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Trajectory Tracking Control of Underwater Vehicle-Manipulator System Using Discrete Time Delay Estimation

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ABSTRACT A new nonlinear robust control scheme is proposed and investigated for the trajectory tracking control problem of an underwater vehicle-manipulator system (UVMS) using the discrete time delay estimation (DTDE) technique. The proposed control scheme mainly has two parts: the DTDE part and the desired dynamics part. The former one is applied to properly estimate and compensate the complex unknown lumped dynamics of the system, using the intentionally time-delayed system's information. The latter one is used to obtain the desired dynamic characteristic of the closed-loop control system. Thanks to the DTDE technique, the proposed control scheme no longer requires the detailed system dynamic information or the acceleration signals, bringing in good feasibility for actual applications and satisfactory control performance. The stability of the closed-loop control system is analyzed and proved using the bounded input bounded out stability theory. Finally, nine degree of freedoms (DOFs) simulation and seven DOFs pool experiment studies were conducted to demonstrate the effectiveness of the proposed control scheme with an UVMS developed in our laboratory. Corresponding results show that our proposed control scheme can ensure satisfactory control performance with relative small control gains and obtain a precision of 0.064 m for the end effector in the task space.

INDEX TERMS Trajectory tracking control, underwater vehicle-manipulator system, UVMS, discrete time delay estimation, DTDE.

I. INTRODUCTION

Nowadays the underwater vehicle-manipulator system (UVMS) has been widely adopted in the scientific and commercial oceanic exploitations owe to its good working capabilities in the deep ocean [1]–[3].There are mainly three types of UVMS based on its operating mode. The first one, named human occupied vehicle-manipulator system (HOVMS), is operated by the onboard operators leading to a tremendous and expensive system. The second one, called remotely operated vehicle-manipulator system (ROVMS), is operated through an umbilical cable. Therefore, the operators for ROVMS can just stay on the support ship, which leads to a relative smaller and cheaper system compared with the former one. Finally, the third one is the autonomous underwater vehicle-manipulator system (AUVMS), which is designed to realize the completely autonomous underwater working. Compared with HOVMS and ROVMS, the AUVMS no longer requires the usage of umbilical cable and support ship, and all the tasks can be completed autonomously. Therefore, the AUVMS can ensure high working efficiency meanwhile need relative lower working cost thanks to this autonomous working mode [4], [5]. Due to these advantages, lots of scholars and engineers have thrown themselves into the control research of UVMS to improve the automation level hoping to realize autonomous manipulation [6]–[8].

However, the control scheme designing for UVMS is very difficult. The main difficulties include the significant nonlinearities of the system dynamics, complex parametric uncertainties and unknown external disturbance. To solve the trajectory tracking control problem of UVMS under above difficulties, some control schemes had been presented and investigated for the past few decades [9], [10]. Combining sliding mode control (SMC) and H_∞ control, the reduction of dynamics coupling is realized and a new control scheme was proposed and investigated with both control methods for UVMS [10]. To compensate the linear and angular position errors caused by the interaction effects between the underwater vehicle and the manipulator, a model reference adaptive control (MRAC) method was proposed for AUVMS [11]. The proposed method was demonstrated with numerical simulations. Using a nonlinear H_∞ optimal control with a disturbance observer (DOB), a novel control scheme is proposed for the tracking control of UVMS. Corresponding effectiveness of the proposed control scheme was also verified through numerical simulation studies. To ensure the simplicity for practical applications and satisfactory control performance, a novel control scheme combining fuzzy PD control with a neural network compensator was presented and demonstrated by simulations with a 9 degrees of freedom (DOFs) UVMS [13]. Although some exciting achievements had been obtained concerning above works, corresponding controllers still require the detailed system dynamics or introduce lots of extra parameters, which is not suitable for practical applications.

Time delay estimation (TDE) can solve above issues in a simple but effective matter [14]–[16]. The central thought of TDE is to estimate and compensate the lumped unknown system dynamics using the time-delayed control efforts and accelerations [17]–[19]. Therefore, no detailed system dynamics are required with TDE and still keep the concision feature compared with other model-free method [20]. On the other hand, the requirement of acceleration may limit the application of TDE to some extent. Therefore, the discrete TDE (DTDE) was proposed [21], which no longer requires the acceleration signals while still keeps the advantages of traditional continuous TDE. Compared with the traditional continuous TDE, the newly proposed DTDE scheme can provide with more smooth control effort and better robustness against measurement noise. Inspired by [21], a new nonlinear robust control scheme using DTDE is proposed and investigated for the trajectory tracking control of UVMS under complex lumped disturbance. Compared with the one given in [21], our main contributions are: (1) extend the application from underwater vehicle to much more complex UVMS; (2) extend the control parameter $\bar{M}$ from a fixed one to a relative large range, which is good for practical applications in different situations. Moreover, the whole stability analysis using this non-fixed parameter is presented theoretically.

The reminder of this paper is organized as what follows. Section II gives the brief description of UVMS. Section III presents the main results of this paper. Afterwards, 9 DOFs simulation and 7 DOFs pool experiment are conducted and corresponding results are given and analyzed in Section IV and V, respectively. Finally, Section VI concludes this paper.

