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Trajectory Tracking Controller Design for Underactuated AUVs based on Adaptive Robust Control

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Abstract—**In this paper, the trajectory tracking problem for underactuated Autonomous underwater vehicles (AUVs) is investigated. First, a nonlinear 4-DOF AUV model is adopted, considering the unknown parameters and external distances. Two control objectives and corresponding error dynamics are established according to different tracking errors. To achieve accurate AUV tracking control, an adaptive robust control strategy is proposed, combining the backstepping control ideology. This controller could adaptively estimate uncertain model parameters and disturbances recursively and compensate for the estimation errors robustly. Theoretical analysis demonstrates that the proposed control scheme can ensure system stability, enhance the transient response, and give great trajectory tracking performance, which is validated again by the numerical simulations.**

Keywords—Autonomous underwater vehicles (AUVs), Trajectory tracking, Adaptive robust control

I. INTRODUCTION

With increasing demand for oceanic exploration and utilization, Autonomous underwater vehicles (AUVs) have attracted much attention in the past few decades [1]. Underwater tasks are more complex than those conducted by unmanned surface vehicles due to the complicated underwater environment and the low communication efficiency. Under such conditions, a stable and precise trajectory tracking controller contributes to ensuring the performance of AUV: the realization of autonomous control would reduce the need for manual operations [2]; otherwise, if the controller frequently fails to handle unknown disturbances, AUV would deviate from scheduled routes, which might be hazardous and unsafe.

Many scholars have developed AUV trajectory tracking controllers based on different algorithms. J. Kim proposed an integral sliding mode controller to enhance the time-delay performance for AUV position control, given that the feedback frequency of the DVL is relatively lower than other sensors [3]. D. Gao combined sliding mode control and linear quadratic regulator, which makes the AUV robust to parameter perturbations and random disturbances [4]. In [5], H. Ban formulated the AUV tracking problem into the T-S fuzzy framework, eliminating the position and heading error with nonlinearity and model inaccuracy. Model predictive control (MPC), reflecting the idea of optimal control, is also a hot research topic in AUV trajectory tracking. In [6], Z. Yan used the feedback linearization method to convert the coupled nonlinear AUV model into a second-order affine form, which reduces the computational burden while maintaining tracking stability. S. Heshmati-Alamdari designed a robust nonlinear MPC to steer the AUV to follow the desired trajectory in an utterly unknown environment, considering the input and state constraints and external disturbances [7]. N. Yang proposed an economic MPC controller to reduce the energy cost in the AUV trajectory tracking tasks [8]. S. Kong advanced a cascade architecture with a governor to generate reference tracking velocity and a disturbance rejection dynamic controller [9].

The biggest challenge AUV tracking control faces is still the external environmental interferences and the model uncertainties. The adaptive robust control theory, proposed in [10], could effectively solve these two problems. Model uncertainties could be estimated online by the recursive least square (RLS) adaptation law and compensated to the nominal model. Other parts that are still not estimated would be offset by the robust term in this framework. This theory has been mainly applied in robotic arms and hydraulic systems, and its superiority has been widely recognized [11].

This paper investigates the trajectory tracking problem of an underactuated AUV. For simplicity and consistency with our AUV, a 4-DOF underactuated AUV dynamic model is adopted, i.e., surge, sway, heave, and yaw are considered. Then, the trajectory tracking control problem is formulated into two separate stages: approaching and tracking. To deal with the model uncertainty and environmental disturbance, the adaptive robust control strategy is combined with the backstepping control theory, which could estimate the unknown parameters online and improve the controller's performance, thereby achieving accurate tracking control. Moreover, the controller's stability of is proven, and the tracking error can converge. Finally, simulations are conducted to demonstrate the effectiveness of the proposed controller, and the results are consistent with the theoretical analysis.

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The rest of this paper is organized as follows: the AUV model is introduced in Section II; in Section III, the trajectory tracking problem is formulated and the controller is designed based on the ARC and backstepping theory; simulations and corresponding results are demonstrated in Section IV and conclusion is given in Section V.

