Combined dynamics and kinematics networked fuzzy task priority motion planning for underwater vehicle-manipulator systems

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Abstract
The underwater vehicle-manipulator systems (UVMS) face significant challenges in trajectory tracking and motion planning because of external disturbance (current and payload) and kinematic redundancy. Former algorithms can finish the tracking of end-effector (EE) and free of singularity redundancy solution alone. However, only a few analytical studies have been conducted on coordinated motion planning of UVMS considering the dynamics controller. This article introduces a combined dynamics and kinematics networked fuzzy task priority motion planning method to solve the above problems. It avoids the assumption of perfect dynamic control. Firstly, to eliminate the kinematics error, a dynamic transformation method from joint space to task space is proposed. Without chattering, an outer loop sliding mode controller is designed for tracking EE’s trajectory. Further, to ensure the underwater vehicle’s posture stability and joint constraint, a task priority frame with kinematics error is used to planning the coordinated motion of UVMS, in which the posture and joint limits map into the null space of prioritized tasks, and weight gains are adopted to guarantee orthogonality of secondary tasks. On top of that, the gain weighted are updated by the networked fuzzy logic. The proposed algorithm achieves better coordinated motion planning and tracking performance. Effectiveness is validated by numerical simulation.

Keywords
Underwater vehicle-manipulator systems, coordinated motion planning, dynamics transformation, outer loop sliding mode controller, multitask priority, networked fuzzy logic

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Introduction
The vehicle-manipulator system has a more complex external environment and force characteristics in the space and ocean. It realizes more effective motion control and grasping accurately, which highlighted its research significance.1–3 The underwater vehicle-manipulator systems (UVMS), remote operating vehicle (ROV), or autonomous underwater vehicle (AUV) with manipulators is a vital tool...
for underwater tasks such as marine science, marine engineering, and military applications. However, given the kinematics redundancy, processing the constraints of each joint (inequality condition) and the motion stability of AUV is still not available in the unified form. When facing parameter uncertainty and external disturbance, the controller still has some problems, mainly reflected in poor convergence, insufficient stability and chattering. In summary, the practical solutions to the abovementioned issues are rarely examined in the research.

Although the redundancy of the UVMS increases manipulability, it causes the kinematics solution to be non-unique and leads to the necessity of redundant decomposition in trajectory planning. This redundancy seriously affects online trajectory planning and motion coordination. Offline trajectory planning tasks cannot be effective in a harsh environment. There are two solutions to the UVMS redundancy: one approach is the augmented Jacobin, which may bring the algorithm singularity, and the other is based on pseudoinverse approaches to assume the end-effector (EE) path, which brings space inconsistencies.

Once the trajectory of the EE is given, the motion of AUV and each joint needs to be considered. Antonelli proposed a fuzzy redundancy coordinated motion control method and adopted the inequality condition to activate secondary tasks. Based on the pseudoinverse approach, Santos used a fuzzy expert system to avoid singularity posture on the UVMS. Both overcome the kinematics singularity effectively. However, they still fail to solve optimal redundancy.

To the best of the authors’ knowledge, researchers have proposed a variety of trajectory planning methods for UVMS at different criteria, such as obstacle avoidance, proposed a variety of trajectory planning methods for mal redundancy. However, they still fail to solve optimal posture on the UVMS. Both overcome the kinematics singularity effectively. However, they still fail to solve optimal redundancy.

The first solution is to consider the disturbance and uncertainty as to the lumped uncertainty; the second solution is to deal with them separately by subdividing each characteristics. In the first solution, Ahmed and Fateh approximated the lumped uncertainty through the Taylor series, and Han et al. designed an inertial delay controller to estimate it and improved the control effect using a fuzzy compensator. Although this method resulted in a relatively simplified controller, a bottleneck was encountered to control accuracy. The second solution, more targeted, is often based on the characteristics of disturbance and uncertainty. Considering (b) and (d), Mohan and Kim adopted the extended Kalman filter (EKF) algorithm to construct disturbance compensation; Salloom et al. analyzed (c) as an unknown external disturbance and considered the nonparametric uncertainties as (f); the literature designed EKF, adaptive algorithm, and observer compensation, respectively, for (d). Before using the time delay estimator, Yang et al. summarized (c) as (d). The abovementioned classification of disturbance terms is the basis to provide a compelling for the optimization of the controller. Similarly, the parameter uncertainty term in the uncertainty is passed through Legendre polynomial, respectively, achieved online estimation. Sadly, the kinematics redundancy of UVMS is less reflected in the controller designed with lumped uncertainty.

Under the highly coupling of UVMS dynamics, Kim et al. proposed a sliding mode control (SMC) with UVMS motion redundancy considered to ensure task completion successfully when the target object’s shape, inertia, and others are unknown. Combined kinematics and dynamics control method for UVMS was proposed for underwater swimming manipulator by Borlaug et al. It allows us to design the kinematic and dynamic subsystems together without the assumption of perfect dynamic control. In this article, the SMC in position needs to be further strengthened. A condition is set that model can be decoupled in dynamics and kinematics separately. The singularly robust multitask priority framework (SRMTP) eliminates this condition. It brings us an idea. However, in the process of combined kinematics and model uncertainty error, the quality of control still needs to be improved.
Inspired by the above studies, a novel motion planning and coordinated controller for UVMS is proposed in this article. This contribution to this article is that the proposed method within the multitasks can achieve precise and robust performance under the disturbances. First, an outer-loop sliding mode controller is proposed, where the dynamics transform from joint space to task space for avoiding joint error accumulation, and the outer loop eliminates the kinematics error in the task space. Second, the multiple TP motion planning and coordinated frame of UVMS is constructed, where weighted gains are adopted in the null space of prioritized tasks to guarantee orthogonality of secondary tasks, and the task error is feedback to the controller. Third, to determine secondary tasks’ contribution, a networked fuzzy logic is employed, instead of traditional fuzzy redundant rules. Last, the effectiveness and feasibility of the proposed method are verified by numerical simulations.

