SLIDING MODE-PID FUZZY CONTROLLER WITH A NEW REACHING MODE FOR UNDERWATER ROBOTIC MANIPULATORS

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Abstract—Design of an accurate and robust controller is a challenging topic in underwater manipulator control. This is due to hydrodynamic disturbances in underwater environment. In this paper a sliding mode control (SMC) included a PID sliding surface and fuzzy tunable gain is designed. In this proposed controller robustness property of SMC and fast response of PID are incorporated with fuzzy rules to reduce error tracking. In the control law, for removing of chattering, the exponential function is used. And also the system is analyzed in terms of stability by direct Lyapunov method. By tuning gains with fuzzy logic, the proposed controller does not require an accurate model of underwater manipulator dynamics. Hence the modeling and simulation studies are done for an underwater manipulator to verify the effectiveness of the proposed method in presence of unmodeled dynamic (variable masses of links) and external disturbance. Both new proposed controller and conventional SMC are simulated. The results of simulation show the high performance of proposed controller in comparison to conventional SMC.

Keywords—Sliding Mode Control, Fuzzy Logic, Gain Tuning, Underwater Manipulator.

I. INTRODUCTION

Oceanic environment covers a large part of the earth, which included marine structures, oil/gas pipe lines and mines. Therefore, role of underwater manipulation has been increased in underwater intervention. In addition, robotic manipulator is mounted on a mobile platform like Autonomous Underwater Vehicle (AUV) or Remotely Operated Vehicle (ROV) that in this way Underwater Vehicle-Manipulator Systems (UVMS) made up that will have so many applications in underwater manipulation. In recent studies, there is not a reliable and robust controller for the underwater manipulators. Liceaga Castro and Qiao (1991) used a variable structure system (VSS) for design a robust controller. Levesque and Richard (1993) presented a stochastic adaptive controller that was a model based design. This controller could represent efficient robustness in a turbulent flow, but it does not have a proper precision for trajectory tracking goals. The control system based on machine vision was proposed by Smith et al. (1994). This system does not have a robust property in presence of uncertainties for the reason of using PID controller. Furthermore, Baicu et al. (1995) used a hybrid, robust-adaptive controller for tracking of a single link underwater manipulator. A PD control method was used for robust controller that does not have a proper robustness in presence of disturbances which are under the sea. McLain and Rock (1996) improved an exact model of hydrodynamic forces that were used at a single link manipulator. Lee and Choi (2000) presented scheme of a robust control with multi layer neural network and with learning algorithm of an error back propagation. Lee et al. (2007) improved a four DOF underwater manipulator for inspection and maintain a nuclear reactor. System has been used for removing loose parts from the bottom of a vessel of a nuclear reactor. Rahman et al. (2007) presented modeling of parameters for an underwater manipulator; also, they survey and studied the effect of hydrodynamic forces on torque of a puma560 manipulator by simulation. Xu et al. (2007) used a robust and exact SMC controller for tracking of the underwater manipulator. They used saturation function for destroying chattering. In this system, there is not a parameter estimator for the controller and SMC parameters have been adjusted with try and error. Moreover, Wang et al. (2008) presented a new controlling method that was based on Cerebellar Model Articulation Controller (CMAC) that this is a neural network based on models of human memory and neuromuscular control. But it does not have high robustness. Pandian and Sakagami (2010) designed a Fuzzy-Neural controller for an underwater manipulator that was used a PD controller with Fuzzy gain regulator and a dynamic estimator with using of neural network. Gunusel and Ozmen (2011) presented modeling and controlling of a two degree of freedom underwater manipulator with a flexible link. They presented an exact modeling for drag forces on flexible link. Several researchers have studied sliding mode fuzzy control (SMFC) for different applications (El-Bakly and Fouda, 2009; Ryu and Park, 2001). However, little research has so far been conducted on SMFC’s for the underwater manipulators. The rest of the paper is organized as follows; the dynamics of the underwater manipulator is modeled in Section II that it includes uncertain added mass, drag force, buoyancy and frictional forces. The section III presents the characteristics of a conventional SMC with PID sliding surface. Section IV presents the robust fuzzy SMC-PID using fuzzy self-tuning control gain. The computer simulation results are shown in section V. Finally, the conclusion is presented in section VI.
II. UNDERWATER MANIPULATOR

The coupled effect between manipulator and vehicle is neglected and ROV/AUV is assumed stationary during manipulator movement. Fig. 1 illustrates the n-D.O.F. UVMS.