II. AUV Modelling and Problem Formation

A. AUV Modelling

A complete AUV model is described with 6 degrees of freedom (DOF), i.e., three linear velocities: surge, sway, heave, and three angle velocities: pitch, roll, yaw. To depict 6-DOF motions of AUVs, two coordinate systems are introduced. As shown in Fig. 1, the world coordinate system, mainly used to describe the position and attitude, is preset and maintained still, while the body coordinate system, mainly used to describe the speed, is fixed at the AUV's center of gravity [6].

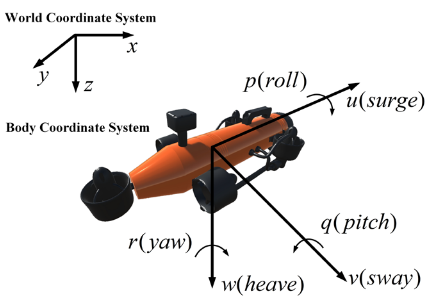

Fig. 1. Coordinate systems for AUV kinematic and dynamic modelling

Considering the AUV we are using can maintain pitch and roll stability through the front and rear three horizontal propellers and can control forward and steering through two vertical propellers in the middle, shown in Fig. 1, an underactuated AUV model with 4-DOF is considered in this paper, i.e., pitch and roll are neglected [3].

The kinematic equations of 4-DOF AUV are given as [9]:

$$\dot{\boldsymbol{X}} = \boldsymbol{J}(\varphi)\boldsymbol{v} \tag{1}$$

$$\boldsymbol{J}(\varphi) = \begin{bmatrix} \cos\psi & -\sin\psi & 0 & 0 \\ \sin\psi & \cos\psi & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

where $\boldsymbol{X}=[x,y,\psi,z]^T$ is the position and attitude vector defined in the world coordinate, and $\boldsymbol{v}=[u,v,r,w]^T$ is the velocity vector defined in the body coordinate. $\boldsymbol{J}(\varphi)$ is the transformation matrix between these two coordinate systems.

The dynamic motions of AUV could be described as [5]:

$$\boldsymbol{M}\dot{\boldsymbol{v}} + \boldsymbol{C}(\boldsymbol{v})\boldsymbol{v} + \boldsymbol{D}(\boldsymbol{v})\boldsymbol{v} + \boldsymbol{g}(\boldsymbol{X}) = \boldsymbol{\tau} + \boldsymbol{J}^{-1}\varsigma + \boldsymbol{\Delta} \tag{3}$$

$$\boldsymbol{C}(\boldsymbol{v}) = \begin{bmatrix} 0 & 0 & -m_v v & 0 \\ 0 & 0 & m_u u & 0 \\ m_v v & -m_u u & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{4}$$

where $\boldsymbol{M}$=diag(m_u,m_v,m_r,m_w) is the mass matrix, $\boldsymbol{C}(\boldsymbol{v})$ is the Coriolis and centripetal matrix denoted later, $\boldsymbol{D}(\boldsymbol{v})$= diag($d_u$,$d_v$,$d_r$,$d_w$)=diag($k_u+k_{|u|u}|u|$,$k_v+k_{|v|v}|v|$,$k_r+k_{|r|r}|r|$,$k_w+k_{|w|w}|w|$) is the damping matrix [7], $\boldsymbol{g}(\boldsymbol{X})=[0,0,0,-W]^T$ is the buoyance vector, $\varsigma=[\varsigma_u,\varsigma_v,\varsigma_r,\varsigma_w]^T$ is the constant unmodelled uncertainties in the world coordinate to be estimated, $\boldsymbol{\Delta}=[\Delta_u, \Delta_v, \Delta_r, \Delta_w]^T$ is other time-varying uncertainty and $\boldsymbol{\tau}=[\tau_u,0,\tau_r,\tau_w]^T$ is the underactuated input vector.

