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Robust control of robot manipulators with torque saturation using fuzzy logic

Hyeung-Sik Choi

Korea Maritime University, Division of Mechanical & Information Engineering, Dongsam-Dong, Yeongdo-Ku, Pusan (Korea)
E-mail: hchoi@hanara.kmaritime.ac.kr

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SUMMARY
Robot manipulators, which are nonlinear structures and have uncertain system parameters, are complex dynamically when operated in an unknown environment. To compensate for estimate errors of the uncertain system parameters and to accomplish the desired trajectory tracking, nonlinear robust controllers are appropriate. However, when estimation errors or tracking errors are large, they require large input torques, which may not be satisfied due to torque limits of actuators such as driving motors. As a result, their stability cannot be guaranteed. In this paper, a new robust control scheme is presented to solve stability problems and to achieve fast trajectory tracking of uncertain robot manipulators in the presence of torque limits. By using fuzzy logic, new desired trajectories which can be reduced are generated based on the initial desired trajectory, and torques of the robust controller are regulated so as to not exceed torque limits. Numerical examples are shown to validate the proposed controller using an uncertain two degree-of-freedom underwater robot manipulator.

KEYWORDS: Robot control; Robot manipulators; Torque saturation; Fuzzy logic.

1. INTRODUCTION

Robot manipulators are operated in uncertain surroundings such as underwater or space. In such uncertain surroundings, robot manipulators which are highly nonlinear systems and have uncertain parameters, are applied to trajectory tracking operations such as welding. To control the tracking motion of the uncertain and nonlinear robot manipulators, a number of robust control schemes have been developed.

One of the robust controllers is the sliding mode controller[1,2] where parameter uncertainty and external disturbances can be tolerated while still keeping the sliding surface if the sliding condition is satisfied. Once on the surface, the system trajectories remain on the surface. The other robust controller is motivated by a min-max controller[3] where uniform asymptotic stability is guaranteed, but control action is discontinuous. An improved robust controller was developed guaranteeing uniform ultimate boundedness of every system response within an arbitrarily small neighborhood of the zero state.[4] The control algorithm presented in reference [4] was applied to coordinating robot manipulators with uncertain parameters in conjunction with a computed torque type of control.[5,6]

Robust controllers are designed to compensate for estimate errors of the system parameters which usually contain signals of state errors and external disturbances. When parameter estimation errors, disturbances, or the state errors become large, the controllers require large input torques to compensate for them. However, there exists a torque saturation of actuators in all dynamic systems. The torque saturation slows down the system response and even deteriorates the stability of the system. In designing dynamic systems, actuators with enough torque capacity are selected to fully actuate the systems. However, enough capacity of actuators cannot be selected in most robot manipulators since the actuating motors of robot manipulators are serially placed on links.

In dealing with saturation problems of the control systems, there are a number of papers mainly related with the linear systems.[7–10] One of these is concerned with the wind-up problem in PID or PI controller.[7] In another paper, an analysis is performed on the robust control of the uncertain linear system with saturated actuators.[8] In the time domain approach, there is an analysis on the stability of the linear system with saturated actuators.[9] Similarly, in the frequency domain, the stability of the linear system with saturated actuators is analyzed.[10]

In trajectory control of robot manipulators, there are a number of papers to solve the input saturation problem.[11–13] There, a sliding mode control algorithm is applied to control the nonlinear and uncertain robot dynamics. To prevent torque saturation of the controller, a new robot trajectory is generated based on the initial trajectory using a point-wise optimal scheme.[11,12] In another paper, a robust H_∞ controller is applied to coordinate robot manipulators where an input torque control based on a logical algorithm is used.[13] The algorithm regulates the tracking time such that the torque of the H_∞ controller is controlled.

Here, a new control algorithm is proposed to solve the torque saturation problem of the robust controller for robot manipulators. The proposed control algorithm is applied to coordinate highly uncertain and nonlinear underwater robot manipulators with limited input torques. A control algorithm is designed using fuzzy logic to control the tracking velocity which affects the magnitude of input torques. The proposed algorithm generates a new trajectory based on the

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desired one such that the arriving time of robot manipulators to the target point can be reduced while regulating the torque of the robust controller as not to exceed the torque limit. Numerical examples are shown to validate the proposed controller using a two degree-of-freedom underwater robot manipulator.

2. DYNAMICAL MODEL OF UNDERWATER ROBOT MANIPULATORS

In this paper, the dynamic equations of underwater robot manipulators are taken from references [14–18]. The bases of manipulators are assumed to be attached to the underwater vehicle which are positioned on the ground. Even in this case, the dynamics of the manipulator is altered by several uncertain factors such as buoyancy, added mass, added moment of inertia, frictional force, and drag force. Reflecting the buoyancy, added mass, and added moment of inertia into the robot dynamics we have

$$H^*(q)\ddot{q}+C^*(q,\dot{q})\dot{q}+G^*(q)=\tau \tag{1}$$

where $q\in R^{n\times 1}$ is the joint angle vector, $H^*(q)\in R^{n\times n}$ is the inertia matrix where the added mass and added moment of inertia are included, $C^*(q,\dot{q})\in R^{n\times 1}$ is the nonlinear force vector including the centripetal and Coriolis forces where the added mass and added moment of inertia are included as shown in reference [15], $G^*(q)\in R^{n\times 1}$ is the gravity force whose weight is reduced by buoyance; $\tau\in R^{n\times 1}$ is the joint torque vector.

