A Time Delay Controller included terminal sliding mode and fuzzy gain tuning for Underwater Vehicle-Manipulator Systems

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ABSTRACT

An improved Time Delay Control (TDC) method for an Underwater Vehicle-Manipulator System (UVMS) is proposed. The proposed controller consists of three terms: a time-delay-estimation term that cancels nonlinearities of the UVMS dynamics, a Terminal Sliding Mode (TSM) term that provides a fast response and a PID term that reduces the tracking error. In addition the proposed controller uses fuzzy rules to adaptively tune the gains of TDC and PID terms. A full dynamic of UVMS is presented and some simulation studies are done. Simulation results demonstrate the effectiveness of proposed method. The proposed controller not only provides the high performance in trajectory tracking, but it also has an acceptable robustness in presence of the external disturbance and unknown forces/torques in comparison with conventional sliding mode controller.

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1. Introduction

Recently underwater manipulation has been developed because of needs in marine industries. Underwater Vehicle-Manipulator Systems (UVMS) are used in oceanic environments for tasks such as welding, nondestructive test of the marine structures or underwater oil/gas pipes and ocean exploration. The UVMS consists of a mobile platform such as Autonomous Underwater Vehicle (AUV) and one or more manipulators. In the presence of hydrodynamic disturbances and the dynamic coupling between manipulator and AUV, the trajectory control of the UVMS is complicated. The hydrodynamic effects on the underwater manipulators have been studied recently through approximated generalized torques and an indirect adaptive control method (Jun et al., 2011; Mohan and Kim, 2012), but they do not guarantee the robustness for systems like UVMS with high uncertainties.

In the oceanic conditions, the real hydrodynamic disturbances acting on the UVMS are difficult to measure or estimate accurately. Therefore, robust, precise and fast convergence control scheme should be developed for the appropriate operation of UVMS. Sarkar and Podder (2001) proposed a method to generate the desired trajectory for reducing drag force acting on the whole system. An adaptive tracking control based on the virtual decomposition has also been proposed (Antonelli et al., 2004). Sun and Cheah (2004) designed an adaptive set point controller based on Lyapunov’s direct method and Lasalle’s invariance principle. Some researchers have proposed methods based on estimation of the dynamics models of the UVMS (Canudas et al., 2000; Antonelli, 2003).

Some researches about control of UVMS focused on fuzzy controllers. For avoiding the problems of gain tuning, Xu et al. (2006) designed a sliding mode fuzzy controller, in which inputs of the fuzzy controller are error and derivative of error, respectively. Furthermore, a PD sliding surface is used. Piltan et al. (2011a) showed that a PID sliding surface has a better performance in comparison with PD sliding surface. Amer et al. (2012) designed an adaptive fuzzy sliding mode controller which was consisting of three main parts: the equivalent control of SMC as a model-based control term; a new estimation technique to estimate the perturbation from the dynamics of the sliding surface; and a two-supervisory fuzzy self-tuning controller. A mathematical tunable gain model free PID-like sliding mode fuzzy controller (GTMFC) is designed by Piltan et al. (2011b) to achieve the best performance. A simplified fuzzy logic controller for an underwater vehicle is proposed by Ishaque et al. (2011). They showed that Mamdani and Sugeno type fuzzy logic controller give identical response to the same input sets. However their method is not robust in presence of ocean disturbances.

Esfahani et al. (2014) studied the sliding mode PID fuzzy controller for underwater manipulators without considering time delay terms. Also, Fuzzy Logic as an incorporated section of main controller is used in control of some underwater robotics manipulators (Sebastian and Vázquez, 2006; Sebastian and Sotelo, 2007; Song and Smith, 2006). However, being sensitive to disturbances
Multiple Impedance Control (MIC) is proposed for dual arm UVMS in Farivarnejad and Moosavian (2014). This controller is an effective controller, especially when the end-effector interacts with the environment but has not proper robustness in the presence of hydrodynamic disturbances. An optimized robust controller was proposed in Thangavel et al. (2010) based on bond graph method. Several researchers have studied Time Delay Control (TDC) for different applications (Park and Kim, 2011; Cho et al., 2005; Lim et al., 2010; Xu and Yang, 2011; Han et al., 2011). But this method is not applied on UVMS. Although lots of works are done in this area, still there is not complete model of UVMS considering full dynamic terms and proper controller for it. Generally, none of previous works consider full dynamic of UVMS, Time Delay Controller and terminal sliding mode.