In this article, the model of UVMS kinematics and dynamics is derived in the second section, and the third section is concerned with a tracking controller combined with kinematics error. In the fourth section, the proposed coordinated motion planning method is constructed. The fifth section verifies the effectiveness of the proposed method by simulation experiments. Conclusions are presented in the sixth section.

**Problem setting**

UVMS consists of the AUV and the manipulator. Figure 1 shows the UVMS in each coordinate frame, the AUV is connected to the EE through link \( L_s \) and joint \( q_i \) (it could be either prismatic or revolute). The following coordinate systems have been established: \( \{ \Sigma_f \} \) is the inertial frame in the earth, \( \{ \Sigma_b \} \) expresses the frame of AUV body, and \( \{ \Sigma_0 \} \) represents the frame, where joint \( q_1 \) is connected to AUV body and \( \{ \Sigma_e \} \) is the manipulator EE frame with respect to inertial frame. The total dimension of freedom (DOF) is \( 6 + n \), in which \( q = [q_1,q_2 \ldots q_n] \in R^n \) is the joint vector of \( n \) DOF manipulator, \( v_1 = [u \ v \ w]^T \) and \( v_2 = [p \ q \ r]^T \), respectively, represent the position/orientation velocity of AUV.

The velocity kinematics equation of the UVMS is

\[
\dot{x}_E = J(R_{b}^{T},q)\xi
\]

(1)

where \( \dot{x}_E = [p_r \ r_d] \in R^6 \) represents the desired EE velocity in \( \{ \Sigma_I \} \), \( p_r \) and \( r_d \) are the position and orientation vectors, respectively. \( \xi = [v_1 \ v_2 \ \dot{q}]^T \in R^{6+n} \) is the system velocity in the joint space with respect to inertial frame, \( J(R_{b}^{T},q) \in R^{6×(6+n)} \) is the Jacobian matrix of EE and each joint in the AUV body frame \( \{ \Sigma_b \} \), as the function of \( R_{b}^{T} \) and \( q \), and \( \xi \) is the skew-symmetric matrix.

Consider the dynamics of UVMS in joint space as follows

\[
M(q,\eta)\ddot{\xi} + C(q,\xi)\dot{\xi} + D(q,\xi)\dot{\xi} + G(q,R_{b}^{T}) = \tau + \tau_d
\]

(2)

where \( \dot{\xi} \) is the time derivate of UVMS velocity \( \xi, \eta \) is the rotation matrix of AUV, one of the independent variables of \( M(q,\eta) \). \( M(q,\eta) \in R^{(6+n)×(6+n)}, \ C(q,\xi) \in R^{(6+n)}, \) and \( D(q,\xi) \in R^{(6+n)} \) are the inertia matrix (AUV with manipulator inertia), Coriolis and centripetal matrix, and damping matrix (hydrodynamic term), respectively.

Under the corresponding accurate model, \( M^*, \ C^* \) and \( D^* \) are known matrices in equation (2). Due to the error from model measurement and motion in the current, the unknown/uncertain matrix terms are considered in this article as \( \Delta M, \Delta C, \) and \( \Delta D \). \( G(q,R_{b}^{T}) \) is gravity and buoyancy term. \( \tau_d \) represents the external disturbance (current or payload changes).

Further, equation (2) with unknown matrix terms can be expressed as

\[
\tau + \tau_d = (M^*(q,\eta) + \Delta M)\ddot{\xi} + (C^*(q,\xi) + \Delta C) + (D^*(q,\xi) + \Delta D)\dot{\xi} + G(q,R_{b}^{T})
\]

(3)

Consider the unknown matrix terms abovementioned as an external disturbance. This idea can be compensated and estimated in real time using the controller designed in the next section.

So, rewrite equation (3) as follows

\[
M^* \ddot{\xi} + C^*\dot{\xi} + D^*\dot{\xi} = \tau + \tau_f
\]

(4)

where \( \tau_f = \Delta M\ddot{\xi} + \Delta C\dot{\xi} + \Delta D\dot{\xi} - \tau_d - G \).

In the UVMS model, the AUV is underactuated in the AUV body frame, and its design parameters are given in Table 1.

| Name               | Design specifications | Name               | Design specifications |
|--------------------|-----------------------|--------------------|-----------------------|
| Body length        | 1.6 m                 | Endurance          | 5 h                   |
| Diameter           | 0.26 m                | Max depth          | 200 m                 |
| Weight             | 75 kg                 | Max thrust         | 50 N                  |
| Buoyancy           | 0.30 kg/m             | Max speed          | 4 knot                |

AUV: autonomous underwater vehicle.

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**Table 1. Design indicators for AUV.**

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**Figure 1. Sketch of underwater vehicle-manipulator systems.**
Table 2. Joints parameters in manipulator subsystem.

| Joint | Type   | Actuator | Range of angle |
|-------|--------|----------|----------------|
| q₁    | Revolute | Servo motor | −360° to 360° |
| q₂    | Revolute | Servo motor | −142° to 142° |
| q₃    | Revolute | Servo motor | −230° to 230° |

The manipulator, ₙ = 3, consists of three joints ₁, ₂, and ₃, as shown in Figure 1. Those revolute joints are actuated by servo motor. According to the manipulator’s mechanical characteristic, the joints limit is considered in this article, as given in Table 2. The DH parameters of the manipulator are given in detail by Han et al. ¹⁰ It takes no attention to the impact of change in AUV’s center of gravity.

**Design of a tracking controller**

It is worth noticing that the problem of uncertainty and external disturbance, as the precondition of UVMS coordinated motion planning, is based on a sliding mode controller. ²²

Given the EE desired velocity ₓₓ, the SMC eliminates the error in velocity space. Unfortunately, the EE’s desired trajectory is unachievable, reflecting in the static error of position space. So, an outer loop (position loop) is proposed to solve this problem.