II. SYSTEM DESCRIPTION

Despite its attractive model-free feather, the model structure is still needed to design the proposed nonlinear robust control

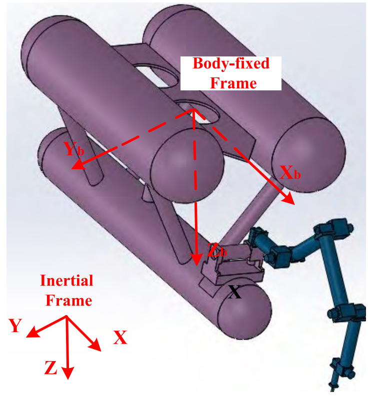

FIGURE 1. **Inertial frame and body-fixed frame definition of UVMS.**

scheme with DTDE. The simplified model of a 9 degree of freedoms (DOFs) UVMS with 4 DOFs vehicle and 5 DOFs manipulator, as shown in Fig.1, can be expressed as

$$M(\varsigma)\dot{\xi} + C(\varsigma,\xi)\xi + D(\varsigma,\xi)\xi + g(\varsigma) + \tau_d = \tau \tag{1}$$

$$\dot{\varsigma} = J_{\text{joint}}\xi \tag{2}$$

where $\varsigma = \left[\eta^{\text{T}}\ q^{\text{T}}\right]^{\text{T}}, \eta = [x, y, z, \psi]^{\text{T}}, q = [q_1, \ldots, q_5]^{\text{T}}$ stands for the position and orientation vector of the system in the inertial frame, $\xi = \left[\nu^{\text{T}}\ \dot{q}^{\text{T}}\right]^{\text{T}}, \nu = [u, v, w, r]^{\text{T}}, \dot{q} = [\dot{q}_1, \ldots, \dot{q}_5]^{\text{T}}$ is the linear and angular velocity vector of the system in body-fixed frame. $M(\varsigma), C(\varsigma,\xi), D(\varsigma,\xi)$ stand for the inertial matrix, Coriolis and centripetal forces, hydrodynamic damping term of the system, respectively. $g(\varsigma)$ is the vector of gravitational forces and moments, which is almost zero since the UVMS we built is nearly neutral buoyancy. τ_d stands for the external disturbance which is mainly caused by the ocean current. τ represents the control effort provided by the propellers and joint motors. J_{joint} stands for the system's Jacobian matrix in the joint space as

$$J_{\text{j}} = \begin{bmatrix} J(\eta) & 0_{4\times5} \\ 0_{5\times4} & I_5 \end{bmatrix},\ J(\eta) = \begin{bmatrix} \cos\psi & -\sin\psi & 0 & 0 \\ \sin\psi & \cos\psi & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

where $J(\eta)$ is underwater vehicle's Jacobian matrix. More details concerning the dynamics of UVMS can be found in [3].

Assumption 1: The system initial matrix $M(\varsigma)$ is positive definite diagonal matrix.

Remark 1: In practical applications, the initial matrix $M(\varsigma)$ is actually not a rigorous diagonal matrix. However, this kind of approximation is precise enough for most practical applications. It should be noted that the model Eq. (1) will not be used in the proposed control scheme given afterwards, and it is given here mainly to show the controller design procedure.

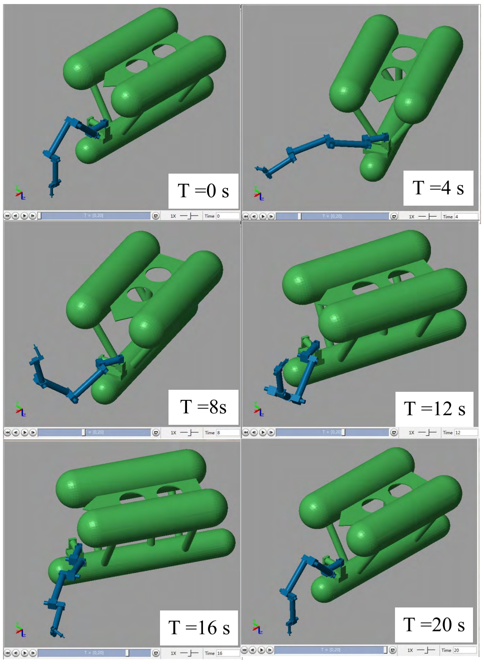

FIGURE 2. The posture transformation of UVMS during the simulation.

III. NONLINEAR ROBUST CONTROL SCHEME DESIGN WITH DTDE

Following assumption is necessary.

Assumption 2: The desired trajectory ς_d is smooth, *i.e.,* $\dot{\varsigma}_d$, $\ddot{\varsigma}_d$ exist and bounded.

A. DYNAMIC MODEL DERIVATION FOR THE APPLICATION OF DTDE

In order to apply DTDE, rewritten Eq. (1) as

$$M(\varsigma)\dot{\xi}(t) + h(t) = \tau(t) \tag{4}$$

where $h(t) = C(\varsigma, \xi)\xi + D(\varsigma, \xi)\xi + g(\varsigma) + \tau_d$.

Equation (4) can be discretized by integrating it with respect to time over a sample period as

$$M(\xi(k+1) - \xi(k)) + \int_{kT}^{(k+1)T} h(t)\,\mathrm{d}t = T\tau(k) \tag{5}$$

where T stands for the sample time, k and $k+1$ stand for the moment kT and (k+1)T.

