POLISH MARITIME RESEARCH 4 (100) 2018 Vol. 25; pp. 39-48
10.2478/pomr-2018-0130

PATH FOLLOWING CONTROL OF FULLY ACTUATED AUTONOMOUS UNDERWATER VEHICLE BASED ON *LADRC*

Habib Choukri Lamraoui
Zhu Qidan
Harbin Engineering University, Harbin, China

ABSTRACT

This paper presents an active disturbances rejecter controller (ADRC) for position and path following control of a fully actuated autonomous underwater vehicle (AUV). The unmodeled, undesirable dynamics and disturbances reduce the performances of classical controllers and complicate the design of appropriate and efficient controllers. In the proposed approach, the different modeling complexities; such as uncertain parameters, non-linearities, and external disturbances are considered all as a part of disturbance which is estimated in real-time by the extended state observer ESO, and effectively compensated from the control law. The ESO is also able to estimate the position and velocity of the system in real-time, in case where the full state measurement of the AUV is not possible during experiments. Computer simulations demonstrate the high ability of the AUV tracking control based on ADRC, to follow the desired trajectory in the horizontal plane and space with high precision, and showed high robustness and efficiency in rejecting the external and internal disturbances caused by significant changes in parameters of the system, and the added position disturbances.

Keywords: ADRC, Path following, AUV, uncertain parameters, ESO, Control law.

INTRODUCTION

An autonomous underwater vehicle (AUV) is a type of unmanned underwater vehicles (UUV), operating independently of the human intervention. AUVs have been widely studied and took part in a lot of research and works due to their huge use and domain of application; such as surveillance, reconnaissance [1], anti-submarine warfare, mine countermeasures, mapping of the ocean floor, and pipeline inspection.

The control of AUVs appears imperatively as a pertinent topic of study in order to enable the AUV to execute its task autonomously and reach the desired system behavior. Classical controllers were firstly considered in the AUV's control. A survey of traditional controllers applied to AUV's and their limitations were well addressed in [2]

In order to ameliorate the robustness and accuracy, several control technique and strategies have been proposed such as: proportional-integral-derivative (PID) [3] Integer and fractional order PID controllers in trajectory tracking [4], robust adaptative control [5–6], robust Fuzzy Logic and PID Control in [7], time delay controller in [8].

More robust controllers have been designed in this area; including a feedback linearization controller for AUV's control [9], self-adaptative fuzzy PID [10], and a combination of different control techniques (adaptative, FLC and Sliding Mode Control (SMC)) in order to reduce the chattering of the SMC to maintain the robustness of the model uncertainties in [11].

In the last decade, the Active Disturbance Rejection Controller (ADRC) introduced by Han in [12], has presented the best immunity to the internal and external disturbances and proved its robustness and independence of mathematical models. Very encouraging results in terms of disturbance rejection have been reported for the ADRC approach, in the control of a cross-coupled highly non-linear aerodynamic system in [13], and in terms of robustness to significant modeling uncertainty in the control of 2-DOF manipulator [14], in the control of mobile robots [15], quadrotors [16] and manipulators [17]. The results obtained in the works mentioned above encouraged the authors to consider this approach in this work.

The contribution of this paper is the design of an appropriate controller based on ADRC, for position and path following control to force the AUV to track the desired trajectory in the dynamic environment in the presence of disturbances and modeling uncertainties. ADRC contains an extended state observer ESO which is able to estimate in real-time, firstly the position and velocity of the vehicle without the need of using sensors, secondly an extended state variable that represents the value of disturbances, uncertainties and unknown dynamics missed in the modeling, and other undesired dynamics such as the coupling terms. The estimated value of disturbances will be compensated from the control signal which ameliorates the controller's performance and robustness.

For simplicity, the linear version of ADRC called LADRC, and some assumptions were considered in the AUV's modeling and control design. Numerical simulations were run in MATLAB/Simulink, and they illustrate the efficiency of the proposed controller in tracking the desired trajectory and rejecting the different undesired effects. The obtained results are very satisfactory compared to some existing approaches; bio-inspired velocity regulation for three-dimensional trajectory tracking for underactuated AUVs with constant disturbances in [18], and adaptative tracking control for AUV under hydrodynamic parametric uncertainties in [19], nonlinear model predictive control (NMPC) method for the trajectory tracking problem of an autonomous underwater vehicle [20], robust non-linear controller of an autonomous underwater vehicle (AUV) in [21], and L2 Disturbance Attenuation Control for Path Following of AUV in 3D [22].

The paper is organized as follows. Section 2 presents the kinematic and dynamic modeling of the AUV. The design of LADRC based control law for the AUV to track the desired trajectory is developed in Section 3. To verify the efficiency and robustness of the proposed control law, numerical simulations are made. Results discussion is provided in Section 4. Finally, conclusions are presented in Section 5.

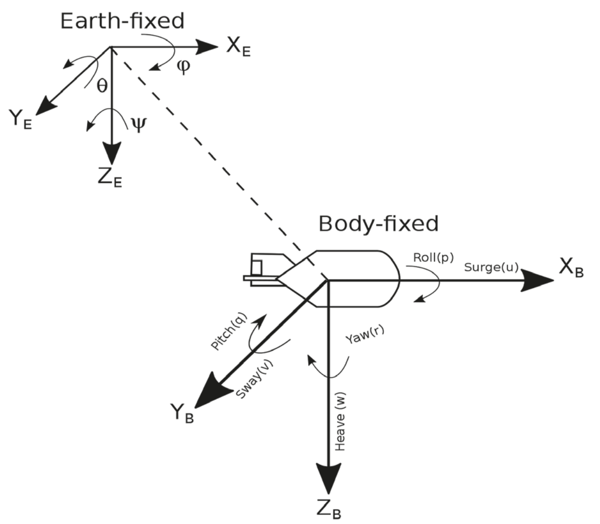

Fig. 1. AUV coordinate system

SYSTEM MODELING

KINEMATICS

The kinematic description represents the motion of the vehicle regardless of the effect of the forces acting on it.