**Dynamics from joint space to task space**

Firstly, EE error is defined in the task space

\[ e = x_x - x \]  

(5)

Further, get the time derivation of \( e \)

\[ \dot{e} = \dot{x}_x - \dot{x} \]  

(6)

In equation (6), \( \dot{x}_x \in R^6 \) is the desired velocity of EE, while \( \dot{x} \in R^6 \) is the actual velocity.

Introduce \( e_s \)

\[ e_s = k_e e + \dot{e} \]  

(7)

where \( k_e \) is the error gain, expressed as constant.

Differentiate it

\[ \dot{e}_s = k_e \dot{e} + \dot{k}_e e + \ddot{x}_x - \ddot{x} \]  

(8)

Combined with equations (1), (3), and (8), the dynamics in task space is as follows

\[ M^* J^* \ddot{\xi} + C^* J^* \dot{\xi} + D^* J^* \dot{\xi} = r_s J^* + (r_f + r_e) J^* \]  

(9)

where \( r_e \) represents external disturbance.

Rewrite as equation (10)

\[ \ddot{M} \xi + \dot{C} \xi + D \xi = r_p - d(\xi, \dot{\xi}) + (\dot{C} + D) e_s \]  

(10)

where \( \dot{M} = M^* J^* \), \( C = C^* J^* \), \( D = D^* J^* \), \( r_p = r J^* \), and \( d(\xi, \dot{\xi}) = -(\tau_f + \tau_e) J^* \).

Assuming that \( d(\xi, \dot{\xi}) \) meets the following conditions: ²⁴

(1) \( d(\xi, \dot{\xi}) \) is bounded, \( |d(\xi, \dot{\xi})| \leq \delta_b \), \( \delta_b \) is the maximum external disturbance and (2) \( d(\xi, \dot{\xi}) \) is instantaneous, satisfying \( \dot{d}(\xi, \dot{\xi}) = 0 \).

From the abovementioned, the tracking error of EE in the task space consists of two. The first is the accumulation, in the task space, of trajectory tracking errors from joint space, and the other comes from the kinematics of the desired pose in the joint space, as shown in equation (1). This error in the task space from the desired pose of EE is caused by IK. Rewriting equation (3) into equation (10), expression in the task space can more intuitively reflect EE’s control error. Next, the controller designed is to avoid error accumulation.

**Outer loop sliding mode controller**

Further, get \( \ddot{x} \) from equation (10)

\[ \ddot{x} = M^{-1}(r_p - d(\xi, \dot{\xi}) - C \dot{x} - D \dot{y}) \]  

(11)

Substituting equation (11) into equation (8), rewrite \((\dot{C} + D)\) to \( H \)

\[ \dot{e}_s = \ddot{x}_x - M^{-1}(r_p - d(\xi, \dot{\xi}) - H \dot{x}) + k_e e \]  

(12)

The SMC is defined as follows

\[ r_p = \dot{M}(\ddot{x}_x + k_e \dot{e}) + H \dot{x} + \mu e_s + \rho_1 \text{sgn}(e_s) \]  

(13)

Substituting equation (13) into equation (12)

\[ \dot{e}_s = -M_q^{-1}(\dot{C} e_s + \mu e_s + \rho_1 \text{sgn}(e_s) - d(\xi, \dot{\xi})) \]  

(14)

where \( \mu > 0, \text{sgn}(\cdot) \), as a sign function, is used to ensure the state’s continuity. ²³

To ensure the accuracy of the EE posture trajectory, an outer loop (position loop) is introduced based on the SMC to achieve precise control.

Assuming N.1, when \( \epsilon \to 0 \), there exist \( \epsilon > 0 \) for which the equation holds \( \dot{x} = \ddot{x}_x + \epsilon \).

Define the error \( e_o \) in the outer loop, and its derivative form as equation (16)

\[ e_o = e + k_o \int_0^t \epsilon \text{d}t \]  

(15)

\[ \dot{e}_o = \dot{e} + k_o \dot{e} = \dot{x}_x - \dot{x} - \epsilon + k_o e \]  

(16)

Further

\[ \dot{x} = \ddot{x}_x + k_o e_o + \rho_2 \text{sgn}(e_o) \]  

(17)

where \( \rho_2 > 0, k_o \) is a positive constant.

Then, the integrated control law combined equation (13) with equation (17). The outer-loop SMC structure is shown in Figure 2, and its stability analysis is followed in the next subsection.
Stability analysis

Further, we propose the Lyapunov-like positive definite function $V$ as equation (18)

$$V = \frac{1}{2} e_s^T \dot{M} e_s + \frac{1}{2} e_o^T \dot{e}_o \tag{18}$$

With the properties$^2$$^3$ of $e_s^T \left( \dot{M} - \dot{\bar{C}} \right) e_s = 0$, assume N.2 $\rho_1 > \left| d(\xi, \tilde{\xi}) \right|$. Let us take the derivative of $V$ as following

$$\dot{V} = e_s^T \dot{M} \dot{e}_s + \frac{1}{2} e_s^T \dot{\dot{M}} e_s + \frac{1}{2} e_o^T \dot{\dot{e}}_o + \frac{1}{2} e_o^T \dot{\dot{e}}_o$$

$$= -e_s^T (\dot{C} e_s + \mu e_s + \rho_1 \text{sat}(e_s) - d(\xi, \tilde{\xi})) + e_o^T \dot{C} e_o + e_o^T \dot{e}_o \tag{19}$$

Applying equation (16) to equation (17) yields

$$\dot{\dot{e}}_o = -\rho_1 \text{sgn} e_o - \dot{e} \tag{20}$$

Using equations (14) and (20), equation (19) can be rewritten as

$$\dot{V} = -\mu \|e_s\| - (\rho_1 \| e_s \| - e_s^T d(\xi, \tilde{\xi})) - \rho_2 \| e_o \| + e_o^T \dot{e}_o$$

$$\leq -\mu \| e_s \| - (\rho_2 \| e_o \|) \tag{21}$$

If and only if $e = 0$, $\dot{V} = 0$. To satisfy equation (21), $\rho_2$ needs enough large for $\rho_2 \geq \| e_s \|, e_o^T \dot{e}_o \leq 0$, then $\dot{V} < 0$. It is worth noticing that $\dot{e}$ is bounded at every time. Thus, the proposed controller is designed in the condition $\rho_2 \geq \| e_s \|$, and the tracking error asymptotically converges to zero as $t \rightarrow \infty$.