B. Trajectory Tracking Problem Formation

The trajectory tracking problem could be divided into two stages: at the beginning of the task or when the reference trajectory suddenly undergoes significant changes, AUV may not be near the given trajectory. Then, the objective at this time is to approach the reference points and reduce tracking errors; as the error enters the allowable ranges, the objective turns to follow the reference trajectory and maintain stable tracking. The switch between different stages can be a hard switch by setting a distance threshold or a soft switch mode using a hyperbolic tangent function to effectively combine the advantages of the above two control objectives in both stages and to avoid jumps and oscillations caused by a hard switch.

Let the reference trajectory be $\boldsymbol{X}_d=[x_d,y_d,z_d]^T$ in the world coordinate, which should be continuous and fourth-order differentiable before discretization. Since the AUV is underactuated and without side thrusts, it cannot follow any arbitrary trajectory. Thus, the control objective is to eliminate the radial error in the first approaching stage:

$$\rho_e = -\sqrt{x_{ew}^2 + y_{ew}^2} \tag{5}$$

$$\gamma_e = \psi + \text{atan2}(\frac{v}{u}) - \text{atan2}(\frac{-y_{ew}}{-x_{ew}}) \tag{6}$$

$$z_e = z - z_d \tag{7}$$

where $x_{ew}=x-x_d$ and $y_{ew}=y-y_d$.

When entering the second following stage, the radial error is already quite small. If the previous control objective is maintained, it will cause fluctuations and instabilities. Hence, in the second stage, the control objective is to minimize the errors shown below:

$$\rho_e = x_{eb} = x_{ew}\cos\psi + y_{ew}\sin\psi \tag{8}$$

$$\gamma_e = \psi + \text{atan2}(\frac{v}{u}) - \text{atan2}(\frac{\dot{y}_d}{\dot{x}_d}) \tag{9}$$

where x_{eb} and y_{eb} (used later) are the forward and lateral errors defined in the body coordinate. In this way, AUV would track the reference trajectory as long as the tracking error does not deviate from the preset threshold.

C. Error Dynamics

Inspired by the backstepping control theory, virtual speed control errors are given as:

$$e_u = u - \alpha_u \tag{10}$$

$$e_r = r - \alpha_r \tag{11}$$

$$e_w = w - \alpha_w \quad (12)$$

Depending on the stages, the auxiliary variables α_u, α_r, and α_w also have different designs. In the approaching stage:

$$\alpha_u = \frac{1}{x_{eb}}\left(-vy_{eb} + x_{ew}\dot{x}_d + y_{ew}\dot{y}_d - k_\rho \rho_e^2\right) \quad (13)$$

$$\alpha_r = -\frac{u\dot{v} - v\dot{u}}{u^2 + v^2} + \frac{x_{ew}\dot{y}_{ew} + y_{ew}\dot{x}_{ew}}{\rho_e^2} - k_\gamma \gamma_e \quad (14)$$

$$\alpha_w = \dot{z}_d - k_{wz} z_e \quad (15)$$

where $k_{u\rho}$ and $k_{r\gamma}$ are preset positive real numbers, affecting the speed of error convergence.

Under such a virtual speed control law design, the derivatives of (5), (6) and (7) would be:

$$\dot{\rho}_e = k_{ub}\frac{x_{eb}}{\rho_e} e_u - k_\rho \rho_e \quad (16)$$

$$\dot{\gamma}_e = k_{rb} e_r - k_{r\gamma}\gamma_e \quad (17)$$

$$\dot{z}_e = k_{wb} e_w - k_z z_e \quad (18)$$

It is noted that as the speed error decreases, the tracking error can converge almost exponentially. Then, the controller will be designed to minimize speed errors as quickly as possible. On the other hand, in the tracking stage:

$$\alpha_u = -r y_{eb} + \dot{x}_d \cos\psi + \dot{y}_d \sin\psi - k_\rho \rho_e \quad (19)$$

$$\alpha_r = -\frac{u\dot{v} - v\dot{u}}{u^2 + v^2} + \frac{\ddot{y}_d \dot{x}_d - \ddot{x}_d \dot{y}_d}{\dot{x}_d^2 + \dot{y}_d^2} - k_\gamma \gamma_e \quad (20)$$

Since the control objective in the heave direction does not change, α_w remains the same as (15). The derivatives of (5), (6), and (7) also remain the same as the former stage.