To do this, Earth reference frame {E} and a Body-Fixed reference {B} frame are employed as showed in Fig.1.

The different degrees of freedom of the AUV are detailed in Table.1, and the position and velocity vectors of the AUV defined in the body frame {B} are χ and υ respectively as:

$$\chi = [x_B, y_B, z_B, \varphi_B, \theta_B, \psi_B] \tag{1}$$

$$\upsilon = [u, v, w, p, q, r] \tag{2}$$

Tab. 1. Degrees of freedom of the AUV

Degree Of Freedom	Positions and Euler angles	Linear and angular velocities
motions in the x-direction (Surge)	x	u
motions in the y-direction (Sway)	y	v
motions in the z-direction (Heave)	z	ω
rotation about x-axis (Pitch)	φ	p
rotation about y-axis Roll	θ	q
rotation about z-axis (Yaw)	ψ	r

The motion of the AUV can be described by:

$$\dot{\eta} = R(\eta)*\upsilon \tag{3}$$

Where $\dot{\eta}$ is the velocity vector expressed in the earth frame {E}, and R is the transformation matrix between {B} and {E} determined by

$$R(\eta) = diag\,\{R1(\varphi, \theta, \psi), R2(\varphi, \theta, \psi)\} \tag{4}$$

$$R1 = \begin{bmatrix} C\theta C\psi & -C\varphi S\psi + S\varphi S\theta C\psi & S\varphi S\psi + C\varphi S\theta C\psi \\ C\theta S\psi & C\varphi C\psi + S\varphi S\theta S\psi & -S\varphi C\psi + C\varphi S\theta S\psi \\ -S\theta & S\varphi C\theta & C\varphi C\theta \end{bmatrix} \tag{5}$$

$$R2 = \begin{bmatrix} 1 & S\varphi T\theta & C\varphi T\theta \\ 0 & C\varphi & -S\varphi \\ 0 & S\varphi / C\theta & C\varphi / C\theta \end{bmatrix} \tag{6}$$

Where C.= cos(.), S.=sin(.), and T.=tan(.)

$R1$ is a derivation of the rotation matrix and $R2$ a derivation of the coordinate transform matrix.

DYNAMICS

The dynamic modeling is a study of the motion of the vehicle taking into consideration the forces affecting it and the physical characteristics of the robot. Since these forces and the AUV's dynamics are highly complex, some assumptions have been considered to simplify the control design task:

- The AUV operates at low speed.
- The AUV is symmetric in the XZ plane and YZ plane.
- Roll and Pitch degrees of freedom are neglected.

Considering these assumptions, several terms can be eliminated from the dynamic model matrices. Any unmodeled dynamics will be considered as a disturbance and, they will be estimated by the LESO, and compensated from the control law.

After considering the previous assumptions, the simplified kinematics are represented by (7)

$$\begin{cases} \dot{x} = u\cos(\psi) - v\sin(\psi) \\ \dot{y} = u\sin(\psi) + v\cos(\psi) \\ \dot{z} = w \\ \dot{\psi} = r \end{cases} \tag{7}$$

$$M\dot{v} + C(v)v + D(v)v + g(\eta) = \tau \tag{8}$$

The terms of the dynamic model defined by (8), can be simplified and presented in the following subsections.

Mass and Inertia Matrix:

The mass and inertia matrix consist of the mass and inertia of the rigid body M_B and the added mass matrix M_A, with

$$M = M_B + M_A \tag{9}$$

$$M_B = \begin{bmatrix} m & 0 & 0 & 0 \\ 0 & m & 0 & 0 \\ 0 & 0 & m & 0 \\ 0 & 0 & 0 & I_{zz} \end{bmatrix} \tag{10}$$

$$M_A = \begin{bmatrix} -X_{\dot{u}} & 0 & 0 & 0 \\ 0 & -Y_{\dot{u}} & 0 & 0 \\ 0 & 0 & -Z_{\dot{u}} & 0 \\ 0 & 0 & 0 & -N_{\dot{u}} \end{bmatrix} \tag{11}$$

Coriolis and Centripetal Matrix

The Coriolis and centripetal matrix consists of the rigid body term C_B and the added mass term C_A with

$$C = C_B + C_A \tag{12}$$

$$C_B(v) = \begin{bmatrix} 0 & 0 & 0 & -mv \\ 0 & 0 & 0 & mu \\ 0 & 0 & 0 & 0 \\ mv & -mu & 0 & 0 \end{bmatrix} \tag{13}$$

$$C_A(v) = \begin{bmatrix} 0 & 0 & 0 & Y_{\dot{v}}v \\ 0 & 0 & 0 & -X\,u \\ 0 & 0 & 0 & 0 \\ Y_{\dot{v}}v & X_{\dot{u}}u & 0 & 0 \end{bmatrix} \tag{14}$$