Fuzzy multitask priority motion planning method

Given EE position/orientation, coordinated motion planning for joints and AUV body is required; secondly, this step is to execute the path planned through the control law reflecting in the joints and EE pose. Then, there exists an error between the desired and the actual pose, in which the designed controller eliminates. It is considered that the closed-loop form not only needs to combine dynamics and kinematics models but also designs a motion planning algorithm for multiple tasks.

When the EE position and orientation is desired, the motion of each joint and the AUV body will be planned in the general form

$$\xi = J^T \dot{x}_E \tag{22}$$

where $J^T = J^T (J J^T)^{-1}$ is the pseudoinverse of $J$. $\xi$ is calculated by IK.

Combined dynamics and kinematics task priority motion planning method

The general form of the TP solution of equation (22) is as follows$^13$

$$\xi = J^T \dot{x}_E + (I_N - J^T J) \zeta_x \tag{23}$$

where $I_N \in \mathbb{R}^{(6+n) \times (6+n)}$ is the identity matrix, and $\zeta_x$ represents an arbitrary vector.

The $\zeta_x$ can be mapped to the secondary tasks, which is related to gradient of the target optimization function$^6$

$$\zeta_x = \sum_{i=1}^s k_i \Delta H_i(q) \tag{24}$$

where $s$ is the total number of secondary tasks and $H_i(q)$ is the objective function to be optimized with the scalar gain factor $k_i$. If $k_i > 0$, the motion will change in the direction of gradient $\nabla H_i(q)$; otherwise, it will vary in the direction of $\nabla H_i(q)$ decreasing.

Combining equations (23) and (24), we obtain

$$\xi = J^T \dot{x}_E + (I_N - J^T J) \sum_{i=1}^s k_i \Delta H_i(q) \tag{25}$$

It can be seen from equation (25) that $\xi$ includes two items, namely pseudoinverse and null-space solutions. Defining the $J^T \dot{x}_E$ by the pseudoinverse method is the prioritized task. The null space solution $k_i (I_N - J^T J) \Delta H_i(q)$ is the secondary task to complete the UVMS self-motion and optimize the movement of each joint.

The prioritized task of UVMS is $\eta_p \in \mathbb{R}^m$, where $m$ is the dimension of this task, and the corresponding Jacobian matrix is $J_p(q) \in \mathbb{R}^{m \times N}$, then the relation between $\dot{n}_p$ and arbitrary vector of priority task $\zeta_{ap}$ can be expressed as

$$\dot{n}_p = J_p(q) \zeta_{ap} \tag{26}$$
Setting the EE position/orientation as the prioritized task when facing the UVMS motion planning problem. So, in this article, it meets the following condition: \( \eta_p = x_E \).

Similarly, the secondary tasks \( \eta_s \in \mathbb{R}^r \), where \( r \) is the dimension of the tasks, and the corresponding Jacobian matrix is \( J_s(q) \in \mathbb{R}^{r \times N} \), then the equation of time derivate and arbitrary vector of secondary task \( \zeta_{as} \) can be expressed in equation (27)

\[
\dot{\eta}_s = J_s(q)\zeta_{as}
\]

(27)

The motion planning algorithm, including secondary objectives, based on TP can be obtained by equations (25) to (27)

\[
x = J^+ (\eta_p + (I_N - J^+J) \sum_{i=1}^{k} J^+_{si}(q)\eta_{si})
\]

(28)

where \( \eta_{si}(i = 1, 2, ..., k) \) is the \( i \)'th secondary task and \( J_{si}(q)(i = 1, 2, ..., k) \) is the Jacobian matrix of the corresponding secondary tasks.

It can be seen from equation (28) that the prioritized and secondary tasks do not conflict, the secondary task requirements can be met simultaneously in the space of the prioritized task. However, when the two tasks conflict, it is necessary to ensure that the prioritized task is completed. When the position is obtained by integrating the velocity, it may cause a numerical drift problem. So, according to the dynamics–kinematics controller and equation (28), the closed-loop form is introduced

\[
\xi = J^+ (\dot{\eta}_p + K_p e) + (I_N - J^+J) \sum_{i=1}^{k} \alpha_i J^+_{si}(q, \dot{q})(\dot{\eta}_{si} + K_{si} e_{si})
\]

(29)

where \( e \) is the error between the EE position and orientation desired and the actual value, \( e_i \) is the error between the desired and achieved values of the secondary tasks, \( K_p \) and \( K_{si} \) are the corresponding gain matrix, respectively.

Based on equation (29), algorithm error of secondary tasks is zero when \( J^+ \) and \( J^+_{si} \) meet the orthogonality. It effectively ensures the accuracy of highest priority tasks and can control the errors of secondary priority tasks. As a result, TP avoids algorithm singularity through null space.17 Sadly, they cannot satisfy this strict condition in real time.30 In this article, adopting the weight form of equation (22) to achieve that each secondary task’s errors are zero. And \( K_{si} e_{si} \) in equation (29) as a compensator under the external disturbance is uncertain.

Summly, the weighted TP with compensator, as shown in Figure 3 can be obtained,

\[
\xi = J^+_{w}(q, \dot{q})(\dot{\eta}_p + K_p e) + (I_N - J^+_{w}J) \sum_{i=1}^{k} \alpha_i J^+_{wi}(q, \dot{q})(\dot{\eta}_{si} + K_{si} e_{si})
\]

(30)

where \( J^+_{w} \) is the weighted pseudoinverse of the Jacobian matrix,7 and \( \alpha_i \in [0, 1] \) is the priority scale factor of the secondary task \( i \). As an open field, \( \alpha_i \) will be realized by networked fuzzy logic in “Networked fuzzy logic for secondary tasks gains” section.