Then, the error dynamics could be calculated by taking the derivative on both sides of equation (3) and bringing equations (10), (11), and (12) into it:

$$m_u \dot{e}_u = m_v v r - d_{11} u + \tau_u + \varsigma_u \cos\psi + \varsigma_v \sin\psi + \Delta_u - m_u \dot{\alpha}_u \quad (21)$$

$$m_r \dot{e}_r = (m_u - m_v) u v - d_r r + \tau_r - \varsigma_r + \Delta_r - m_u \dot{\alpha}_r \quad (22)$$

$$m_w \dot{e}_w = -d_w w + \tau_w + W + \varsigma_w + \Delta_w - m_w \dot{\alpha}_w \quad (23)$$

III. Adaptive Robust Controller Design

A. Parameter Adaptation

In most cases, the system model is subject to model uncertainties, and the controller can improve performance through parameter adaptation. Usually, the proportional relationship of the dynamic parameters of AUVs can be obtained through various types of identification experiments. However, their amplitudes, related to the quality matrix, cannot be entirely determined. Environmental interferences and buoyancy are also challenging to determine in advance. Hence, the dynamic equation (3) will be rewritten to facilitate the parameter identification, and a low-pass filter $H_f(s)$ will be applied to both sides. Then, the linear regression model could be obtained as follows:

$$\boldsymbol{\upsilon}_f = \boldsymbol{\varphi}_f^T \boldsymbol{\theta} \quad (24)$$

in which

$$\boldsymbol{\upsilon} = \begin{bmatrix} -d_u u + \tau_u & -d_v v & -d_r r + \tau_r & -d_w w + \tau_w \end{bmatrix}^T \quad (25)$$

$$\boldsymbol{\theta} = \begin{bmatrix} m_u & m_v & m_r & m_w & W & \varsigma_u & \varsigma_v & \varsigma_r & \varsigma_w \end{bmatrix}^T \quad (26)$$

$$\boldsymbol{\varphi} = \begin{bmatrix} \dot{u} & -vr & 0 & 0 & 0 & -\cos\psi & -\sin\psi & 0 & 0 \\ ur & \dot{v} & 0 & 0 & 0 & \sin\psi & -\cos\psi & 0 & 0 \\ -uv & uv & \dot{r} & 0 & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & \dot{w} & -1 & 0 & 0 & 0 & -1 \end{bmatrix}^T \quad (27)$$

$\bullet_f$ represents the output from the filter, and $\boldsymbol{\theta}$ is the vector to be estimated. The prediction error $\boldsymbol{\sigma}_p$ could be defined as:

$$\sigma_p = \boldsymbol{\varphi}_f^T \hat{\boldsymbol{\theta}} - \boldsymbol{\upsilon}_f = \boldsymbol{\varphi}_f^T \tilde{\boldsymbol{\theta}} \quad (28)$$

Then, the RLS adaptation law is given as [11]:

$$\boldsymbol{\zeta} = -\frac{\boldsymbol{\varphi}_f(\boldsymbol{\sigma}_p)}{1 + \kappa \operatorname{tr}(\boldsymbol{\varphi}_f^T \boldsymbol{\Gamma} \boldsymbol{\varphi}_f)} \quad (29)$$

$$\dot{\boldsymbol{\Gamma}} = \begin{cases} \mu \boldsymbol{\Gamma} - \dfrac{\boldsymbol{\Gamma}\boldsymbol{\varphi}_f \boldsymbol{\varphi}_f^T \boldsymbol{\Gamma}}{1 + \kappa \operatorname{tr}(\boldsymbol{\varphi}_f^T \boldsymbol{\Gamma} \boldsymbol{\varphi}_f)}, & \text{if } \lambda_{\max}(\boldsymbol{\Gamma}(t)) \le \lambda_M \\ 0, & \text{otherwise} \end{cases} \quad (30)$$

where $\mu \ge 0$ is the forgetting factor, λ_M is the preset upper bound for the eigenvalues of the positive definite gain matrix $\boldsymbol{\Gamma}$, and $\kappa \ge 0$ is a normalizing factor.