To adopt DTDE, rearrange Eq. (5) as following

$$\bar{M}\xi(k+1) + H(k) = T\tau(k) \tag{6}$$

$$H(k) = M(\xi(k+1) - \xi(k)) - \bar{M}\xi(k+1) + \int_{kT}^{(k+1)T} h(t)\,\mathrm{d}t \tag{7}$$

where $H(k)$ can be regarded as the complex unknown system dynamics, including hydrodynamics, external disturbance and parametric uncertainties. $\bar{M}$ is a constant diagonal parameter matrix to be designed. Eq. (6) and Eq. (7) can be treated as the discrete accurate but unknown dynamic model of UVMS.

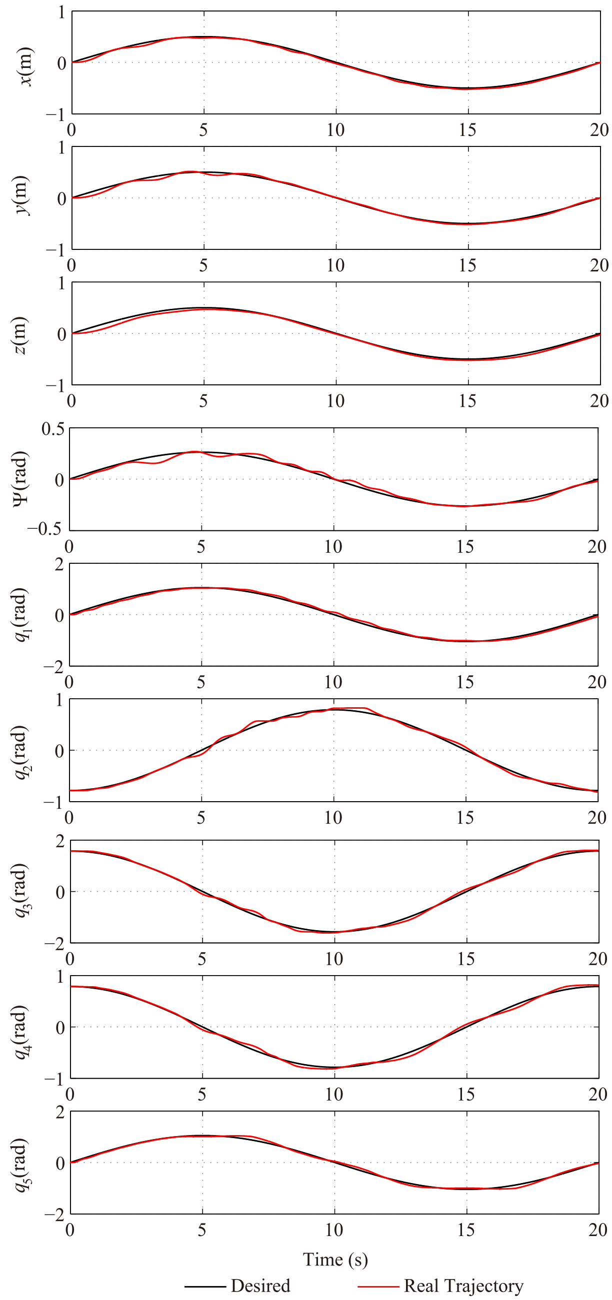

FIGURE 3. Simulation results of trajectory tracking control performance.

B. NONLINEAR ROBUST CONTROL SCHEME DESIGN WITH DTDE

Define the tracking error as $e = \varsigma_d - \varsigma$, then the proposed controller with DTDE can be given as

$$\tau(k) = T^{-1}\left[\bar{M}u(k) + \hat{H}(k)\right] \tag{8}$$

$$u(k) = J^{-1}(k+1)\left(\dot{\varsigma}_d(k) + K_D\dot{e}(k) + K_P e(k)\right) \tag{9}$$

where $J = J_{\text{joint}}$ for concision. And $\hat{H}(k)$ is the estimation of $H(k)$ given in Eq. (7), which is often very hard to obtain precisely with traditional methods.

In order to balance the good control performance and the simplification for practical applications, the DTDE is used