In this study, an improved robust TDC is designed. It proposes a new method for control of UVMS through adding two concepts, a PID-Sliding Mode Controller (SMC) and a fuzzy controller for gain tuning of SMC. The aim is to reduce tracking error and increase the speed of converging to the desired path in comparison with the conventional TDC. This paper is outlined as follows. In Section 2, general form of UVMS is modeled considering full dynamic terms. The conventional TDC is presented in Section 3. An improved robust and accurate TDC is proposed in Section 4. The computer simulation results are shown in Section 5 and finally, the conclusion is presented in Section 6.

2. Dynamics of Underwater Vehicle-Manipulator System

UVMS is an underwater vehicle with a robotic manipulator mounted on it. Fig. 1 illustrates a two-Degrees Of Freedom (2 DOF) manipulator mounted on an underwater vehicle. The coupled effect between the manipulator and the vehicle should be considered in the modeling.

The motions of underwater vehicle consist of three linear and three revolute motions. Three linear motions are along the x, y and z axes that are named surge, sway and heave respectively. Additionally, three revolute motions are about x, y and z axes that are named roll, pitch and yaw, respectively. The Denaviat-Hartenburg parameters for UVMS with considering only revolute motions are shown in Table 1. Fig. 2 illustrates a 7 DOF Underwater Vehicle-Manipulator System.

2.1. Energy of UVMS

Added mass of an Underwater Vehicle-Manipulator System is included in the system dynamics in the form of kinetic energy. Neglecting the kinetic energy of the manipulator due to added mass, total kinetic energy of the UVMS is written as Eq. (1)

\[
T = T_{RB} + T_A
\]

Kinetic energy of the UVMS due to rigid body is expressed as Eq. (2)

\[
T_{RB} = \frac{1}{2}m_0x_0^2 + \frac{1}{2}m_1x_1^2 + \frac{1}{2}m_2x_2^2 + \frac{1}{2}l_1^2q_1^2 + \frac{1}{2}l_2^2q_2^2 + \frac{1}{2}l_3^2q_3^2 + \frac{1}{2}l_4^2q_4^2 + \frac{1}{2}l_5^2q_5^2 + \frac{1}{2}l_6^2q_6^2
\]

where \( \rho \) is the water density and \( l_c \) is the radius of spherical vehicle. Kinetic energy of the spherical vehicle due to added mass is

\[
T_A = \frac{1}{2}r^2[M_{sh}

2.2. Lagrange formulation

Consider the UVMS as an 8 DOF dynamic system. The Lagrange equation of motion in the matrix form is (Korayem et al., 2010)

\[
\frac{d}{dt} \left( \frac{\partial T}{\partial \dot{q}} \right) - \frac{\partial T}{\partial q} = Q = [F_1, F_2, F_3, \tau_x, \tau_y, \tau_z, \tau_\theta]^T
\]

where \( T \) is the total kinematic energy of the system which is obtained from Eq. (1) and \( Q \) is the vector of generalized forces and torques applied to the UVMS. Also, \( q \) is vector of generalized positions and \( \dot{q} \) is the vector of generalized velocities. The vector of

<table>
<thead>
<tr>
<th>Joint</th>
<th>( \alpha )</th>
<th>( \alpha )</th>
<th>( \alpha )</th>
<th>( d )</th>
<th>( \theta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>-90</td>
<td>-90</td>
<td>0</td>
<td>( q_1 )</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>+90</td>
<td>-90</td>
<td>0</td>
<td>( q_2 )</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>( l_c )</td>
<td>( q_3 )</td>
</tr>
<tr>
<td>4</td>
<td>( d )</td>
<td>+90</td>
<td>0</td>
<td>0</td>
<td>( q_4 )</td>
</tr>
<tr>
<td>5</td>
<td>( l_i )</td>
<td>-90</td>
<td>-90</td>
<td>0</td>
<td>( q_5 )</td>
</tr>
</tbody>
</table>

Fig. 1. Underwater Vehicle-Manipulator System (UVMS).