Based on the above knowledge, the indirect parameter estimation is utilized:

$$\dot{\hat{\boldsymbol{\theta}}} = \operatorname{Proj}_{\hat{\theta}}(\boldsymbol{\Gamma}\boldsymbol{\zeta}) \quad (31)$$

The projection mapping operation is completed by elements, and the detailed form is defined as [10]:

$$\operatorname{Proj}_{\hat{\theta}}(\bullet_i) = \begin{cases} 0, \text{ if } \boldsymbol{\theta}_i \ge \boldsymbol{\theta}_{i\max} \text{ and } \bullet_i > 0 \\ 0, \text{ if } \boldsymbol{\theta}_i \le \boldsymbol{\theta}_{i\min} \text{ and } \bullet_i < 0 \\ \bullet_i, \text{ otherwise} \end{cases} \quad (32)$$

The following two properties hold no matter how the adaptation function $\boldsymbol{\zeta}$ changes.

$$\text{P1: } \hat{\boldsymbol{\theta}} \in \boldsymbol{\Omega}_{\theta} = \left\{\hat{\boldsymbol{\theta}} : \boldsymbol{\theta}_{\min} \le \hat{\boldsymbol{\theta}} \le \boldsymbol{\theta}_{\max}\right\} \quad (33)$$

$$\text{P2: } \tilde{\boldsymbol{\theta}}^T(\boldsymbol{\Gamma}^{-1}\operatorname{Proj}_{\hat{\theta}}(\boldsymbol{\Gamma}\boldsymbol{\zeta}) - \boldsymbol{\zeta}) \le 0, \forall \boldsymbol{\zeta} \quad (34)$$

B. ARC Control Law

Perform the same linear regression operation on the error dynamics (21), (22) and (23):

$$m_i \dot{e}_i = \boldsymbol{\Psi}_i^T \boldsymbol{\theta} - d_i i + \tau_i + \Delta_i - m_i \dot{\alpha}_i, i = u, r, w \quad (35)$$

where

$$\boldsymbol{\Psi}_u = \begin{bmatrix} -\dot{\alpha}_u & vr & 0 & 0 & 0 & \cos\psi & \sin\psi & 0 & 0 \end{bmatrix}^T \quad (36)$$

$$\boldsymbol{\Psi}_r = \begin{bmatrix} uv & -uv & -\dot{\alpha}_r & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}^T \quad (37)$$

$$\boldsymbol{\Psi}_r = \begin{bmatrix} 0 & 0 & 0 & -\dot{\alpha}_w & 1 & 0 & 0 & 0 & 1 \end{bmatrix}^T \quad (38)$$

The ARC law could be synthesized as three parts here: one for the adaptive control law, one for the feedback control law, and another for backstepping design (for i=u, r, w):

$$\tau_i = \tau_{ia} + \tau_{is} + \tau_{ib} \quad (39)$$

where

$$\tau_{ia} = -\boldsymbol{\Psi}_i^T \hat{\boldsymbol{\theta}} + d_i i + m_i \dot{\alpha}_i \quad (40)$$

which is the model compensation that is needed for the system to track the auxiliary variables.