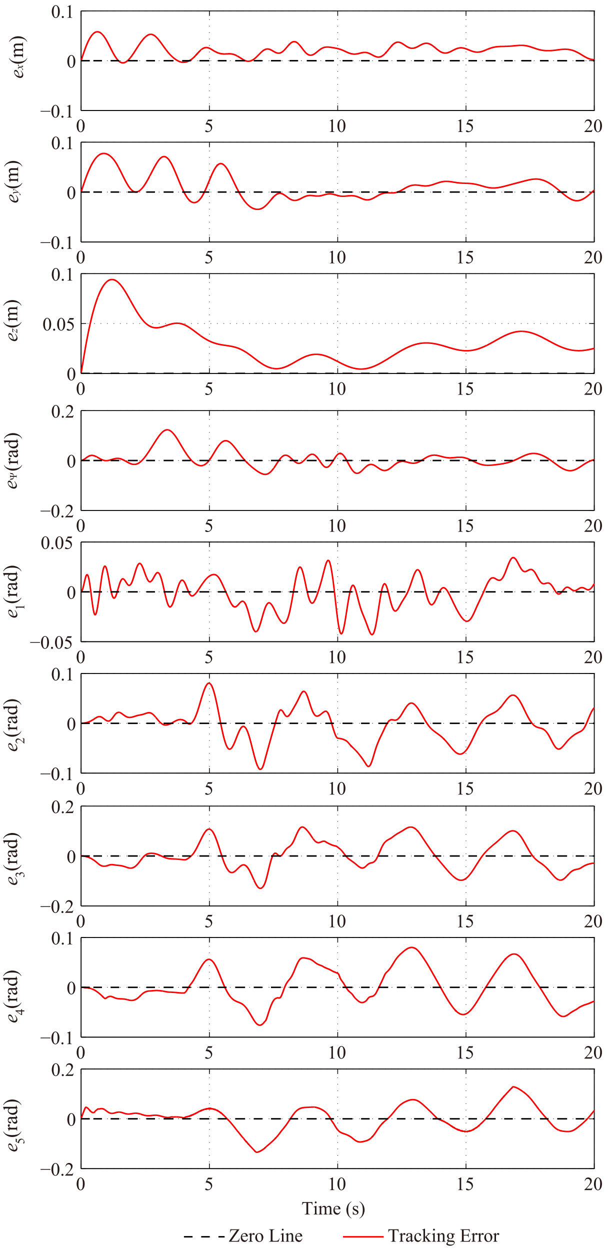

FIGURE 4. Simulation results of trajectory tracking error.

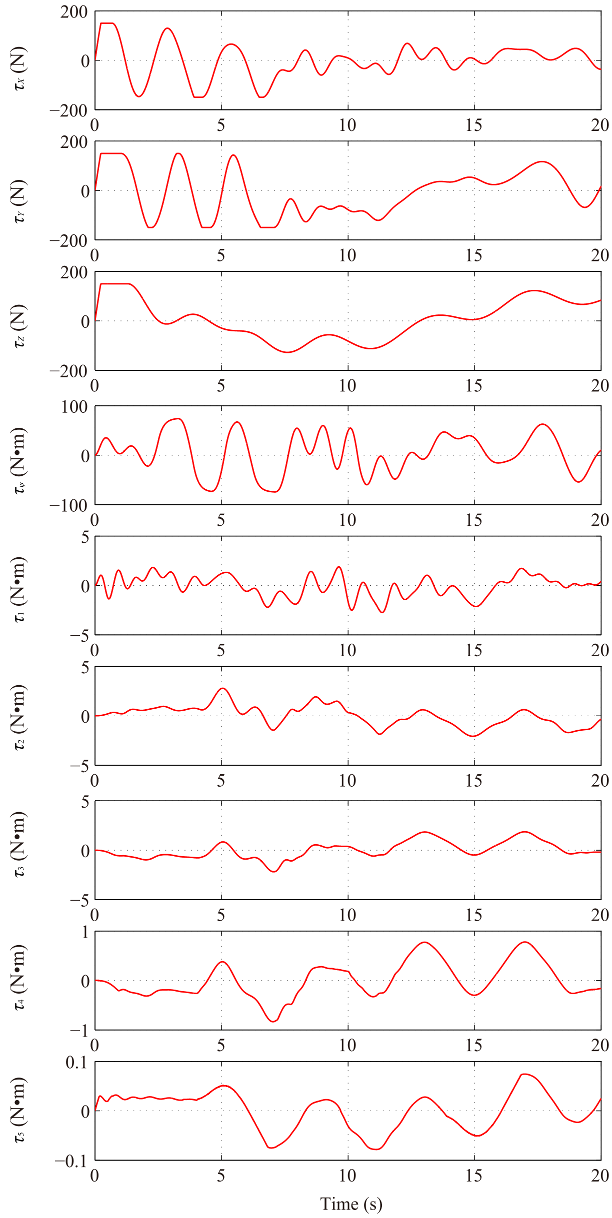

FIGURE 5. Simulation results of control effort.

here to obtain the estimation of $H(k)$ as

$$\hat{H}(k) = H(k-1) = T\tau(k-1) - \bar{M}\xi(k) \tag{10}$$

It can be seen from Eq. (10) that smaller sampling time T will lead to more precise estimation. Combining Eq. (8), Eq. (10) with Eq. (2), we can have the DTDE-based controller as

$$\tau(k) = \underbrace{\bar{M}'J^{-1}(k+1)\left(\dot{\varsigma}_d(k) + K_D\dot{e}(k) + K_Pe(k)\right)}_{\text{Desired Dynamics}} + \underbrace{\tau(k-1) - \bar{M}'J^{-1}(k)\dot{\varsigma}(k)}_{\text{DTDE}} \tag{11}$$

where $\bar{M}' = T^{-1}\bar{M}$.

Remark 2: It can be seen from Eq. (11) that our proposed controller mainly contains two terms. The first one is the DTDE term and the second one is the desired dynamics term. The former is used to properly estimate and compensate system's complex unknown lumped dynamic leading to an attractive model-free nature. The latter is adopted to regulate the control performance of the system. It can also be observed that the detailed system dynamic information is totally not used in the proposed controller Eq. (11), which will greatly guarantee the easiness in practical applications. Moreover, our proposed controller with DTDE no longer requires the acceleration signals, which will result in much more smooth control effort and better robustness against measurement noise compared with the controller using traditional TDE.

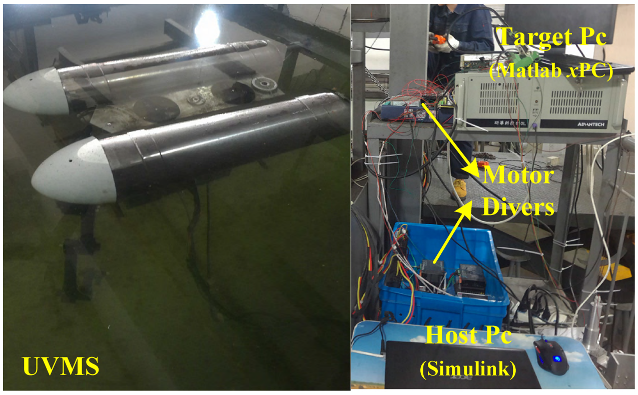

FIGURE 6. UVMS experiment setup.