Fig. 2. UVMS with only revolute motions.
generalized positions is shown as Eq. (7)

\[ q = [x_v, y_v, z_v, q_1, q_3, q_2]^T \]  

(7)

Substituting the above expression in Eq. (6), the dynamic equations of motion which includes rigid body and added mass is obtained as follows:

\[ Q = M(q)\ddot{q} + C(q, \dot{q}) \]  

(8)

2.3. Drag force

Drag force in UVMS is divided into two parts. The first part is derived from following equations with regarding to link 1 and link 2 of the manipulator (Shinohara, 2011):

\[ D_1 = \frac{\rho}{2} c_d d_1 \int_0^{d_1} v_1^2 dx_1 \]  

(9)

\[ D_2 = \frac{\rho}{2} c_d d_2 \int_0^{d_2} v_2^2 dx_2 \]  

(10)

Where \( d_1, d_2 \) and \( c_d \) are the diameter of link 1, the diameter of link 2 and the drag coefficient, respectively. \( v_1, v_2 \) are translational velocities of links. The second part \( (D_v) \) is the drag force applied on the underwater vehicle (Sun and Cheah, 2003)

\[ D_v = \text{diag}(d_1 | x_v, \dot{x}_v, \dot{z}_v, q_1, q_3, q_3, q_1 | d_1 | \dot{q}_1, \dot{q}_3, \dot{q}_3, \dot{q}_1)F \]  

(11)

Where \( d_1, d_2 \) and \( d_3 \) are translational quadratic damping factor, angular quadratic damping factor and angular linear damping.
factor respectively. Therefore, the total drag force applied on UVMS is conveyed as Eq. (12)
\[ D(q, \dot{q}) = [D_v \ D_1 \ D_2]^T \]  

(12)

2.4. Gravitational and buoyant forces

Buoyancy force is equal to the weight of the fluid displaced by link/body and acts through the center of buoyancy of the link/vehicle (Fossen, 1994). It is in the opposite direction of gravitational force (Eq. (13))
\[ F_U(q) = G(q) - B(q) = mg - \rho g \]  

(13)

Where \( v \) is the volume of the link/vehicle. Therefore, this force affects the heave motion of vehicle and link 2. Through calculating the force \( F_U(q) \) in all directions, the potential energy \( (u) \) is achieved. Therefore the matrix \( h(q) \) is expressed as Eq. (14)
\[ h(q) = -\frac{d}{dt} \frac{\partial u}{\partial \dot{q}} + \frac{\partial u}{\partial q} \]  

(14)

in which
\[ h(q) = [h_1, h_2, h_3, h_4, h_5, h_6, h_7, h_8]^T \]  

(15)

In the Eq. (15), all of the components are zero except \( h_3 \) and \( h_8 \).
\[ h_3 = g m_v - \rho g v_v \]  

(16)

\[ h_8 = -0.5 l m \frac{g}{2} \cos(q_2 + q_y) + 0.5 g \cos(q_2 + q_y) v_l \]  

(17)

In which, \( v_v \) and \( v_l \) are volume of the spherical vehicle and the cylindrical link, respectively.

2.5. Final dynamic equation of UVMS

By using Eqs. (8), (12) and (14) the final form of the dynamic equations of the UVMS is derived as
\[ Q = M(q)\ddot{q} + C(q, \dot{q}) + D(q, \dot{q}) + h(q) \]  

(18)

3. Time Delay Controller

Suppose the reference input trajectory is denoted by \( q_d \), then the control objective is to track \( q_d \). Eqs. (19–21) define the tracking error and its first and second derivatives as
\[ e = q_d - q \]  

(19)

\[ \dot{e} = \dot{q}_d - \dot{q} \]  

(20)

\[ \ddot{e} = \ddot{q}_d - \ddot{q} \]  

(21)

in which, \( q \) is the position vector. In Eq. (18) let \( M(q) \) be approximated with \( M(q) \) as a constant matrix. Hence, Eq. (18) is rewritten as Eq. 22
\[ \tau = M\ddot{q} + H(q, \dot{q}, \ddot{q}) \]  

(22)

Where
\[ H = (M - M)\ddot{q} + C(q, \dot{q}) + D(q, \dot{q}) \]  

(23)

According to the computed torque method, the input is expressed as
\[ \tau = M\ddot{u} + H(q, \dot{q}, \ddot{q}) \]  

(24)

\[ U = \ddot{q}_d + k_d \dot{e} + k_p e \]  