The added mass force results from the interaction of fluid in the prompt proximity of an underwater link which is accelerating relative to the fluid. The dynamic equations of motion are developed by using Lagrange formulation as follow:

$$\frac{d}{dt} \left( \frac{dT}{dq} \right) - \frac{dT}{dq} = \tau \quad (1)$$

where \( q \in \mathbb{R}^2 \) is the joint position of robotic manipulator, and \( q \in \mathbb{R}^2 \) is the joint velocity vector of robotic manipulator.

The vector of kinetic energy of the system is written as:

$$T = T_{RB} + T_{AM} \quad (2)$$

where \( T_{RB} = \frac{1}{2} \mathbf{v}^T \mathbf{M}_{RB} \mathbf{v} \) is kinetic energy of manipulator due to rigid body, and \( T_{AM} = \frac{1}{2} \mathbf{v}^T \mathbf{M}_{AM} \mathbf{v} \) is kinetic energy of manipulator due to added mass. The added mass matrix for each cylindrical link of a manipulator is represented as:

$$\mathbf{M}_AM = \text{diag}(0, a_1, a_2, 0, b_1, b_2) \quad (3)$$

where \( a_i = \frac{\pi}{4} \rho_i l_i^2 \). Substituting the total kinetic energy in Eq. 1, we obtain dynamic equation of motion which includes rigid body and added mass as follows:

$$M(q)\ddot{q} + C(q, \dot{q}) = \tau \quad (4)$$

$$M(q) = \begin{bmatrix} l_1^2m_1 + 2l_1l_2m_1c_2 + l_2^2(m_1 + m_2) & l_1^2m_1 + l_1l_2m_2c_2 \\ l_1^2m_1 + l_1l_2m_2c_2 & 0 \end{bmatrix} \quad (5)$$

$$C(q, \dot{q}) = \begin{bmatrix} -l_1l_2m_1c_1c_2\dot{q}_1 - l_1l_2m_2c_1\dot{q}_1 + l_2^2\dot{q}_2 \\ l_1l_2m_1c_1c_2\dot{q}_1 \end{bmatrix} \quad (6)$$

The added mass of the links \( m_i \) for cylindrical manipulator are expressed by Fossen (2002) in follow equation as per Fossen:

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The drag force on a link is relative to the square of the link’s translational velocities. Drag torques are expressed in (8):

$$\tau_i = \frac{\rho}{2} \int_0^L v_i^2 \text{sign}(v_i) dx \quad (8)$$

$$\tau_{di} = \frac{\rho}{2} \int_0^L v_i^2 \text{sign}(v_i) dx \quad (8)$$

$$D(q, \dot{q}) = \begin{bmatrix} T_{11} \\ T_{21} \end{bmatrix} \quad (9)$$

The sign of the drag force direction has to be determined according to the motion of the underwater manipulator. The added mass force results from the interaction of fluid in the prompt proximity of an underwater link which is accelerating relative to the fluid. The dynamic equations of motion are developed by using Lagrange formulation as follow:

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$$m_{ai} = \frac{\pi}{4} \rho_i l_i^3 \quad (7)$$
Combining equations of (4), (8), (9), (13) we can write the final form of the dynamic equations of motion of the underwater manipulator with external disturbance:

\[ M(q)q + C(q, \dot{q}) + D(q, \ddot{q}) + h(q) + F(\dot{q}) + T_d = \tau \tag{14} \]

where \( M(q) \in \mathbb{R}^{2 \times 2} \) is inertia matrix including rigid body and added mass terms, \( C(q, \dot{q}) \in \mathbb{R}^2 \) is vector of centrifugal and coriolis forces which included rigid body and added mass terms, \( D(q, \ddot{q}) \in \mathbb{R}^2 \) is vector of drag torques, \( h(q) \in \mathbb{R}^2 \) is vector of gravity and buoyancy forces, \( F(\dot{q}) \in \mathbb{R}^2 \) is vector of frictional forces, \( T_d \in \mathbb{R}^2 \) is the external disturbance, and \( \tau \in \mathbb{R}^2 \) is vector of torques acting on underwater manipulator. \( \tau \) and \( q \) are defined such that the above equation is satisfied.

\( \tau = \tau_{eq} + \tau_1 \) (15)\n
\( \dot{\tau}_{eq} = \dot{\tau}_1 \) (16)\n
\( \dot{\tau}_1 = N \dot{k}_{sec} \) (17)

where \( \tau_{eq} \) is the control law for sliding mode and \( \tau_1 \) is the control law for reaching mode. Structure of \( \tau_1 \) is the main reason of chattering as undesired oscillation around the sliding surface. Thus, to overcome this problem, the structure of \( \tau_{sec} \) should be modified by reducing the variations rate of \( \tau_1 \) around the sliding surface. Now, we introduce a control law that includes an exponential term that make the reaching trajectory smooth, consequently, prevents the oscillation of the states around sliding surface. Comparing a-conventional structure and b-proposed structure trajectories in Fig. 3 can give better understanding.

Differentiating Eq. (20) with respect to time and replacing from Eq. (19), we obtain

\[ \dot{\tau}_1 = N \dot{k}_{sec} \] (21)

\[ k_1 = N k_{sec} \] (22)

\[ k_2 = N k_{sec} \] (23)

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part and a two-input single-output SM-PIDFC in which
Mamdani’s fuzzy algorithm is used.
k_1, k_2 in Eq. (21) are expressed as follow:
\[ k_1 = N_1 k_{fuzz} \]
\[ k_2 = N_2 k_{fuzz} \]
where \( N_1, N_2 \) are the normalization factor of the output
variable, and \( k_{fuzz} \) is the output of the SM-PIDFC,
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. \( s(t), \dot{s}(t) \) and \( k_{fuzz} \) are decomposed into
eighteen fuzzy partitions respectively. The fuzzy controller consists of four steps: Fuzzification,
Rules evaluation, Aggregation and Defuzzification. The
fuzzy rule base has been 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:
\[ R^{i1} : \text{IF} \ s(t) \text{ is } A_i^l \text{ and } \dot{s}(t) \text{ is } A_i^s \]
\[ \text{THEN} \ k_{fuzz} \text{ is } B_i \]
where \( A_i^l \) and \( A_i^s \) are the labels of the input fuzzy sets.
\( B_i \) is the labels of the output fuzzy sets. \( l=1,2,\ldots,15 \)
denotes the number of the fuzzy IF-THEN rules. Fuzzy
implication is modeled by Mamdani’s minimum oper-
a\-tor, 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 cen-
troid defuzzification method is used and calculated by
the following equation:
\[ z = \frac{\sum_{i=1}^{n} c_i \mu_{A_i}(x) \mu_{B_i}(y)}{\sum_{i=1}^{n} \mu_{A_i}(x) \mu_{B_i}(y)} \]  
(31)
The fuzzy control surface of the output \( k_{fuzz} \) is
shown in Fig. 7.