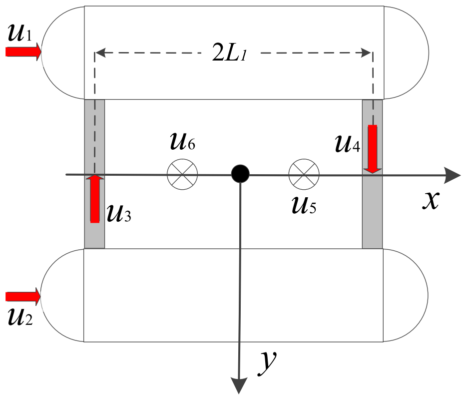

FIGURE 7. Arrangement diagram of underwater vehicle's propellers.

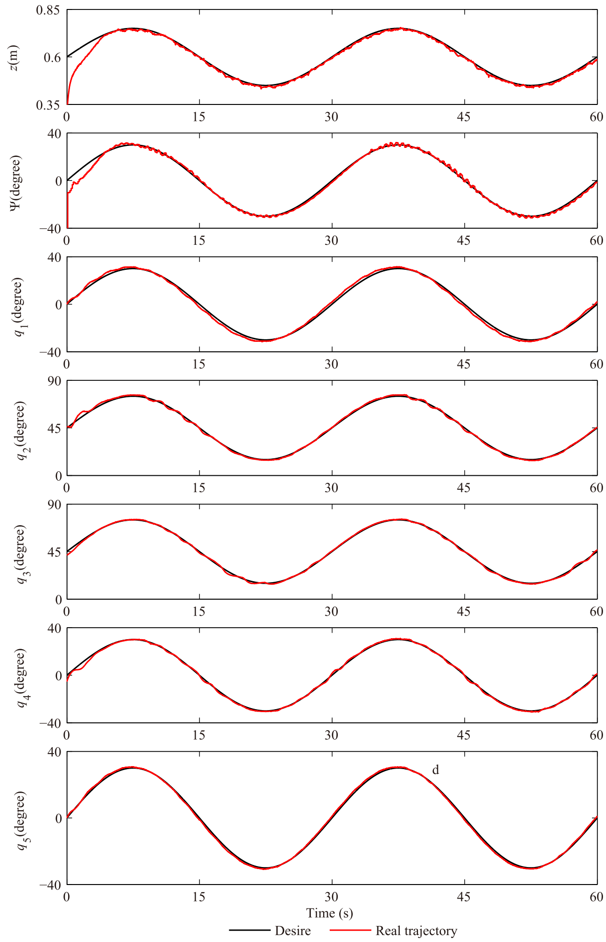

FIGURE 8. Experiment results of trajectory tracking control performance.

C. STABILITY ANALYSIS OF THE CLOSED-LOOP CONTROL SYSTEM

The stability analysis procedure is similar with the one given in [21] except that the key control parameter $\bar{M}$ has a broader range of choice instead of a fixed one, leading to relative broad application.

Substituting the controller Eq. (8) and Eq. (9) into Eq. (6), we have

$$u(k) - \xi(k+1) = \varepsilon(k) \tag{12}$$

where $\varepsilon(k) = -\bar{M}^{-1}\left(\hat{H}(k) - H(k)\right)$ is the estimation error vector after applying DTDE and its boundedness will be proved afterwards.

Combining Eq. (2), Eq. (9) and Eq. (12), yields

$$\dot{e}(k+1) + K_D\dot{e}(k) + K_P e(k) = J(k+1)\varepsilon_1(k) \tag{13}$$

where $J(k+1)\varepsilon_1(k) = J(k+1)\varepsilon(k) + (\dot{\varsigma}_d(k+1) - \dot{\varsigma}_d(k))$.

Based on forward difference approximations, Eq. (13) can be arranged as

$$\begin{aligned} TJ(k+1)\varepsilon_1(k) &= e(k+2) + (K_D - I)e(k+1) \\ &\quad + (TK_P - K_D)e(k) \end{aligned} \tag{14}$$

The term in Eq. (14) can be regarded as external disturbance input. According to the bounded input bounded output (BIBO) stability theory, the tracking error $e(k)$ will be bounded with proper selection of K_P and K_D under the condition that $\varepsilon_1(k)$ is bounded. Based on Assumption 2, $\dot{\varsigma}_d(k+1) - \dot{\varsigma}_d(k)$ is bounded. Therefore, the boundedness of $\varepsilon_1(k)$ and $\varepsilon(k)$ is equivalent.

Now, the boundedness of $\varepsilon(k)$ will be proved afterward. Combining Eq. (5) and Eq. (12) yields

$$\begin{aligned} M\varepsilon(k) &= Mu(k) - M\xi(k+1) \\ &= Mu(k) + \bar{H}(k) - T\tau(k) \end{aligned} \tag{15}$$

where $\bar{H}(k) = -M\xi(k) + \int_{kT}^{(k+1)T} h(t)\mathrm{d}t$.