(25)

where \( H, k_d \) and \( k_p \) are the estimated value of \( H \), the derivative and the proportional gain matrices, respectively. Substituting Eqs. (24), (25) into Eq. (22), the target error dynamic equation is
\[ \ddot{e} + k_d \dot{e} + k_p e = 0 \]  

(26)

In the TDC approach, with assuming that the time delay \( L \) is very small, \( H(t) \) could be approximated as Eq. (27) (Cho and Chang, 2005)
\[ H(t) = H(t - L) = \dot{H}(t) = \tau(t) - L \dot{M}(q(t) - L) \]  

(27)

Combining Eqs. (24), (25) and (27), the TDC law is obtained as Eq. (28)
\[ \tau = \tau(t) - L \dot{M}(q(t) - L) - \dot{M}(q_d(t) - L) + k_d \dot{e} + k_p e \]  

(28)

Incidentally, the past acceleration \( \ddot{q}(t - L) \) is given by numerical differentiation as Eq. (29)
\[ \ddot{q}(t - L) = \frac{q(t) - 2q(t - L) + q(t - 2L)}{L^2} \]  

(29)

According to Eq. (23), to guarantee the stability of control system, the constant matrix \( \dot{M} \) should be designed as follows:
\[ \dot{M} = \gamma I, \ 0 < \gamma < 2 \alpha \]  

(30)

where \( \alpha \) is the minimum bound of eigenvalues \( (\lambda_i) \) of \( M(q) \) for all \( q \). Fig. 3 shows the TDC for UVMS.

4. Proposed controller

To improve the performance of the proposed controller, two terms are added to the obtained control law in Eq. (28). The first term is Terminal Sliding Mode (TSM) which increases rate of the convergence to zero for tracking error (Jin et al., 2011). Furthermore, sliding mode gain and PID gains are tuned through fuzzy logic. The second term has the features of PID controller that leads to decreasing of the tracking error in transient and steady state. Therefore Eq. (28) is rewritten as follows:
\[ \tau = \tau(t) - L \dot{M}(q(t) - L) + \dot{M}q_d + \dot{k}_d e + k_p e + k_1 \text{sat} \left( \frac{\dot{e}}{\dot{q}} \right) + k_2 s \]  

(31)

\[ k_1 = N_1 K_{fuzz}, \ k_2 = N_2 K_{fuzz}, \ s = \dot{e} + \frac{\lambda_1}{2} \int \dot{e} \]  

The saturation function for chattering reduction is used in control torques. In the above equation, the term \( k_1 \text{sat}(\dot{e}/\dot{q}) \) performs as the TSM. The term \( k_2 \dot{e} \) operates as a PID controller because sliding surface is selected in the form of proportional, integral and derivative of the error. \( k_1 \) and \( k_2 \) are the control gains which are set according to the output gain of fuzzy controller \( K_{fuzz} \). \( N_1 \), \( N_2 \) are the fuzzy gains normalizing factors. Fig. 4 illustrates modified TDC controller Block Diagram.
4.1. Fuzzy gain tuning of TSM and PID

In the conventional TSM and PID, control gains depend on uncertainties. This dependence is a defect for complex dynamics system. To solve this problem a fuzzy controller is designed here. Furthermore using fuzzy logic, gains are tuned based on the distance of the states to the sliding surface. The main advantage of fuzzy control is that the tracking error and control effort are reduced. The configuration of our TSM–Fuzzy–PID Control (TSMF–PID) scheme is shown in Fig. 4; it includes a sliding surface and a two-input single-output fuzzy controller in which Mamdani’s fuzzy algorithm is used. It is commonly is used in systems with

Fig. 9. Simulation Results of SMC (saturation function), (a) Trajectory tracking, (b) Tracking error and (c) Input forces and torques.
two inputs and one output. In fact, the Mamdani controller is closer to approximation expression for implementation of complex nonlinear controllers. $k_{uzz}$ is the output of the fuzzy controller, which is determined by inference on input linguistic variables $s(t)$ and $\dot{s}(t)$. The membership function of input linguistic variables and the membership functions of output linguistic variable are shown in Figs. 5 and 6, respectively. The fuzzy controller consists of four steps: fuzzification, rules evaluation, aggregation and defuzzification. The fuzzy rule base is given in Table 2 in which the following symbols have been used: NB: negative big; NS: negative small; ZE: zero; PS: positive small; PB: positive big; N: negative; Z: zero; P: positive; M: medium; B: big; S: small. These linguistic fuzzy rules are defined heuristically in the following form:

\[ R(l) : \text{If } s(t) \text{ is } A_{1}^{l} \text{ and } \dot{s}(t) \text{ is } A_{2}^{l} \text{ then } k_{uzz} \text{ is } B^{l} \]