Joint limit constraint and coordinated motion of underwater vehicle-manipulator systems

It is hoped that the AUV-body move with a minor pitch and the joints cannot exceed its mechanical limit. For example, the \( q_2 \) should motion within \([-230^\circ, 230^\circ]\). The weight matrix in equation (26) not only meet the orthogonality of \( J^+ \) and \( J^+_{si} \) but also can be used to avoid the joint limit in this article.
Specifically, a diagonal matrix $W_J \in \mathbb{R}^{N \times N}$ is used, when the joint $i$ is in the middle of the allowable range, $W_{J(i,i)} = 1$. When the joint $i$ approaches its limit, $W_{J(i,i)} = \infty$, this DOF motion is constrained. $H_J(q)$ represents the function of joint limit to be optimized. Then, the partial derivative of joint $i$ is defined as $\partial H_J(q)/\partial q_i$.

There are certain problems in restricting joint constraints only by the size of the defined $W_{J(i,i)}$. When the median is infinitely close to the bounds or the bounds return to the median with the equal assignment, the same constraint is applied to the return motion, which does not match expectations.

Introduce the norm $||\partial H_J(q)/\partial q_i||$ and its trend $\Delta||\partial H_J(q)/\partial q_i||$:

1. When in the situation of $\Delta||\partial H_J(q)/\partial q_i|| \geq 0$, in other words, joint $i$ is approaching its limit, $W_{J(i,i)} = 1 + ||\partial H_J(q)/\partial q_i||$.
2. Only in the situation of $\Delta||\partial H_J(q)/\partial q_i|| < 0$, we consider that the joint $i$ is away from bounds, $W_{J(i,i)} = 1$.

This article mainly studies the motion planning of UVMS combining kinematics and dynamics. There is still a key point in this topic to realize the coordinated motion of the AUV and manipulator. This question is of great significance to the total system. Under the TP framework in the task space, the EE posture is the prioritized task.

In equation (26), weighted matrix $W$ can also be used to achieve this task. In this article, the AUV-body and manipulator’s coordinated motion is taken as one of the secondary tasks, so that this item meets the unified form in equation (29), and is set as the inverse form of the weighted matrix to realize the coordinated motion control of UVMS. Setting $\beta \in [0, 1]$ to measure the motion distribution of AUV body and manipulator, $\beta = 0$ corresponds to the sole AUV-body motion, while $\beta = 1$ corresponds to the sole manipulator motion

$$W_C^{-1} = \begin{bmatrix} (1-\beta)I_6 & 0_{6 \times N} \\ 0_{N \times 6} & \beta I_n \end{bmatrix}$$

The weighted matrix in equation (30) can be written as the product of the weighted matrix with joint constraints and coordinated motion

$$W = W_J W_C$$

The following discusses the characteristics of the $W$:

1. Exchangeability
   Both $W_J$ and $W_C$ are diagonal matrices, then $W = W_J W_C = W_C W_J$, $W^{-1} = (W_J W_C)^{-1} = W_C^{-1} W_J^{-1}$.
2. Free of singularity
   The singularity of $W$ depends on the singularity of $W_C$ and $W_J$. From the abovementioned, $|W_J| \geq 1$, $W_C$ exists inverse matrix, then $|W| \neq 0$, $W^{-1}$ exist, so $W$ is free of singularity.

Networked fuzzy logic for secondary tasks gains

“Combined dynamics and kinematics task priority motion planning method” and “Joint limit constraint and coordinated motion of underwater vehicle-manipulator systems” sections construct the UVMS multitask motion planning algorithm of equation (30). It can ensure EE’s control accuracy, simultaneously complete secondary tasks (avoiding joint limit, coordinated motion of AUV body and manipulator, etc.) in its null space. Sadly, it cannot effectively determine the weight of each secondary task. Fuzzy logic and neural networks are usually used to solve this problem. Fuzzy logic, as a higher-level supervisor, considers here. Simultaneously, based on fuzzy logic, the logic is networked that how secondary tasks are allocated.

It is vital to avoid the joint limit when task execution, the distance to the joint limit is taken as the first secondary task

$$\dot{\eta}_{s1} = \begin{bmatrix} \dot{q}_2 \\ \dot{q}_3 \\ J_{s1} \end{bmatrix}$$

Holding the position and posture stability of the AUV body during underwater operations is important for UVMS coordinated control. Considering that the AUV pitch maps a significant effect for UVMS, it is taken as second secondary task in this article

$$\dot{\eta}_{s2} = \dot{\theta} \begin{bmatrix} 0 \quad 0 \quad 0 \quad 0 \quad 1 \quad 0 \quad 0 \end{bmatrix}^T$$

Here, $\dot{\theta}$ is the time derivate of pitch $\theta$. Define that the range of the AUV pitch is $[-20^\circ, 20^\circ]$, the range of motion for $q_2$ and $q_3$ are $[-142^\circ, 142^\circ]$ and $[-230^\circ, 230^\circ]$, respectively.
The abovementioned secondary tasks can be activated by fuzzifier with the three inputs \((q_2, q_3, \dot{q})\). In this article, normalized inputs, respectively, are considered within the range of \([0,1]\). Two rules are considered: Joint limits (JL) \(= \{\text{close, not close}\}\) and vehicle attitude (VA) \(= \{\text{small, not small}\}\).

Then, a networked fuzzy inference engine is constructed, based on the traditional fuzzy logic\(^2\), a hidden layer neural network is introduced into the fuzzy inference engine layer as shown in Figure 4. Through the neural layer, weights are shared to obtain more effective outputs. The neural layer is as the following

\[
B_i = \sum_{i=1}^{2} \sum_{j=1}^{3} \mu_i' A_j
\]  

where \(B_i\) corresponds to the \(i\)’th output imported into de-fuzzifier. \(A_j\) represents the contribution of the \(j\)’th input to the \(i\)’th output, and \(\mu_i' \in [0, 1]\) is the corresponding weight. Further, the inputs normalized with the corresponding fuzzy rules, as the network’s input, satisfy \(A'_1 = A'_2\). The output \(B_i\) of the network further generates \(\alpha_i\) through the de-fuzzifier.