Hydrodynamic Damping Matrix

The hydrodynamic damping of AUV is composed of the drag and lift forces since the AUV is assumed to be operating in low speed so the lift force can be neglected, and the drag force consists of two terms; linear D_l and quadratic D_q where

$$D = D_l + D_q \tag{15}$$

and

$$D_l = \begin{bmatrix} -X_u & 0 & 0 & 0 \\ 0 & -Y_v & 0 & 0 \\ 0 & 0 & -Z_\omega & 0 \\ 0 & 0 & 0 & -N_r \end{bmatrix} \tag{16}$$

$$D_q = \begin{bmatrix} -X_{u|u|}|u| & 0 & 0 & 0 \\ 0 & -Y_{v|v|}|v| & 0 & 0 \\ 0 & 0 & -Z_{\omega|\omega|}|\omega| & 0 \\ 0 & 0 & 0 & -N_{r|r|}|r| \end{bmatrix} \tag{17}$$

Gravitational and Buoyancy Matrix

$$g(\eta) = \begin{bmatrix} 0 \\ 0 \\ -(W-B) \\ 0 \end{bmatrix} \tag{18}$$

where

$$W = mg \quad \text{and} \quad B = \rho g \nabla \tag{19}$$

The full AUV dynamic model for 4 DOF is

$$\begin{cases} (m - X_{\dot{u}})\dot{u} - (X_u + X_{u|u|}|u|)u - (m - Y_{\dot{v}})vr = \tau_x \\ (m - Y_{\dot{v}})\dot{v} - (Y_v + Y_{v|v|}|v|)v + (m - X_{\dot{u}})ur = \tau_y \\ (m - Z_{\dot{\omega}})\dot{\omega} - (Y_\omega + Y_{\omega|\omega|}|\omega|)\omega = \tau_\omega \\ (m - N_{\dot{r}})\dot{r} - (N_r + N_{r|r|}|r|)r + (X_{\dot{u}} + Y_{\dot{v}})uv = \tau_r \end{cases} \tag{20}$$

CONTROL SYSTEM

ADRC

Contrary to traditional approaches dependent on mathematical modeling of the system, and the disturbances acting on it, the ADRC approach is less dependent on mathematical modeling. This control technique presented in [12], has the ability to react in real-time to external and internal disturbances affecting the system, thanks to the ESO which actively estimates the total disturbances, then compensates them from the control signal. Since the unmodeled dynamics and the model uncertainties are considered as a part of the total disturbance, the accurate mathematical models are no more indispensable to accomplish the desired tasks.

APPLICATION OF LADRC TO AUV

Considering the dynamic model of the AUV for 4 DOF, LADRC has been designed for each degree of freedom, the control design for the surge channel illustrated in Fig.2 is presented in this section. The other degrees of freedom are controlled in the same way.

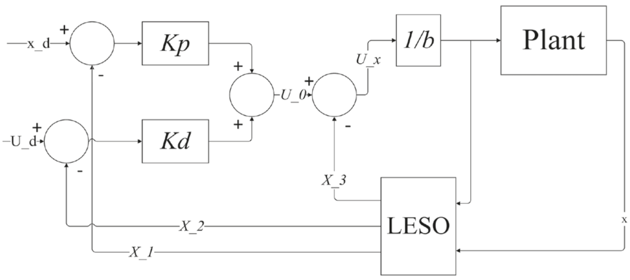

Fig. 2. Surge control loop based on

By considering the assumptions made in the previous section and the full AUV dynamic model for 4 DOF, the one degree of freedom (surge) dynamic equation is:

$$m_{11}\dot{u} - d_{11}u - m_{22}vr = \tau_x \tag{21}$$

where

$$\begin{cases} m_{11} = m - X_{\dot{u}} \\ m_{22} = m - Y_{\dot{v}} \\ d_{11} = X_u + X_{u|u|}|u| \end{cases} \tag{22}$$

Equation (21) can be expressed in the Body frame {B} as

$$\ddot{x} = 1/m_{11}(d_{11}\dot{x} + m_{22}\dot{y}\dot{\psi} + \tau_x) + ds \tag{23}$$

d_s is the disturbance term, then the disturbance function f_x is introduced in (24)

$$\ddot{x} = f_x(\dot{x}, \dot{y}, \dot{\psi}, t, ds) + b_x U_x \tag{24}$$

where $b_x = \dfrac{1}{m_{11}}$ and $U_x = \tau_x$,

The state space form of the system can be written as:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f_x(\dot{x}, \dot{y}, \dot{\psi}, t, ds) + b_x U_x \\ y = x_1 \end{cases} \tag{25}$$

Then, the state space is extended by an additional state variable $x_3 = f_x(\dot{x}, \dot{y}, \dot{\psi}, t, ds)$, which estimates total disturbances, and the extended system state is presented below:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_3 + b_x U_x \\ \dot{x}_3 = f_x \end{cases} \tag{26}$$

Now, a following third order LESO is designed for the above system:

$$\begin{cases} \dot{\hat{x}}_1 = \hat{x}_2 - \beta_1 \varepsilon_1 \\ \dot{\hat{x}}_2 = \hat{x}_3 - \beta_2 \varepsilon_1 + b_x U_x \\ \dot{\hat{x}}_3 = -\beta_3 \varepsilon_1 \end{cases} \tag{27}$$

The control law of the surge is described by the following equation:

$$U_x = \frac{U_0 - \hat{x}_3}{b_x} \tag{28}$$

$\hat{x} = \hat{f}_x$, and U_0 is a simple PD controller chosen for each LADRC control loop.

$$U_0 = K_p(x_r - \hat{x}_1) + K_d(\dot{x}_r - \hat{x}_2) \tag{29}$$

To simplify the tuning of the parameters of the LESO and the controller, they have been set as (30), and the tuning is reduced from 5 to 2 parameters.

$$\begin{cases} \beta_1 = 3\omega_0 \\ \beta_2 = 3\omega_0^2 \\ \beta_2 = \omega_0^3 \\ K_p = \omega_c^2 \\ K_d = 2 * \omega_c \end{cases} \tag{30}$$

where ω_0 is the observer bandwidth and ω_c is the closed loop bandwidth. The LESO and controller gains are set as (30) to ensure the Hurwitz stability [23–24].