Where $A_{1}^{l}$ and $A_{2}^{l}$ are the labels of the input fuzzy sets and $B^{l}$ is the labels of the output fuzzy sets. $l = 1, 2, \ldots, 15$ denotes the number of the fuzzy rules. Fuzzy implication is modeled by Mamdani’s minimum operator, the conjunction operator is Min, the t-norm from compositional rule is Min and for the aggregation of the rules the Max operator is used. In this paper the centroid defuzzification method is used and calculated by the following equation:

\[ Z = \frac{\sum_{i=1}^{n} c_{i} \mu_{A_{i}}(x) \mu_{B_{i}}(y)}{\sum_{i=1}^{n} \mu_{A_{i}}(x) \mu_{B_{i}}(y)} \]  \hspace{1cm} (32)

The degree of membership function is chosen for the input and output variables based on (S.E. Shaffei, 2010). Increasing PID gains results in: (a) reducing the “reaching time to sliding surface” and (b) increment of the oscillations in the input torque around the sliding surface. Therefore, if the gains are tuned based on the distance of the states to the sliding surface, more acceptable performance will be achieved. Hence, the degree of membership function for the input and output is taken to be variable. Variable gain may be a disadvantage because of more computational cost in comparison to fixed gain (which could be solved by using high performance computers). Furthermore, to increase the precision of tracking and sensitivity, the membership functions are considered thinner around zero point.

The fuzzy control surface of the output $k_{uzz}$ is shown in Fig. 7.

5. Simulation results

In this section, the simulation results of the proposed controller, which is performed on a 4 DOF UVMS, are presented. In this case study for surge motion ($x_v$) and heave motion ($z_v$), sine and cosine desired trajectories with zero initial conditions are chosen respectively. The trajectory generates a circular path in $x$-$z$ plane for vehicle. The desired orientation of vehicle in pitch direction ($q_y$) and desired path of $q_2$ is taken to be as Eq. (33)

\[ q_y = q_2 = \pi \left(1 - e^{-t/2}\right) \]  \hspace{1cm} (33)

The vector of positions is shown in Eq. (34)

\[ q = [x_v, z_v, q_y, q_2]^T \]  \hspace{1cm} (34)

Fig. 8 illustrates 4 DOF Underwater Vehicle-Manipulator System with vector of positions expressed in Eq. (34).

Table 3 shows the parameters of the UVMS which is used in case studies. In this case study (a) the conventional sliding mode controller, (b) proposed controller without external disturbance and (c) proposed controller in presence of external disturbances and uncertainties are compared through simulation. Fig. 9 shows the simulation results of SMC with saturation function and Fig. 10
shows the simulation results of proposed controller in a normal condition. In addition, robustness of the proposed controller with variable parameters in presence of external disturbance is tested (the simulation results of it are shown in Fig. 11). The values of fuzzy gains normalizing factors are equal to 10 ($N_1, N_2 = 10$). The parameters of the proposed control system in Eq. (31) are considered as below

$$M = \text{diag}(0.7, 0.7, 0.1, 0.1)$$

$$k_0 = \text{diag}(20, 20, 20, 20)$$

Fig. 10. Simulation results of proposed controller with $L=0.001$ s, (a) Trajectory tracking, (b) Tracking error, (c) Input forces and torques and (d) Fuzzy gains.
The simulation results of the SMC are shown in Fig. 9, while trajectory tracking of pitch motion of a divergence has occurred in the time interval 2 to 5 s. Additionally, through this controller, the system is not able to track the desired path of joint, and after 3 s, the path is diverging from input reference.