Networked fuzzy logic has the following advantages: (a) Compared with the simplified input-output relationship in Table 3, in this networked fuzzy logic, the output characteristics under each input’s combined action can be obtained, which compensate for the incompleteness of the former. (b) A more detailed fuzzy set can also solve the incompleteness mentioned in (a). It needs to subdivide the input and output rules, often reach more than 32.\(^2\) Unlike this idea, networked fuzzy logic can guarantee the reconfigurability of fuzzy relationships by adjusting the weights, replacing artificial excessive constraints, and still achieving good flexibility and realizability.

**Simulation Conditions**

To verify the proposed method’s performance, simulations were achieved on an AUV, as given in Tables 1 and 2, with a 3-DOF manipulator\(^1\) shown in Figure 1. The initial pose
of EE is $[-0.90\ m, 0.70\ m, 0\ m, 139^\circ, 0^\circ, 90^\circ]$. It is worth noticing that this desired trajectory is part of a circle from $[-0.90\ m, 0.70\ m, 0\ m] \rightarrow [-2.11\ m, 1.10\ m, 1.35\ m]$. The radius of this circle is 1.80 m. The center of the circle is located in $[-2.60\ m, 1.20\ m, -0.36\ m]$. Based on this trajectory, the desired velocity of EE is adopted by the cubic spline. The simulation time is 30 s.

It is assumed that the model uncertainty for dynamic parameter is 10%, $\Delta M = 0.1M$, $\Delta C = 0.1C$, and $\Delta D = 0.1D$. The external disturbance in $q_1$ is $10\text{g} \sin (2\pi t/5)\text{N} \cdot \text{m}$. The weights $\mu_i^j (i=1,2; j=1,2,3)$ in networked fuzzy logic are both 0.5 in the initial time. The parameter values in the weighted matrix $W_C$ are $\beta = 0.7$. The gains in the proposed controller are $k_x = k_y = 1$. The coordinated motion weighed matrix is defined as

$$W_C^{-1} = \begin{bmatrix} 0.21I_{6 \times 6} & \theta_{6 \times 3} \\ \theta_{3 \times 3} & 0.7I_{3 \times 3} \end{bmatrix}$$

(37)

Meanwhile, define the prioritized task is $x_E = [p_d, r_d]^T$, the secondary tasks are expressed as $\eta_i = [\eta_{i1}^T, \eta_{i2}^T]^T$.

The proposed motion plan method is compared with the pseudoinverse method, which is given in equation (22). Besides, combining equation (31), the weighted pseudoinverse method is also used as a comparison. For simple representation, the proposed outer loop controller is termed case 1 (c1). The classic sliding mode controller is termed case 2 (c2). Hence, the proposed motion planning method based on the proposed dynamic controller is termed proposed pathc1. The proposed motion planning method based on the classic SMC is termed proposed pathc2. The pseudoinverse method and weighted pseudoinverse method based on the proposed dynamic controller are termed Pse pathc1 and W-pse pathc1, respectively.

**Simulation results**

The results are shown in Figures 5 to 11. It is assumed that the Pse pathc1 and W-pse pathc1 are free of singularity in this simulation condition.

Figure 5 shows the circular trajectory desired and simulated. Given the desired EE trajectory as a circle with a radius of 1.80 m, the proposed pathc2 failed to reach the endpoint at 30 s and the error up to 0.14 m. The proposed pathc1 can track the desired trajectory well in the first 15 s, while the Pse pathc1 and W-pse pathc1 have better performance at this time. Figure 5 also shows the posture of the UVMS at 0, 15, and 30 s. Pse pathc1 and W-pse pathc1 have a larger pitch of AUV, as shown in Figure 5(a) and (b), the pitch at $t = 15$ s is 63.9° and 56.3°, respectively. The pitch at $t = 30$ s is 45.9 and 38.8, respectively. The angle in the roll and yaw directions under those two algorithms is very small, and the AUV still has the instability of pitch. In contrast, the proposed pathc1 and proposed pathc2 are largely in the yaw direction, and no more than 30°. As shown in Figure 5(c) and (d), the UVMS has attitude stability in the proposed pathc1 and proposed pathc2.

Figure 6 shows the error of EE in $x, y, z$ and $q_1, q_2, q_3$ between the desired and actual. As shown in Figure 6(a) to (c), Pse pathc1 and W-pse pathc1 achieve the position errors in $x, y, z$ within 0.05 m. It embodies the excellent control effect of the outer loop SMC. The maximum error of the proposed pathc2 appears in the $y$ direction at 27 s, reaching 0.12 m. Similarly, the tracking error of the proposed pathc1 is larger than Pse pathc1 and W-pse pathc1. Through the
outer loop, this approach finally reduces the position error within 0.04 m at \( t > 25 \) s. It satisfies the operating of the UVMS. It is worth noticing that the proposed outer loop SMC improves the tracking accuracy of the EE by 18.5%.

What needs to be reviewed in this article is that the proposed plan c1 and proposed plan c2, under the frame of the TP, consider the stability of the AUV attitude as second secondary task. Figure 7 shows the velocity of AUV when tracking the circle trajectory. The velocity of the proposed
plan$_{c1}$ and proposed plan$_{c2}$ in the $q$, $r$ directions is much lower than that of the others, as shown in Figure 7(e) to (f). It ensures the smaller angular displacement of AUV the maximum value does not exceed $30^\circ$, as shown in Figure 10(c). However, the redundancy is not exploited in the pse plan$_{c1}$. For example, when $t = 5$ s, the $v$ of AUV is planned to be 0.15 m/s and the angular velocity $q$ is planned to be 0.16 rad/s, as shown in Figure 7(e), and the desired velocity of $q_1$ is 0.17 rad/s, as shown in Figure 11(a), which leads to the angular displacement of AUV in the $y$ direction up to $28.5^\circ$.