By inserting equation (28) in equation (24), one obtains:

$$\begin{cases} \ddot{x} = f_x(\dot{x}, \dot{y}, \dot{\psi}, t, ds) + b_x U_x \\ \ddot{x} = U_0 \end{cases} \tag{31}$$

The system can now be expressed as the following disturbance-free system

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = U_0 \\ y = x_1 \end{cases} \quad (32)$$

The above model can be rewritten using tracking error:

$$\begin{cases} e_1 = x_d - x_1 \\ \dot{e}_1 = \dot{x}_d - \dot{x}_1 = \dot{x}_d - x_2 \\ \ddot{e}_1 = \ddot{x}_d - \dot{x}_2 = \ddot{x}_d - U_0 \end{cases} \quad (33)$$

where x_d is the desired value of state x, and U_0 is the feedback controller responsible for minimizing the tracking error:

$$U_0 = \ddot{x}_d + K_p(x_r - \hat{x}_1) + K_d(\dot{x}_r - \hat{x}_2) \quad (34)$$

By applying (34) to the last term of (33), the error dynamic equation is obtained as

$$\ddot{e}_1 + K_d\dot{e}_1 + K_p e_1 = 0 \quad (35)$$

According to (35), by setting the controller gains, the exponential convergence of the tracking error to zero for any initial condition will be obtained.

The 4D control loop based on LADRC is presented in Fig. 3

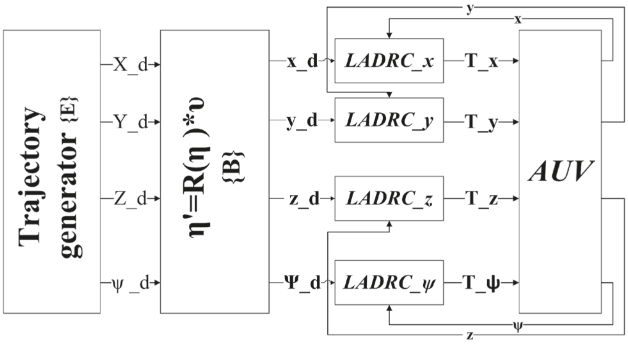

Fig. 3. Control structure of LADRC scheme

SIMULATION AND RESULTS

In order to verify the efficacy of the proposed path following control law, computer simulations are carried out considering different desired trajectories.

The parameters of the AUV used in the numerical simulations are listed in table 2

Tab. 2. AUV's parameters used in simulation

mass (kg)	Damping coefficients (Ns/m)
m_{11} = 215	d_{11} = 70 + 100 | u |
m_{22} = 265	d_{22} = 100 + 200 | v |
m_{33} = 265	d_{33} = 100 + 200 | ω |
m_{44} = 80	d_{44} = 50 + 100 | r |

2D PATH

The AUV is set to track a desired 2D curvy trajectory (red dashed line) in the XY plane as shown in the figure below.

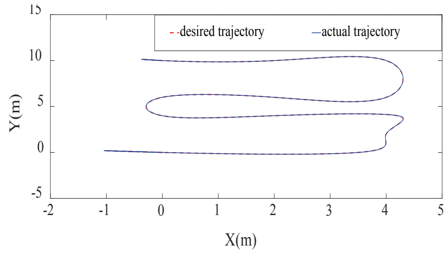

Fig. 4. AUV 2D path following

Fig. 4 shows the matching between the desired and the actual trajectory, which means that a precise tracking was assured by the proposed controller.

Positions and velocities are represented in Fig. 5 and Fig. 6.

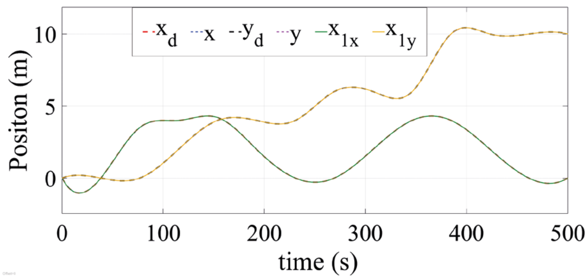

Fig. 5. Actual, estimated and desired positions

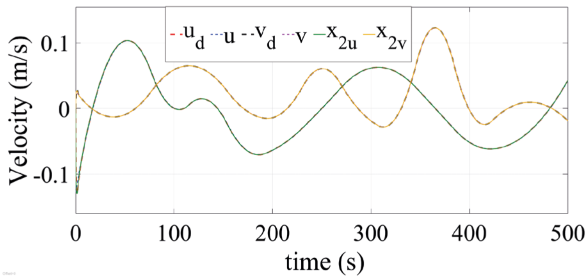

Fig. 6. Actual, estimated and desired velocities

Fig. 5 and Fig. 6 show the match between the estimated, the actual and the desired positions and velocities, respectively, which proves the efficiency of the LESO in estimating the full state of the AUV during the tracking task, and the satisfactory tracking accuracy presented by the proposed controllers.