For the feedback term τ_{is}, it could be divided into two terms:

$$\tau_{is} = \tau_{is1} + \tau_{is2}, \quad \tau_{is1} = -k_{is1} e_i \quad (41)$$

where τ_{is1} is the linear feedback term to maintain the closed-loop stability, and k_{is1} is any positive real number as the feedback gain. τ_{is2} is the robust feedback term to compensate for all the model uncertainties and unidentified nonlinearities. The designed nonlinear robust term should satisfy the following two conditions [10]:

$$e_i \tau_{is2} \le 0 \text{ and } e_i(\tau_{is2} - \boldsymbol{\Psi}_i^T \tilde{\boldsymbol{\theta}} + \Delta_i) \le \varepsilon_i \quad (42)$$

in which ε_i is a real positive number that can be arbitrarily small, related to the robust feedback performance. One example of the robust term that satisfies (42) is:

$$\tau_{is2} = -\frac{1}{4\varepsilon_i} h^2(i,t) e_i, \ h(i,t) \ge \|\boldsymbol{\psi}_i\| \|\boldsymbol{\theta}_{\max} - \boldsymbol{\theta}_{\min}\| + \delta_{\Delta i} \quad (43)$$

where $\delta_{\Delta i}$ denotes the maximum norm of the nonlinear uncertainty. The detailed derivation and other optional robust terms can be found in [10].

To increase controllability and accelerate the error convergence, another feedback term on position errors has also been added to the speed control loop.

$$\tau_{ub} = -k_{ub} x_{eb} \quad (44)$$

$$\tau_{rb} = -k_{rb} \gamma_e \quad (45)$$

$$\tau_{zb} = -k_{zb} z_e \quad (46)$$

Then, the close-loop error dynamics becomes:

$$m_i \dot{e}_i = -k_{is1} e_i + \tau_{ib} + \tau_{is2} - \boldsymbol{\Psi}_i^T \tilde{\boldsymbol{\theta}} + \Delta_i, i = u, r, w \quad (47)$$

Theorem 1: The ARC control law given in (35) guarantees the following result:

- With a positive definite function V_1 defined as:

$$V_1 = \frac{1}{2}\left(k_\rho \rho_e^2 + k_\gamma \gamma_e^2 + k_z z_e^2 + m_u e_u^2 + m_r e_r^2 + m_w e_w^2\right) \quad (48)$$

The following inequation could be obtained:

$$V_1 \le V_1(0)\exp(-2\eta t) + \frac{\varepsilon}{2\eta}\left(1 - \exp(-2\eta t)\right) \quad (49)$$

$$\eta = \min(k_\rho, k_\gamma, k_z, k_{us1}, k_{rs1}, k_{ws1}) \quad (50)$$

$$\varepsilon = \varepsilon_u + \varepsilon_r + \varepsilon_w \quad (51)$$

- If the reference trajectory could satisfy the persistent exciting (PE) condition [10], i.e.:

$$\exists T_1, t_0, \varepsilon_p, \int_t^{t+T_1} \psi_r(\tau) \psi_r^T(\tau) d\tau \ge \varepsilon_p I_p, \forall t \ge t_0 \quad (52)$$

the estimated vector would converge to its actual value.

With Comparison lemma [11], *Theorem 1* can be verified.

IV. Simulation and Results

To verify the effectiveness and accuracy of the proposed ARC controller in underactuated AUV, a series of simulations have been completed. The parameters of the AUV model [5] used in this work are listed in Table I.

TABLE I. AUV Parameters Used in the Simulation

Parameter	Value	Parameter	Value	Parameter	Value
m_u (kg)	391.5	k_u	16	$k_{\|u\|u}$	229.4
m_v (kg)	639.6	k_v	131.8	$k_{\|v\|v}$	328.3
I_z (N·m)	35.3	k_r	45.4	$k_{\|r\|r}$	221.6
m_w (kg)	639.6	k_w	65.6	$k_{\|w\|w}$	296.8
W (N)	-5				

The initial states are set as $[0,0,0,0,0,0]^T$. The reference trajectory is designed as:

$$\boldsymbol{X}_d(t) = \begin{bmatrix} 10*\sin(0.05*t)+5 \\ 10*\cos(0.05*t)+5 \\ 0.1*t+2 \end{bmatrix}$$