Based on pse plan$_{c1}$, a coordinated motion distribution $W_c^{-1}$ is added to ensure the motion stability of the AUV in W-pse plan$_{c1}$. Sadly, the AUV angular velocity under this approach still reaches 0.16 rad/s, which still affect the stability of AUV. It is only as a local optimization of pseudo-inverse method. As shown in Figures 10(a) to (c) and 11(a), under the proposed plan$_{c1}$ and proposed plan$_{c2}$, a large displacement is used in $q_1$ and $x,y$ direction of AUV. It reduces the angular velocity of the AUV to ensure its stability. Taking the pitch as a secondary task, the posture

**Figure 8.** The attitude of end-effector when tracking the circular trajectory.

**Figure 9.** The position of the underwater vehicle when tracking the circular trajectory. (a) The trajectory in $x$ direction; (b) the trajectory in $y$ direction; and (c) the trajectory in $z$ direction.
stability of the AUV in this direction is ensured. Figure 8 shows the posture of EE. The pose of EE at the initial time is \([139^\circ, 0^\circ, 90^\circ]\). Pse plan c1 and W-pse plan c1 have a smaller angular displacement in the \(\theta_e, \psi_e\) direction. On the contrary, the proposed plan c1 and proposed plan c2 have a larger angular displacement in those directions, reaching \(31.5^\circ\), as shown in Figure 8(c). This also further illustrates the effectiveness of the proposed motion planning algorithm in ensuring the stability of AUV. Considering the weight gains of secondary tasks, the idea of networked fuzzy logic is adopted in the proposed plan c1. It further optimizes the coordinated motion of UVMS. The results show that the proposed plan c1 uses real-time inputs \(\dot{\eta}_1\) to adjust secondary task weights \(\alpha_i (i = 1, 2)\), continuously, achieves a smaller control error, and in the case of joint disturbances, it also ensures better stability in direction of pitch and yaw.

Figure 11 demonstrates the desired joint velocity when tracking the circular trajectory. The proposed plan c1 and proposed plan c2 are similar that \(\dot{q}_1\) is relatively large, which can reach \(-4.2\) rad/s. What needs to be reviewed is that the angle range of the revolute joint \(q_1\) is \([-360^\circ\) to \(360^\circ]\). Therefore, the larger \(\dot{q}_1\) does not need to consider the limitation of \(q_1\). However, the redundancy of joints is not fully considered under the pseudoinverse and the weighted approach, \(\dot{q}_1\) is relatively small, as shown in Figure 11(a).

Besides, the conditions for \(q_2\) and \(q_3\) are all satisfied. Among them, \(q_2\) reaches the maximum of \(68.8^\circ\) at \(t = 30\) s under the Pse plan c1, as shown in Figure 5(b). \(q_3\) reaches \(62.0^\circ\) and \(57.3^\circ\) under Pse plan c1 and W-pse plan c1, respectively. As one of the secondary tasks, avoiding joint limit is easily achieved in the proposed plan c1. Furthermore, errors caused by external disturbance (current) must be considered. Given the desired joint velocity \(\dot{q}_1, \dot{q}_2, \dot{q}_3\), the outer loop SMC in the proposed plan c1 has reduced those errors of \(1.8\%\), \(35.0\%\), and \(-2.3\%\), respectively, compared with the traditional SMC in the proposed plan c2. Furthermore, the errors at \(x_e, y_e, z_e\) are further reduced by \(-22.48\%\), \(-1.48\%\), and \(39.64\%\), respectively. Therefore, the proposed outer loop SMC has a positive effect on reducing errors introduced by external disturbance.

Figure 12 maps the energy consumption \(\int ||\tau||dt\) when tracking the circular trajectory. Among them, the proposed plan c2 has the largest energy consumption while the proposed plan c1 is the smallest. At \(3\) s \(< t < 15\) s, under the Pse plan c1 and W-pse plan c1, the EE’s tracking accuracy is enhanced, as shown in Figure 5, the \(||\tau||\) during this time is relatively high. It always keeps a high tracking accuracy at \(t > 15\) s, and \(||\tau||\) is reduced. At \(15\) s \(< t < 25\) s, under the proposed plan c1, the error of EE position is continuously reduced from \(0.12\) m. Its energy consumption \(||\tau||\) is relatively large. It is worth
noticing that the proposed plan$^2$ failed to reach the endpoint. In summary, the proposed plan$^1$, the EE error within 0.1 m, has engineering applicability.

**Conclusions**

In this article, a combined dynamics and kinematics networked fuzzy TP motion planning method is proposed. The underwater vehicle’s posture stability and joint limits are mapped into the null space of EE’s trajectory in this proposed coordinated motion plan approach. An outer loop sliding mode controller is used for the EE’s trajectory tracking precisely. Simulation results show that the proposed plan$^1$ achieves better coordinated motion planning of UVMS. It ensures the smaller angular displacement of AUV, not to exceed 30°. The redundancy of joints is taken

**Figure 11.** The joint velocity desired when tracking the circular trajectory. (a) The velocity desired in joint $q_1$; (b) the velocity desired in joint $q_2$; and (c) the velocity desired in joint $q_3$.

**Figure 12.** The energy consumption $\int ||r|| \, dt$ of UVMS when tracking the circular trajectory. UVMS: underwater vehicle manipulator systems.
fully considered in which a large displacement is used in $q_1$ and $x,y$ direction of AUV. However, the pse plan$_{c1}$ and W-pse plan$_{c1}$ are free of coordinated motion planning. Its pitch reaches $63.9^\circ$ and $56.3^\circ$, respectively, which still affects the stability of AUV. Facing the external disturbance, the proposed plan$_{c1}$ has reduced desired joint velocity’s errors of $1.8\%$, $35.0\%$, and $-2.3\%$, respectively, compared with the traditional SMC in proposed plan$_{c2}$. Furthermore, the errors at $z_2$ are reduced by $39.64\%$, respectively. The proposed plan$_{c2}$ failed to reach the endpoint, while the proposed plan$_{c1}$ has the smallest energy consumption. Even though the coordinated motion plan framework’s effectiveness was validated through simulations, experiments should be carried out to further enhance the simulation results, which will be done in the future.