The simulation results of the improved TDC (the trajectory, tracking errors, torque profiles of joints and fuzzy gains) without

\[
k_p = \text{diag}(5, 5, 5)
\]

\[
L = 0.001 \text{ s}
\]  

(35)
external disturbance are shown in Fig. 10. Primary fluctuations in the plots are results of the low frequency chattering about of sliding surface. This phenomenon is due to two factors in the control law (according to Eq. (31)): (a) the PID sliding surface and (b) fuzzy gains in the fuzzy subsystem. The new proposed controller has a fast response in reaching mode due to using PID sliding surface in TSM (in which integral term $\frac{1}{2} \int e$ is effective in creating the primary fluctuations). Furthermore, fuzzy gain tuning

Fig. 11. Simulation results of proposed controller with external disturbances and uncertainties ($L=0.007$ s) (a) Trajectory tracking, (b) Tracking error (c) Input forces and torques and (d) Fuzzy gains.
is an effective method for adjusting gains of SMC which results in faster response. However, the faster response results in primary fluctuation (that is a normal behavior).

Finally, the simulation results of proposed controller using another time delay $L=0.007\,\text{s}$ and external disturbances are shown in Fig. 11. As example, following functions are considered for disturbances:

1- Unknown disturbance forces/torques, $Q_d = \sin(8\pi t)$
2- Variable mass of coupled link, $m_l = 20 + 5 \cos(t)$

At the first case, unknown disturbance forces/torques are added to Eq. (18) as follows:

$$Q = M(q)\ddot{q} + C(q, \dot{q}) + D(q, \dot{q}) + h(q) + Q_d$$  \hspace{1cm} (36)
6. Discussion

As it is shown in Fig. 9, the SMC based system is unable to track the desired path. According to highly nonlinear terms of hydrodynamic forces, conventional SMC is not suitable for use in UVMs. In addition, the controller diverges temporarily to track the path regarding to pitch. These problems do not exist in the new proposed controller and through it, the system is able to track all of the desired paths with acceptable precision (Fig. 10). Furthermore, some unknown torques and variable mass of coupled link are applied to dynamics model of UVMs as external disturbances. As it is shown in Fig. 11, the proposed method leads to proper results of trajectory tracking and it has an acceptable robustness. However, the larger time delay causes a lower speed in trajectory tracking (and increasing tracking time for specified error). The proposed controller can be performed for larger time delay by changing of elements in \( M(q) \) as a constant matrix in Eq. (22) that it may be weak point of this method. In this paper, sampling times \( L=0.001 \) s and \( L=0.007 \) s are studied as example (it can be larger by using adaptive method for estimation of elements of the matrix \( M(q) \)).

PID sliding surface have a better performance in comparison with PD sliding surface. The proposed controller includes a free chattering TSM and PID with a fuzzy tunable gain. The main idea is that the robustness property of SMC and good response characteristics of PID are combined with fuzzy tuning gain approach to achieve more acceptable performance. The Proportional-Integral switching part of PID is chosen to ensure the stability of the overall dynamics during the entire period i.e. the reaching phase and the sliding phase. Also, to further penalize tracking error, integral part may be used in the sliding surface part. Although PID controller acts better than PD in terms of steady state error, PD–SMC has more steady chattering behavior compared with the PID–SMC (Piltan et al. (2011a)).

7. Conclusion

A time delay estimation based general framework for trajectory tracking control of Underwater Vehicle-Manipulator System is presented. It consists of three elements: (a) “time delay estimation” element that cancels nonlinearities of UVMs dynamics, (b) TSM controller that provided a fast convergence, and (c) PID element that reduced tracking error. In the conventional TSM and PID controllers, gains depend on uncertainties. This dependence is a defect for complex dynamics system. To solve it a fuzzy controller is designed to adaptively tune the gains of TSM and PID elements. Some simulation studies are done to compare it with conventional SMC. The new controller assures fast convergence and accurate trajectory tracking, which facilitates an effective control. In addition, its robustness is tested in presence of some uncertainties and disturbances. The simulation results showed that this procedure has significant properties in trajectory tracking with acceptable precision. Some future works in this area are as follow:

1- Developing the control strategy in which an adaptive method for estimation of inertial matrix \( M(q) \) is used.

2- Considering wave effects as a disturbance for UVMs (we will evaluate control performance in presence water wave effects in the shallow waters).

UVMS is a large scale system with complex nonlinear dynamics. Rather than its application on earth, in near future, it will be useful for investigations on other planets in which there are possible fluids. However, space application of these systems needs much more research in this area.

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