Substituting controller Eq. (8) into Eq. (15) and combining Eq. (10), we have

$$M\varepsilon(k) = \left(M - \bar{M}\right)u(k) + \bar{H}(k) - H(k-1) \tag{16}$$

Based on the definition of $\hat{H}(k)$ and $\bar{H}(k)$, we have

$$\begin{aligned} \hat{H}(k) &= \left(M - \bar{M}\right)\xi(k) - M\xi(k-1) + \int_{(k-1)T}^{kT} h(t)\,\mathrm{d}t \\ &= \left(M - \bar{M}\right)\xi(k) + \bar{H}(k-1) \end{aligned} \tag{17}$$

Substituting Eq. (17) into Eq. (16) leads to

$$M\varepsilon(k) = \left(M - \bar{M}\right)(u(k) - \xi(k)) + \hat{H}(k) - \bar{H}(k-1) \tag{18}$$

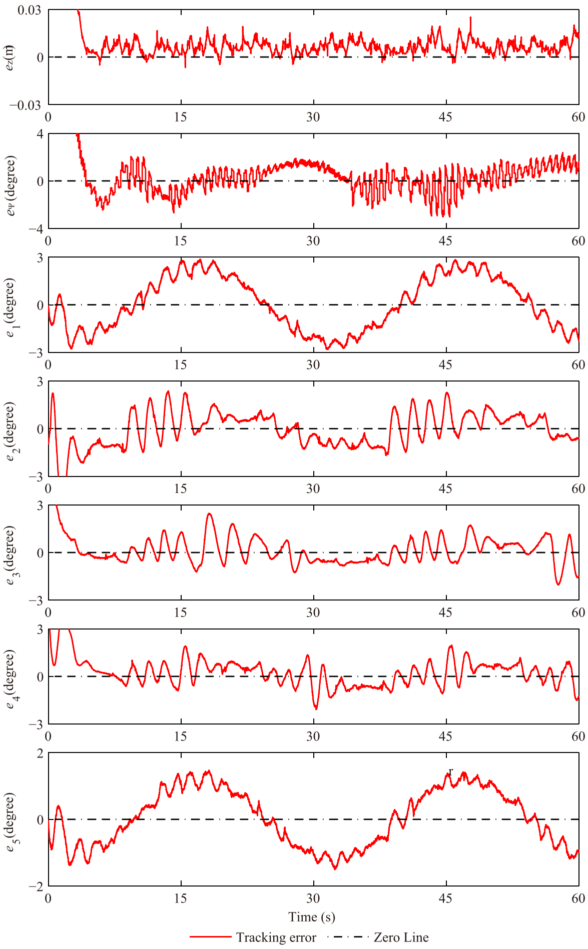

FIGURE 9. **Experiment results of trajectory tracking error.**

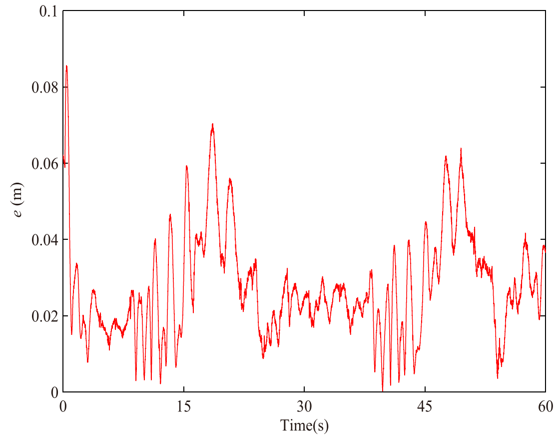

FIGURE 10. **Experiment results of end effector position error.**

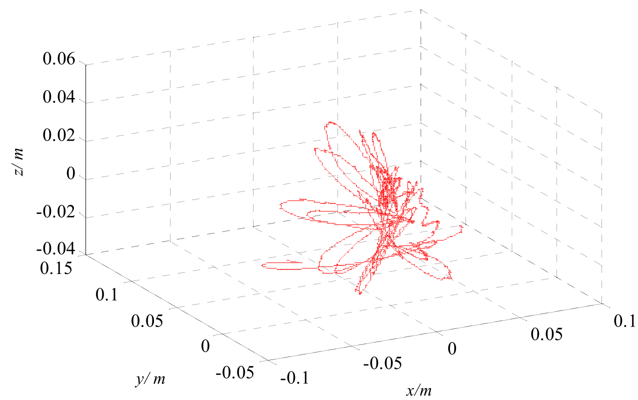

FIGURE 11. **Experiment results of end effector position error in 3-D space.**

Note $\xi(k) = u(k-1) - \varepsilon(k-1)$, Eq. (18) can be rewritten as

$$\varepsilon(k) = \left(I - M^{-1}\bar{M}\right)\varepsilon(k-1) + M^{-1}\left(\bar{H}(k) - \bar{H}(k-1)\right) + \left(I - M^{-1}\bar{M}\right)(u(k) - u(k-1)) \tag{19}$$

Equation (19) can be furfure arranged as

$$\varepsilon(k) = \mu\varepsilon(k-1) + P_1 + P_2 \tag{20}$$

where $P_1 = \mu(u(k) - u(k-1))$, $P_2 = M^{-1}(\bar{H}(k) - \bar{H}(k-1))$ and $\mu = I - M^{-1}\bar{M}$. P_1 and P_2 can be treated as bounded disturbance input, while μ is an unknown diagonal matrix based on Assumption 1.