Positions and velocities errors are represented in Fig. 7 and Fig. 8.

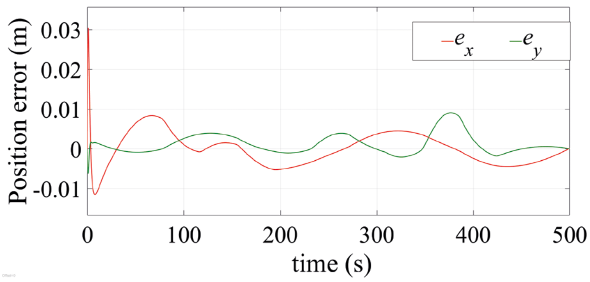

Fig. 7. Position errors

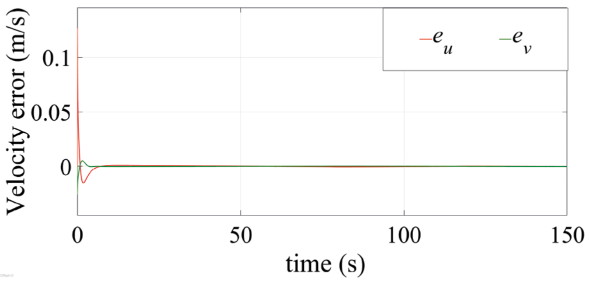

Fig. 8. Velocity errors

Fig. 7 and Fig. 8 show the positions and velocities errors. From these figures, it is observed that the errors converge to zero in less than 5s and the error is acceptable considering the changes due to the turns in the desired trajectory.

Fig. 9 shows the real-time estimation of the disturbances during the tracking.

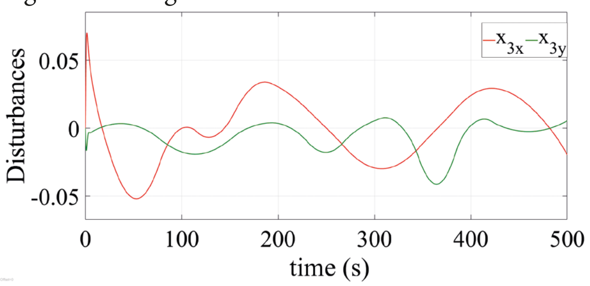

Fig. 9. Disturbances estimator

The torques or control inputs are represented in Fig.10.

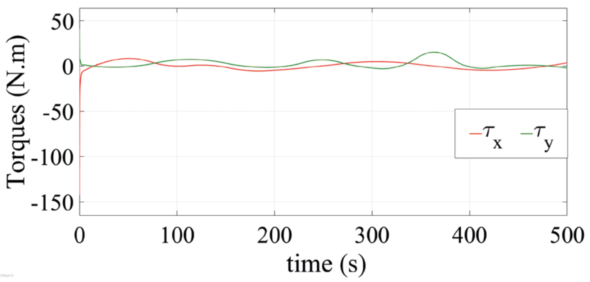

Fig. 10. Torques

Fig. 10 represents the torques or control signals applied to the AUV. It shows that in the first 5 seconds of motion, the torques have high values due to the AUV's trend to catch the desired positions and velocities, which introduce considerable acceleration that will decrease when the trajectory is smooth, and increase a bit when there are sudden changes in the curve.

Fig. 11 represent the trajectory tracking for different initial conditions ($x_0 = -1$, $y_0 = -1$), so initial errors are ($x_e = -1$, $y_e = -1$). From this figure, the fast convergence of the AUV to the desired trajectory is observed with a small initial overshoot.

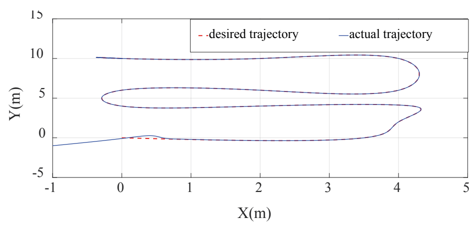

Fig. 11. 2D path following with different initial positions

3D PATH FOLLOWING: SPIRAL PATH

The referenced path presented in Fig.11 is a spiral path in space defined as:

$$\begin{cases} x_d = 10\,sin(0.01t) \\ y_d = 10\,cos(0.01t) \\ z_d = t \\ \psi_d = \pi/3 \end{cases} \quad (36)$$

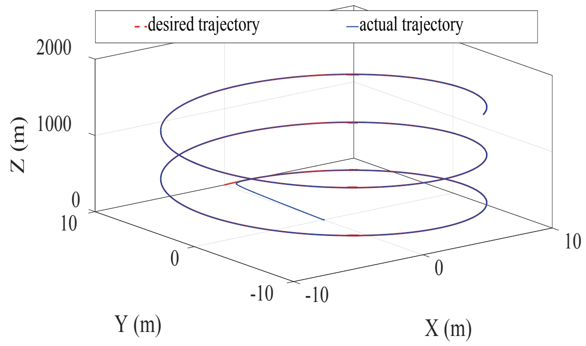

Fig. 12. AUV spiral path following

The XY plane projection of the desired path is illustrated in Fig. 12.