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**References**

1. Sivčev S, Coleman J, Omerdić E, et al. Underwater manipulators: a review. *Ocean Eng* 2018; 163: 431–450.
2. Antonelli G. Underwater Robots: motion and force control of vehicle-manipulator systems. 4th ed. Berlin/Heidelberg: Springer, 2017, pp. 202–217.
3. Huang H, Tang Q, Li J, et al. A review on underwater autonomous environmental perception and target grasp, the challenge of robotic organism capture. *Ocean Eng* 2019; 195: 106644.
4. Tarn TJ, Shoults GA, and Yang SP. A dynamic model of an underwater vehicle with a robotic manipulator using Kane’s method. *Auton Robot* 1996; 3: 269–283.
5. Tarn TJ and Yang SP. Modeling and control for underwater robotic manipulators - an example. *IEEE Int J Robot Autom* 1997; 7: 2166–2171.
6. Soylu S. Redundancy resolution for underwater mobile manipulators. *Ocean Eng* 2010; 37(2–3): 325–343.
7. Park J, Choi Y, Wan Kyun C, and Youm Y. Multiple tasks kinematics using weighted pseudo-inverse for kinematically redundant manipulators. *IEEE Int C Robot and Autom* 2001; 4: 4041–4047.
8. Mohan S and Kim J. Indirect adaptive control of an autonomous underwater vehicle-manipulator system for underwater manipulation tasks. *Ocean Eng* 2012; 54: 233–243.
9. Sallooom T, Yu X, He W, et al. Adaptive neural network control of underwater robotic manipulators tuned by a genetic algorithm. *J Intell and Robot Syst* 2020; 97: 657–672.
10. Han H, Wei Y, Ye X, et al. Motion planning and coordinated control of underwater vehicle-manipulator systems with inertial delay control and fuzzy compensator. *Appl Sci* 2020; 10: 3944.
11. Santos CH. Redundancy resolution for underwater vehicle-manipulator systems using a fuzzy expert system. *IEEE Int C Control Appl* 2006: 2848–2853.
12. Youakim D, Cieslak P, Dornbush A, et al. Multi-representation, multiheuristic A* search-based motion planning for a free-floating underwater vehicle-manipulator system in unknown environment. *J Field Robot* 2020; 37: 925–950.
13. Kim J. Dynamic task priority approach to avoid kinematic singularity for autonomous manipulation. *IEEE/RSJ Int C Intell Robot Syst* 2002: 1942–1947.
14. Ahmadi SM and Fateh MM. Robust control of electrically driven robots using adaptive uncertainty estimation. *Comput Electr Eng* 2016; 56: 674–687.
15. Jonghui H, Jonghoon P, and Kyun CW. Robust coordinated motion control of an underwater vehicle-manipulator system with minimizing restoring moments. *Ocean Eng* 2011; 38: 1197–1206.
16. Zhang Q and Zhang A. Research on coordinated motion of an autonomous underwater vehicle-manipulator system. *Ocean Eng* 2006; 24: 79–84.
17. Antonelli G. Stability analysis for prioritized closed-loop inverse kinematic algorithms for redundant robotic systems. *IEEE Trans Robot* 2009; 25: 985–994.
18. Yumurtaci M and Verm Z. Liquid level control with different control methods based on Matlab/Simulink and Arduino for the control systems lesson. *Int Adv Res Eng J* 2020; 4(3): 249–254.
19. Han H, Wei Y, Ye X, et al. Modeling and fuzzy decoupling control of an underwater vehicle-manipulator system. *IEEE Access* 2020; 8: 18962–18983.
20. Antonelli G and Chiaverini S. A fuzzy approach to redundancy resolution for underwater vehicle-manipulator systems. *Control Eng Pract* 2003; 11: 445–452.
21. Fossen TI. *Handbook of marine craft hydrodynamics and motion control*. Berlin: Springer, 2011.
22. Yang C, Yao F, Zhang M, et al. Adaptive sliding mode PID control for underwater manipulator based on Legendre polynomial function approximation and its experimental evaluation. *Appl Sci* 2020; 10: 1728.
23. Kim D, Choi HS, Kim J Y, et al. Trajectory generation and sliding-mode controller design of an underwater vehicle-manipulator system with redundancy. *Int J Precis Eng Man* 2015; 16: 1561–1570.
24. Tran MD and Kang HJ. Adaptive terminal sliding mode control of uncertain robotic manipulators based on local...
approximation of a dynamic system. *Neurocomputing* 2017; 228: 231–240.

25. Simetti E, Casalino G, Torelli S, et al. Floating underwater manipulation: developed control methodology and experimental validation within the TRIDENT project. *J Field Robot* 2014; 31(3): 364–385.

26. Han H, Wei Y, Guan L, et al. Trajectory tracking control of underwater vehicle-manipulator systems using uncertainty and disturbance estimator. In: *OCEANS MTS/IEEE*, Charleston, SC, USA, 22–25 October 2018.

27. Ahmadi SM and Fateh MM. On the Taylor series asymptotic tracking control of robots. *Robotica* 2019, 37(3): 405–427.

28. Nenchev D, Umetani Y, and Yoshida K. Analysis of a redundant free-flying spacecraft/manipulator system. *IEEE T Robot Autom* 1992; 8: 1–6.

29. Borlaug ILG, Pettersen KY, and Gravdahl JT. Combined kinematic and dynamic control of vehicle-manipulator systems. *Mechatronics* 2020; 69: 102380.

30. Simetti E and Casalino G. A novel practical technique to integrate inequality control objectives and task transitions in priority based control. *J Intell Robot Syst* 2016; 84: 877–902.

31. Nenchev D, Umetani Y, and Yoshida K. Analysis of a redundant free-flying spacecraft/manipulator system. *IEEE T Robot Autom* 1992; 8: 1–6.