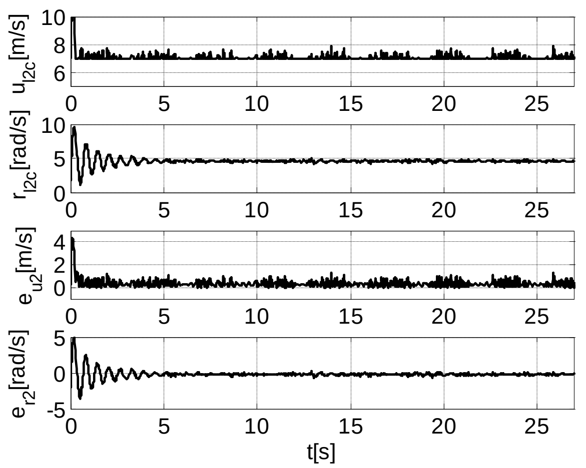

Fig. 13 Fuzzy guidance commands and velocity errors of ROV 2

Remark 5: Observing Figs. 8, 12 and 13, it is evident that the fuzzy control velocities given by the first equation of (26) are in the range shown in (33). It yields:

$$u_{l1r}(t) = 5 = \rho_{11} \le u_{l1c}(t) < \rho_{21} = f_{1\max} + u_{l1r}(t) = 12 + 5$$

$$u_{l2r}(t) = 7 = \rho_{12} \le u_{l2c}(t) < \rho_{22} = f_{2\max} + u_{l2r}(t) = 12 + 7 \qquad (53)$$

The maximum values of the velocities above are lower than the saturation values, because the values of the motion errors of the ROVs are smaller than the expected maximum values of the errors in the fuzzy memberships. Note that the fuzzy linear velocities are forward commands. Due to the dynamics of the underwater vehicles the velocity errors have an initial transient state, where they are not equal to zero.

Figs. 14 and 15 plot the surge forces and the yaw torque control signals given by the dynamical control laws (38).

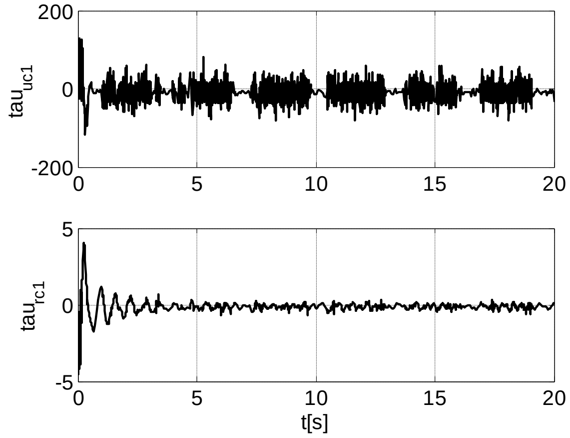

Fig. 14 Surge force control and yaw torque control of ROV 1

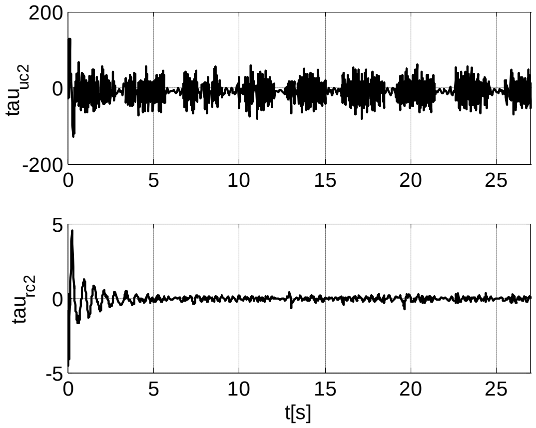

Fig. 15 Surge force control and yaw torque control of ROV 2

Now, consider outside disturbance violating the nominal motion of the ROV 1. The disturbance can be caused by impact of the ROV with the external marine environment. Fig. 16 shows the performance of the closed loop fuzzy control system.

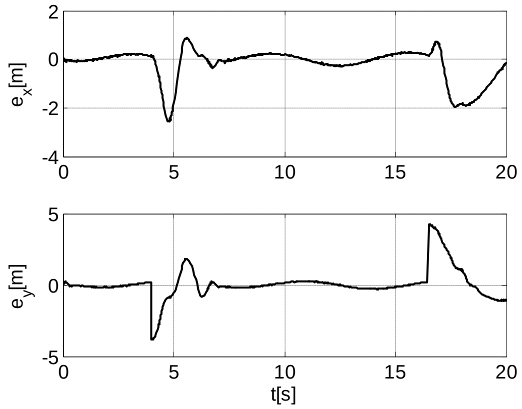

Fig. 16 Longitudinal and lateral motion errors with external disturbance of ROV 1.

Remark 6: Fig 16 shows how the closed loop control system compensates the external disturbances, so that it shows the robustness of the proposed control system.

VI. CONCLUSIONS

In this paper a new strategy of trajectory planning and control for planar motion of multiple underactuated ROVs has been presented. To consider the unactuated sway directions of each vehicle, the mathematical model of the multiple ROVs has been developed using polar coordinates. The cooperation of the ROVs is based on a decentralized trajectory planning algorithm which guarantees the absence of collisions between the closest underwater vehicles. The fuzzy guidance commands of each vehicle ensure forward surge speed control and saturation of all the control signal. The Lyapunov's stability of the equilibrium state of the fuzzy closed loop control system has been demonstrated for a platoon of ROVs. This ensures the stabilization of all the vehicles in the planned trajectories. The kinetic controller ensures the convergence of the fuzzy guidance commands to the actual speed of each cooperative ROV. Simulation experiments show the effectiveness of the proposed trajectory planning and control algorithm and the robustness with respect to outside disturbances violating the nominal motion of the ROVs.

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