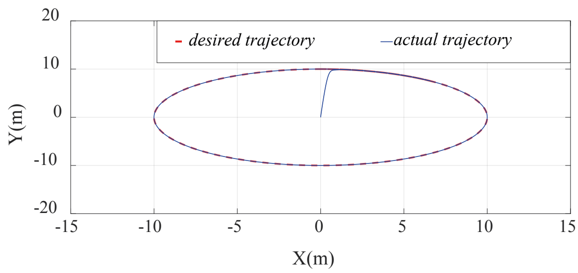

Fig. 13. XY plane projection

Fig. 12 and Fig. 13 illustrate the desired and tracked spiral paths followed by the AUV in the space and the XY plane. From these figures, it is clear that the proposed control law assured a precise tracking of the path.

Fig. 14 and Fig. 15 show the desired and actual positions and velocities. From these figures, the match between the desired and actual positions and velocities of the AUV are well observed which proves good tracking performance of the controller.

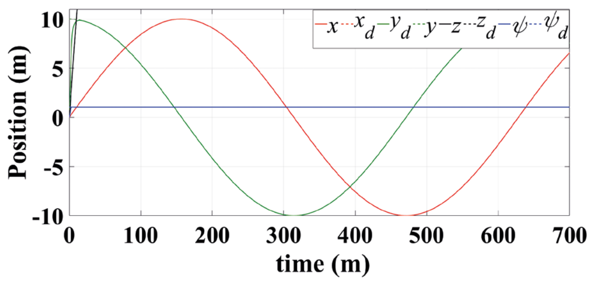

Fig. 14. Actual and desired positions

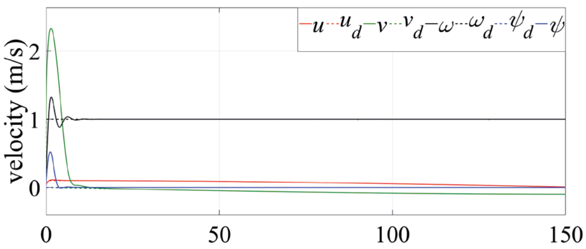

Fig. 15. Actual and desired velocities

Fig. 16 and Fig. 17 show the positions and velocities errors. From these figures, it is observed that the errors in the surge, heave, and yaw converge to zero in 5s and the error in the sway after 10s from the beginning.

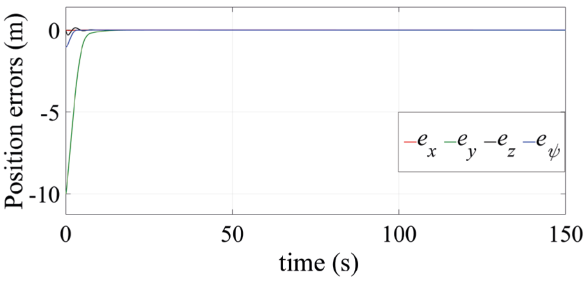

Fig. 16. Position errors

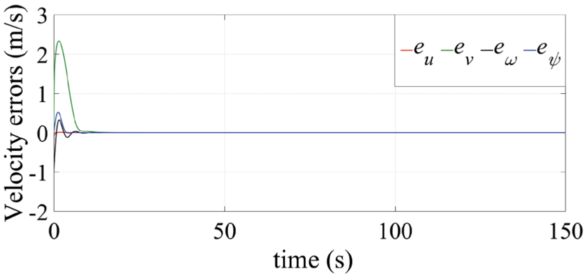

Fig. 17. Velocity errors

Fig. 18 represents the estimated value of the different external and internal disturbances during the tracking time.

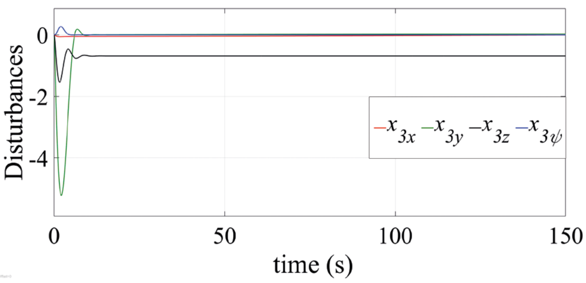

Fig. 18. Disturbances estimator

Fig. 19 illustrates the torques or control signals applied to the AUV. It shows that in the beginning stage of motion torques had peak values due to the AUV's trend to catch the desired positions which provoke a considerable acceleration that will gradually tend to a constant value (zero in the case of z and ψ).

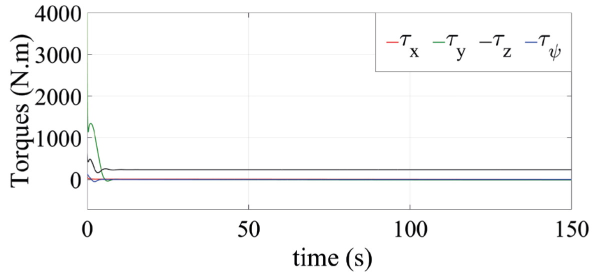

Fig. 19. Torques

SPIRAL PATH FOLLOWING UNDER UNCERTAINTIES AND DISTURBANCES EFFECTS

In order to evaluate the proposed LADRC-based control under parameter uncertainties and external disturbances, the tracking controllers are tested under a perturbed parameters situation as in (36) and (37), and added disturbances to the surge position signal as white noise, and to the heave position signal as a step signal, as detailed in table 3.