It is noted that the initial position of the reference trajectory is not the same as the initial position of the AUV, which would verify the error convergence ability of the proposed control algorithm. The constant disturbance to be estimated and the time-varying nonlinearity are designed as:

$$\varsigma = \begin{bmatrix} 10 \\ 10 \\ 0 \\ 5 \end{bmatrix}, \boldsymbol{\Delta} = \begin{bmatrix} 10*\cos(0.5*t) \\ 10*\cos(0.5*t) \\ 0 \\ 5*\cos(0.5*t) \end{bmatrix}$$

The tracking results are shown in Fig. 2: The red line represents the reference trajectory, while the blue line corresponds to the actual AUV positions. It demonstrates that AUV quickly approaches the expected positions, although AUV has a relatively large distance from the reference at initialization, reflecting the effectiveness and outstanding performance of the algorithm.

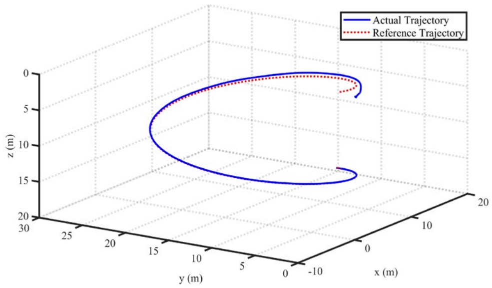

Fig. 2. 3D Tracking Result.

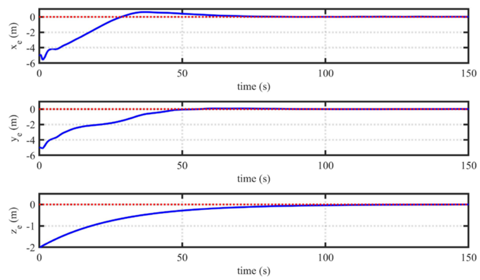

Fig. 3. Distance Tracking Errors.

Fig. 3 shows the distance tracking errors on the three dimensions, separately. Within approximately 50 seconds, the tracking errors in the horizontal directions stabilize to around 0.01 meters. Additionally, the distance error in the *z* direction converges to 0.001 meters, which is in line with the theoretical analysis mentioned above.

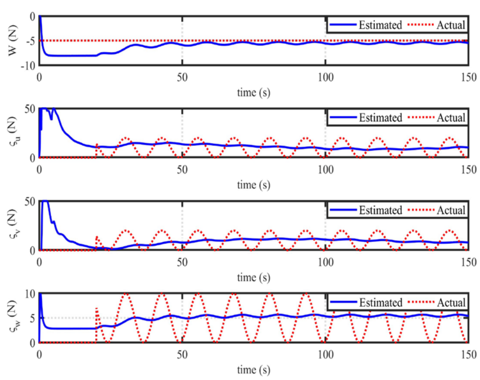

Fig. 4. Buoyance and Disturbances Estimation Results.

Buoyance and disturbances estimation results are given in Fig. 4. Since other parts of the matrix ψ does not satisfy the PE condition, the mass matrix estimation does not converge to its true value, but still converges and keeps stable (not shown in figures). Conversely, when the PE condition is satisfied, the RLS adaptation law could obtain accurate estimation results for the constant values in buoyance and external disturbances, as shown in the blue lines. This would compensate for the nominal model and help the controller maintain stable tracking even under environmental interferences.

V. Conclusion

This paper investigates the three-dimensional trajectory tracking control of an underactuated AUV with parameter uncertainties and environmental distances. First, the virtual control law is established based on the kinematic equations of 4-DOF AUV. Then, an adaptive robust controller is proposed, in which the unknown parameters and external distances could be identified online by the RLS adaptation law to compensate for the nominal model in the controller, and the stability of the controller is proved theoretically: the tracking error could quickly converge and maintain stability. Numerical simulations validated the algorithm's effectiveness, and the results also demonstrate the performance of our proposed controller.

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