Table 2. Fuzzy Rule Base

<table>
<thead>
<tr>
<th>( s )</th>
<th>( \dot{s} )</th>
<th>NB</th>
<th>NS</th>
<th>ZE</th>
<th>PS</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>B</td>
<td>B</td>
<td>M</td>
<td>S</td>
<td>S</td>
<td>B</td>
</tr>
<tr>
<td>Z</td>
<td>B</td>
<td>M</td>
<td>S</td>
<td>M</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>P</td>
<td>B</td>
<td>S</td>
<td>M</td>
<td>B</td>
<td>B</td>
<td>B</td>
</tr>
</tbody>
</table>

V. SIMULATION RESULTS

In this section, we show the design process of the pro-
posed sliding mode-PID fuzzy control algorithm on a
two-link manipulator. In the case study for angle of
joints 1, 2 \( \exp(-t/4) \sin(3t) \) and \( \exp(-t/4) \cos(3t) \) tra-
jectories are chosen respectively. The initial conditions
are set as:
\[ q=[1,0]^T, \cdot \cdot \cdot \]
\[ \dot{q}=[0,0]^T. \]
The external disturbance is:
\[ T_d = \begin{bmatrix} 3.2 + 2 \cos(0.02t) \\ 3.5 + 1.7 \sin(0.02t) \end{bmatrix}. \]

Also in simulation of three kind of controller, we ap-
plied an unmodeled dynamic in form of variable mass
due to added effect in underwater condition. This
unmodeled dynamic is expressed as follow:
\[ m_1 = 3 + 2 \sin(t), \]
\[ m_2 = 1 + 2 \sin(t). \]

Using the values given in Table 1 simulation is carried
out for conventional SMC and sliding mode-PIDFC
controller. Fig.8 shows the trajectory tracking, tracking
error and control inputs when system is subjected to
conventional SMC.

Figure 9 shows the trajectory tracking, tracking
error, control input and fuzzy controller outputs when
system is subjected to SM-PIDFC with the function
\( \text{sign}(s) \).
VI. DISCUSSION

According to highly nonlinear terms of hydrodynamic forces, a conventional sliding mode controller could not be used. On the other hand the high frequency of inputs can damage the actuators. Figures 9 and 10 show the results of new proposed controller. Figure 9 is related to controller with the function \( \text{sign}(s) \), and Fig.10 is related to the controller with the function \( \exp(-\alpha|s|) \text{sign}(s) \). Using Fuzzy controller with intelligent determination of gain in sliding mode controller causes to
A sliding mode-PID fuzzy controller for underwater manipulator has been presented. The proposed controller is designed based on the PID sliding surface and uses fuzzy rules to adaptively tune the gains. In the control law, for removing of chattering, the exponential function has been used. This controller is simple, easy to implement, and robust. In order to confirm the effectiveness of the proposed algorithm, simulations were performed on the trajectory tracking of a 2-DOF underwater manipulator. The results show that the proposed sliding mode-PID fuzzy controller provides accurate and robust tracking performance of the underwater manipulator without any of the chattering, which is superior to the one obtained with a conventional SMC. Table 3 gives the tracking error norms. Also Table 4 gives the percentage of reduced chattering in comparison to conventional SMC. Table 4: percentage of reduced chattering in comparison to conventional SMC.

<table>
<thead>
<tr>
<th>Controller</th>
<th>Reduced Chattering of Link 1</th>
<th>Reduced Chattering of Link 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM-PIDFC with (\text{sign}(s)) function</td>
<td>45%</td>
<td>15%</td>
</tr>
<tr>
<td>SM-PIDFC with (\exp(-\alpha</td>
<td>s</td>
<td>)) (\text{sign}(s)) function</td>
</tr>
</tbody>
</table>

VII. CONCLUSION

A sliding mode-PID fuzzy controller for underwater manipulator has been presented. The proposed controller is designed based on the PID sliding surface and uses fuzzy rules to adaptively tune the gains. In the control law, for removing of chattering, the exponential function has been used. This controller is simple, easy to implement, and robust. In order to confirm the effectiveness of the proposed algorithm, simulations were performed on the trajectory tracking of a 2-DOF underwater manipulator. The results show that the proposed sliding mode-PID fuzzy controller provides accurate and robust tracking performance of the underwater manipulator without any of the chattering, which is superior to the one obtained with a conventional SMC. Table 3 gives the tracking error norms. Also Table 4 gives the percentage of reduced chattering in comparison to conventional SMC.

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