Tab. 3. Disturbances

Perturbation signal	Time	Value
Step	300 s	15 m
White noise	500 s	0.02 m

$$\begin{cases} m_{11} = m_{11} + 20\% m_{11} \\ m_{33} = m_{33} + 20\% m_{33} \end{cases} \quad (37)$$

And

$$\begin{cases} d_{11} = d_{11} + 20\% d_{11} \\ d_{33} = d_{33} + 20\% d_{33} \end{cases} \quad (38)$$

The path tracking under disturbances and uncertain parameters and disturbances is shown with the disturbance-free path, and the desired path in Fig. 20 and the XZ plane projection in Fig. 21.

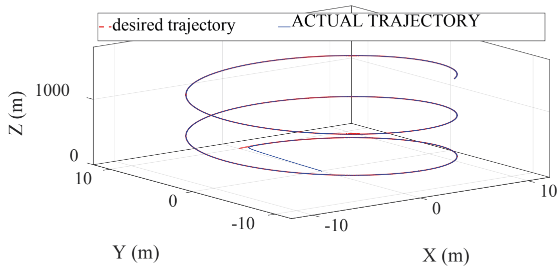

Fig. 20. AUV spiral path following with disturbances and uncertain parameters

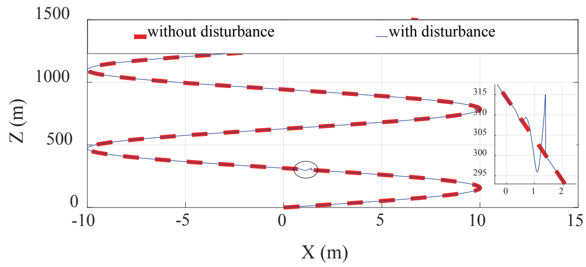

Fig. 21. XZ plane projection

As shown by the figures above, the tracking performances were slightly affected by the uncertainties in parameters values and the added position disturbances.

The LADRC has a strong ability to reject disturbance in a short time and re-join the zero-error steady state, thanks to the compensation of the disturbances values estimated by x_3 as shown in Fig. 22.

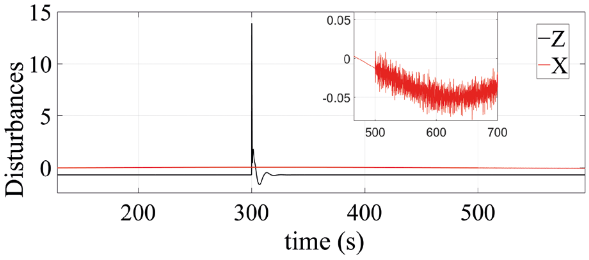

Fig. 22. Disturbances estimator

CONCLUSION

In this paper, the path following control of autonomous underwater vehicles has been carried out. First, a simplified model of the AUV has been established. Then, a LADRC based controller has been designed for each degree of freedom in order to track the desired positions.

The designed extended state observer (ESO) has effectively estimated the full state of the system, which is extremely useful and practical in the case of unmeasured states due to inaccessibility to sensors information during the experiments. The extended state variable has estimated the total disturbances value that were canceled out from the control signal.

The path following control for AUV based on LADRC showed good tracking performance when it is moving in the plane and space, with a satisfactory accuracy that can be concluded by comparing the actual and desired positions and velocities, and the convergence of related errors to zero.

To evaluate the robustness of the proposed controller, the system has been tested under model uncertainties and added disturbances. The obtained results confirm the ability of the LADRC based controllers to reject the different disturbances, and its immunity to the modeling uncertainties.

By analysing the obtained simulation results on the background of some related works [18, 22], the following points has been concluded:

- Comparing to [18, 19]; in the tracking of 3D spiral path, the authors proposed approach presented faster path convergence speed, and better tracking performance in term of tracking errors, overshoot and response time of the system.
- Comparing to [20]; in the tracking of a circular path in the plane, the proposed approach has presented more accurate trajectory tracking.
- Comparing to [21], better tracking performance and robustness has been reported for the authors proposed approach in the tracking of a 2D curved trajectory.
- Comparing to a closer approach which has been presented in [22], basing on disturbances attenuation control, better tracking accuracy, and robustness is also reported.

In the future works, the authors consider the frequency domain study and stability analysis of the proposed system, and validating it with an experimental study.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

REFERENCES

1. S.Karthik, *Underwater vehicle for surveillance with navigation and swarm network communication*, in Indian Journal of Science and Technology, October 2014, Vol 7(S6), pp. 22–31.

2. S. Zhao, *Advanced control for autonomous underwater vehicles*, Ph.D. dissertation, Dept. Mech. Eng., The University of Hawai'i, Aug. 2004. pp 9–17.

3. Duo Qi, Jinfu Feng, An Liu, Junhua Hu, Hu Xu, Yongli Li, Muhammad Aqeel Ashraf, *Stability control of propeller autonomous underwater vehicle based on combined sections method*, POLISH MARITIME RESEARCH, Volume 22, Issue s1 (Sep 2015), pp. 157–162.

4. S. D. Joshi and D. B. Talange, *Integer & fractional order PID Controller for fractional order subsystems of AUV*, 2013 IEEE Symposium on Industrial Electronics & Applications, Kuching, 2013, pp. 21–26.

5. S. Pezeshki, A. R. Ghiasi, M. A. Badamchizadeh, K. Sabahi, *Adaptive Robust Control of Autonomous Underwater Vehicle*, Journal of Control, Automation and Electrical Systems, June 2016, Volume 27, Issue 3, pp 250–262.