$\varepsilon(k)$ will be bounded under the condition that all the eigenvalues of lie inside a unit disc [22], [23], that is

$$|\mathrm{Eig}(\mu)| < 1 \Rightarrow \left|\mathrm{Eig}\left(I - M^{-1}\bar{M}\right)\right| < 1 \tag{21}$$

Then, for the i-th DOF of the system, we have

$$\left|1 - M_{ii}^{-1}\bar{M}_{ii}\right| < 1 \Rightarrow 0 < \bar{M}_{ii} < 2M_{ii} = 2(M_{RB} + M_A)_{ii} \tag{22}$$

where M_{RB} and M_A stand for system's rigid mass and added mass, respectively.

Thus, the stability of the closed-loop control system will be guaranteed with proper choice of $\bar{M}_{ii}$, K_P, K_D based on the condition Eq. (14) and Eq. (22).

D. ANTI-WINDUP SCHEME AND COMPENSATOR DESIGN

The anti-windup [22] is adopted here to enhance the control performance under the existence of hard non-linearities. Moreover, a compensator was designed and turned through experiments to compensate the remaining nonlinearity. Finally, the control scheme is design as

$$\tau = \tau_{fdtde} + \tau_{comp} \tag{23}$$

where τ_{fdtde} is the control signal Eq. (11) coming out from the anti-windup scheme and one-order filter. And the compensator τ_{comp} is designed as $\tau_{comp} = K_w sgn\left(\tau_{fdtde}\right)$, where the K_{w} is constant control gain.

Afterwards, the control efforts for each DOF can be obtained using following thrust distribution equation

$$u = B^{+}\tau \tag{24}$$

where B^{+} is the distribution matrix of the UVMS and is determined by the arrangement of the actuators.

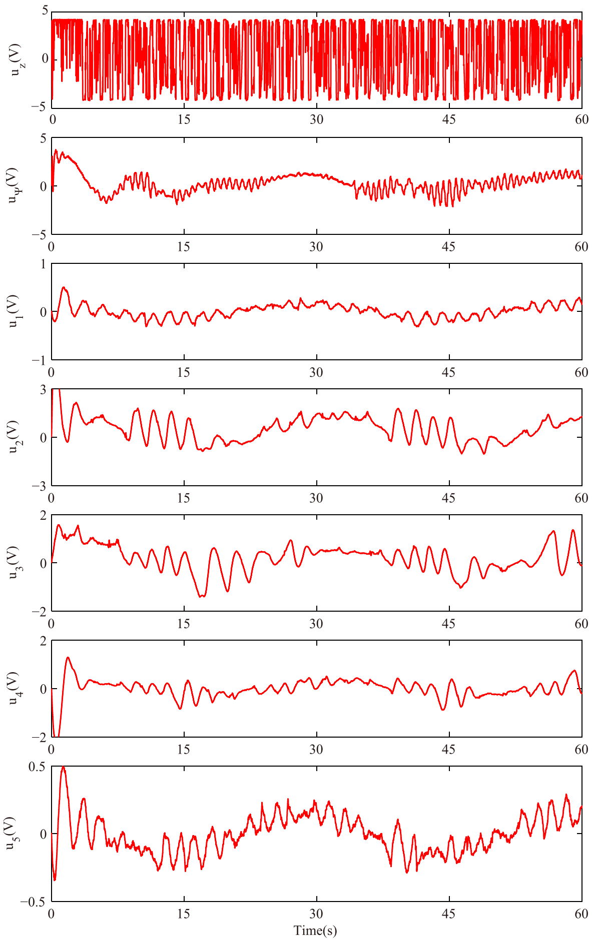

FIGURE 12. Experiment results of control effort.

TABLE 1. Physical parameters of UVMS used in the simulation.

Object	Physical parameters	Quantity
Vehicle	L×H×W / Mass	1.7×0.9×1.1m / 220 Kg
Link 1	Length/Mass	0.172m / 0.8Kg
Link 2-3	Length/Mass	0.33 m / 1.2 Kg
Link 4	Length/Mass	0.242 m / 1.0Kg
Link 5	Length/Mass	0.121m / 0.3Kg

IV. SIMULATION STUDIES

To verify the effectiveness of our proposed control scheme, corresponding 9 DOFs simulation had been conducted based on the UVMS developed in our laboratory.

A. SIMULATION SETUP

Since the detailed dynamic information of the UVMS is extremely difficult to obtain, Matlab/SimMechanics is used to conduct the simulations. The physical parameters of UVMS used in the simulations are listed in Table 1. Taking the nearly neutral buoyancy property of UVMS into consideration in the simulation, therefore g is set to 0.

B. SIMULATION RESULTS

A time-vary lumped disturbance given in Eq. (25) is also added into the system to verify the robustness of our proposed control scheme against unknown external disturbance. The control parameters are selected as $K_P = 0.1\text{diag}\{4,4,4,8,4,8,8,\ 4,4\}$, $K_D = \text{diag}\{3,3,3,2,2,0.05,0.05,0.05,0.05\}$, $\bar{M}' = \text{diag}\{6,6,6,\ 6,2,2,1,0.8,0.06\}$. The simulation setup is selected as 1ms.

$$
\begin{aligned}
&t = 0 \sim 4s: \quad T_{1\sim 9} = 0 \\
&t = 4 \sim 20s: \quad T_{1-9} = K_{dis} \sin\left(\frac{\pi}{2}(t-4)\right) \quad (N/N \cdot m)
\end{aligned} \tag{25}
$$

where $K_{\text{dis}} = \text{diag}\{20,20,20,20,1,1,1,0.5,0.05\}$ is the gain matrix for the disturbance.