6. Ji-Hong Li, Pan-Mook Lee, *Design of an adaptive nonlinear controller for depth control of an autonomous underwater vehicle*, Ocean Engineering, Volume 32, Issues 17–18, 2005, pp. 2165–2181.

7. M. A. Salim, A. Noordin and A. N. Jahari, *A Robust of Fuzzy Logic and Proportional Derivative Control System for Monitoring Underwater Vehicles*, 2010 Second International Conference on Computer Research and Development, Kuala Lumpur, 2010, pp. 849–853.

8. J. Kim, H. Joe, S. c. Yu, J. S. Lee and M. Kim, *Time-Delay Controller Design for Position Control of Autonomous Underwater Vehicle Under Disturbances*, in IEEE Transactions on Industrial Electronics, vol. 63, no. 2, Feb. 2016, pp. 1052–1061.

9. G. Evers et al., *Modeling and simulated control of an under actuated autonomous underwater vehicle*, 2009 IEEE International Conference on Control and Automation, Christchurch, 2009, pp. 343–348.

10. MH Khodayari, S Balochian, *Modeling and control of autonomous underwater vehicle (AUV) in heading and depth attitude via self-adaptive fuzzy PID controller*, Journal of Marine Science & Technology, September 2015, Volume 20, Issue 3, pp. 559–578.

11. Wei Zhang, Zhicheng Liang, Yi Guo, DetaoMeng, Jiajia Zhou and Yunfeng Han, *Fuzzy adaptive sliding mode controller for path following of an autonomous underwater vehicle*, OCEANS 2015 – MTS/IEEE Washington, Washington, DC, pp. 1–6.

12. J. Han, *From PID to Active Disturbance Rejection Control*, in IEEE Transactions on Industrial Electronics 2009, vol. 56, no. 3, pp. 900–906.

13. R. Madoński and P. Herman, *An experimental verification of ADRC robustness on a cross-coupled Aerodynamical System*, Industrial Electronics (ISIE), 2011 IEEE International Symposium Gdansk, pp. 859–863.

14. M. Przybyła, M. Kordasz, R. Madoński, P. Herman, and P. Sauer, *Active Disturbance Rejection Control of a 2DOF manipulator with significant modeling uncertainty*, in The Journal of Polish Academy of Sciences, volume 60, issue 3 December 2012.

15. H. C. Lamraoui and Z. Qidan, *Speed tracking control of unicycle type mobile robot based on LADRC*, 2017 3rd IEEE International Conference on Control Science and Systems Engineering (ICCSSE), Beijing, 2017, pp. 200–204.

16. T. Niu, H. Xiong and S. Zhao, *Based on ADRC UAV longitudinal pitching Angle control research*, 2016 IEEE Information Technology, Networking, Electronic and Automation Control Conference, Chongqing, 2016, pp. 21–25.

17. Y. Zhao, Z. Zhao, B. Zhao and W. Li, *Active Disturbance Rejection Control for Manipulator Flexible Joint with Dynamic Friction and Uncertainties Compensation*, 2011 Fourth International Symposium on Computational Intelligence and Design, Hangzhou, 2011, pp. 248–251.

18. J. Zhou, D. Ye, D. He and D. Xu, *Three-dimensional trajectory tracking of an underactuated UAV by backstepping control and bio-inspired models*, 2017 36th Chinese Control Conference (CCC), Dalian, 2017, pp. 966–972.

19. Basant Kumar Sahu, Bidyadhar Subudhi *Adaptive Tracking Control of an Autonomous Underwater Vehicle*, International Journal of Automation and Computing, vol. 11, no. 3, pp. 299–307, jun. 2014.

20. Chao Shen, Brad Buckham, Yang Shi, *Modified C/GMRES Algorithm for Fast Nonlinear Model Predictive Tracking Control of AUVs*, IEEE Transactions on Control Systems Technology (Volume: 25, Issue: 5, Sept. 2017), pp. 1896–1904.

21. L. Lapierre and B. Jouvencel, *Robust Nonlinear Path-Following Control of an AUV*, in IEEE Journal of Oceanic Engineering, April 2008, vol. 33, no. 2, pp. 89–102.

22. L. Wang, H. M. Jia, L. J. Zhang, L. X. Yang and H. B. Wang, *L2 disturbance attenuation control for path following of AUV in 3D*, 2011 IEEE 3rd International Conference on Communication Software and Networks (ICCSN), Xi'an, 2011, pp. 126–129.

23. Q. Zheng, L. Gao, and Z. Gao, *On stability analysis of active disturbance rejection control for nonlinear time-varying plants with unknown dynamics*, 46th IEEE Conference on Decision and Control 2007, pp. 3501–3506.

24. Y. Zhou, R. Li, D. Zhao and Q. Wu, *Ship heading control using LESO with wave disturbance*, 2016 IEEE International Conference on Robotics and Biomimetics (ROBIO), Qingdao, 2016, pp. 2081–2086.

CONTACT WITH THE AUTHOR

Habib Choukri Lamraoui
e-mail: habib_choukri@yahoo.com
Automation Colleg, Harbin Engineering University
Nantong Str. Nangang Dist.
150001 Harbin
China

Zhu Qidan
e-mail: zhuqidan@hrbeu.edu.cn
Automation College, Harbin Engineering University
Nantong Str. Nangang Dist.
150001 Harbin
China