Corresponding simulation results are given in Fig. 2-5. It can be seen clearly that our proposed control scheme can ensure satisfactory control performance under unknown time-varying lumped disturbance, while ensure relative smooth control efforts. Moreover, it should be noted that the control gains K_P and K_D used in the simulation are very small, which will guarantee good robustness against the complex lumped disturbance.

V. EXPERIMENT STUDIES

A. EXPERIMENT SETUP

The UVMS used in the experiment has 9 DOFs, 4 for the underwater vehicle and 5 for the underwater manipulator, as shown in Fig. 6. The underwater vehicle has 6 propellers driven by 200w 12V DC motors. The propellers can output 30N forward force and 10N backward force. The arrangement of the propellers is shown in Fig. 7 and corresponding distribution matrix B^+ in Eq. (24) for the UVMS is given as

$$
B^+ = \begin{bmatrix} B_1^+ & 0 \\ 0 & B_2^+ \end{bmatrix},
$$

$$
B_1^+ = \begin{bmatrix} 0.5 & 0 & 0 & 0 \\ 0.5 & 0 & 0 & 0 \\ 0 & -0.5 & 0 & 0.6757 \\ 0 & 0.5 & 0 & 0.6757 \\ 0 & 0 & 0.5 & 0 \\ 0 & 0 & 0.5 & 0 \end{bmatrix}, \quad B_2^+ = I_5 \tag{26}
$$

where B_1^+, B_2^+ are the distribution matrices for the underwater vehicle and manipulator, respectively.

The 5-DOFs underwater manipulator has two kinds of joints. The first one is driven by Maxon Re25 with a planet reduction gear GP 32A, which is used in the first four joints. The other one is driven by Maxon A-max 22 with a planet reduction gear GP22A, which is used in the last joints. The depth sensor adopted has an accuracy of 1cm, and a Honeywell HMR 3000 compass with an accuracy of 0.5° is also equipped in the UVMS. The accuracy of the angular sensors used in the underwater manipulator is about 0.03°. Since we have only two sensors for the underwater vehicle, the experiment is conducted with 7 DOFs.

TABLE 2. RMS and maximum values of steady tracking errors in joint space.

DOF (m/ °)	e_z	e_Ψ	e_1	e_2	e_3	e_4	e_5
RMS	0.008	1.11	1.73	0.92	0.74	0.75	0.87
Max	0.025	3.03	2.83	2.29	2.02	2.08	1.50

TABLE 3. RMS and maximum values of steady tracking errors in task space.

DOF (m)	e_P	e_x	e_y	e_z
RMS	0.030	0.015	0.020	0.016
Max	0.064	0.040	0.052	0.037

The control algorithm is implemented in the x PC system with a NI PCI-6229 and a Contec PCI DA12-16 boards as shown in Fig. 6, and the sampling period is chosen as 0.1ms. The control inputs given to the motor drives are limited to [−5, +5] V. Finally, the control parameters for Eq. (11) are selected as $\bar{M}' = 0.01\mathrm{diag}\{15,2,30,30,30,15,20\}$, $K_P = \mathrm{diag}\ \{30,12,2,2,2, 2,2\}$, $K_D = \mathrm{diag}\{75,20,3,3,3,3,3\}$, $K_W = 0.1\mathrm{diag}\ \{5,5,1,1,1,1,1\}$.

B. EXPERIMENT RESULTS

Corresponding experiment results are given in Fig. 8-12. The root mean squared (RMS) and maximum values of the steady tracking error expressed in joint space and task space are given in Table 2 and Table 3, respectively.

As shown in Fig. 8-12 and Table 2 and Table 3, our proposed control scheme can ensure satisfactory control performance, which is mostly consistent with the simulation results. Meanwhile the maximum position error of the end effector in task space is 0.064m, which is precise enough for lots of practical applications. Moreover, the adoption of DTDE effectively reduces the control gains K_P and K_D, leading to good robustness against the measurement noise. On the other hand, it is also obvious that all the control efforts are relative smooth except u_z. This phenomenon can be explained as following. In z direction, the UVMS is a little positive buoyancy; meanwhile the thrust produced by the vertical propeller is relative small to handle this positive buoyancy. Therefore, the thrust is switching fast to ensure the satisfactory control performance. Generally speaking, the proposed control scheme with DTDE can ensure satisfactory control performance and good applicability.

Generally speaking, our proposed control scheme based on DTDE can ensure satisfactory control performance using small control gains, leading to good robustness against the complex lumped disturbance. Moreover, the acceleration signals are no longer required thanks to DTDE, leading to relative smooth control effort. Finally, the simplicity, effectiveness and robustness are demonstrated through both 9 DOFs simulations and 7 DOFs pool experiment studies.

VI. CONCLUSIONS

A new nonlinear robust control method using DTDE is presented and investigated for the trajectory tracking control of UVMS under lumped disturbance in this paper. Thanks to DTDE, the proposed control scheme no longer requires the detailed system dynamics or acceleration signals, which is easy to use in practical applications and robust against measurement noise. The stability of the closed-loop control system is analyzed and proved based on BIBO theory. Afterwards, 9 DOFs simulation and 7 DOFs experiment studies were conducted to verify the effectiveness of our proposed control scheme. Corresponding results show that our proposed control scheme can ensure satisfactory control performance with relative small control gains and obtain a precision of 0.064m for the end effector in the task space. Theoretical researches and more experiments using UVMS or other kinds of robots with DTDE will be conducted to further improve the control performance in the future work.

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