Due to sealing, the frictional force $F(q,\dot{q})\in R^{n\times 1}$ representing the static and Coulomb friction force is not neglectable and is expressed as

$$F(q,\dot{q})=c\ sgn(\dot{q})+\upsilon\dot{q} \tag{2}$$

where $c\ sgn(\dot{q})\in R^{n\times 1}$ and $\upsilon\dot{q}\in R^{n\times 1}$ are the Coulomb and viscous friction vectors respectively. Under the sea, the drag force exerting on the ith link of robot manipulators is expressed as

$$D_{fi}=-C_D(1/2)\rho\upsilon_{ri}|\upsilon_{ri}|A_i' \tag{3}$$

where A_i' is the projected area of the ith link to the vertical direction of the manipulator velocity υ_{ri}, ρ is the density of the water, and C_D is the drag force coefficient. The drag force exerting on the manipulators is expressed by the Euler equation as

$$D_{di}-D_{di+1}+r_{i,ci}\times D_{fi+1}-r_{i-1,ci}\times D_{fi}=0,\ i=1,\ldots,n \tag{4}$$

where $r_{i,ci}$ is the distance between the axis of the ith link and the center of the drag force applied to the ith link. Iterating equation (4) for $i=1,\ldots,$ n yields the torque vector D due to the drag force applied on links. By reflecting the frictional forces and the torque vector D into the equation (1) we have a closed-form matrix equation of the underwater robot manipulators as

$$H^*(q)\ddot{q}+C^*(q,\dot{q})\dot{q}+G^*(q)+F(q,\dot{q})+D=\tau \tag{5}$$

The parameters of the underwater robot dynamics equation are composed of the added mass and added moment of inertia, drag force coefficients, and frictional coefficients which are highly nonlinear and uncertain. These nonlinear and uncertain parameters should be compensated by the control action to yield good performance. In the next section, a robust controller is designed to coordinate the highly nonlinear and uncertain underwater robot manipulators.

3. THE DESIGN OF A ROBUST CONTROLLER

To control underwater robot manipulators, a computed torque type controller is designed as

$$\tau=\hat{H}^*(q)(\upsilon+U)+\hat{C}^*(q,\dot{q})\dot{q}+G^*(q)+\hat{F}(q,\dot{q})+\hat{D} \tag{6}$$

where $\upsilon=\ddot{q}_d+k_v\dot{e}+k_pe$, and $e=q_d-q$. $\hat{H}^*(q)$ and $\hat{C}^*(q,\dot{q})$ are estimates of $H^*(q)$ and $C^*(q,\dot{q})$, respectively. q_d is a desired joint angle, and the controller gains k_p, $k_v\in R^{n\times n}$ are diagonal positive matrices. U is a robust controller which is designed as in reference [4]. The robust controller guarantees uniform ultimate boundedness based on the properties of a Lyapunov function. U for robot manipulators is given as

$$U=\frac{(B^TPe)\rho^2}{\|B^TPe\|\rho+\varepsilon} \tag{7}$$

where ε is selected as a small positive number. B, P, γ are defined later. Applying the controller to robot manipulators and arranging yields

$$\hat{H}^*(\ddot{e}+k_v\dot{e}+k_pe)=\tilde{H}^*\ddot{q}+\tilde{C}^*\dot{q}+\tilde{F}+\tilde{D}-\hat{H}^*U \tag{8}$$

where $\tilde{H}^*=H^*-\hat{H}^*$, $\tilde{C}^*=C^*-\hat{C}^*$. In (6), $\ddot{q}$ is expressed in the first order state equation as

$$\ddot{q}=H^{*-1}\{\hat{H}^*(\upsilon+U)+\tilde{C}^*\dot{q}+\tilde{F}+\tilde{D}\} \tag{9}$$

Applying (9) to (8) and rearranging yields

$$\begin{aligned}\ddot{e}+k_v\dot{e}+k_pe&=\hat{H}^{*-1}[\tilde{H}^*H^{*-1}\{\hat{H}^*(\upsilon+U)-\psi_1\}+\psi_1]-U\\&=(I-H^{*-1}H^*)(\upsilon+U)+H^{*-1}\psi_1-U\end{aligned} \tag{10}$$

where, $\psi_1=\tilde{C}^*\dot{q}+\tilde{F}+\tilde{D}$, and $I-H^{*-1}\hat{H}^*=\hat{H}^{-1}*\tilde{H}^*H^{*-1}\hat{H}^*$.

Equation (10) is expressed in a simplified notation as

$$\ddot{e}+k_v\dot{e}+k_pe=E_1(\upsilon+U)+E_2\psi_1-U \tag{11}$$

where $E_1=I-H^{*-1}\hat{H}^*$, and $E_2=H^{*-1}$. Rewriting (11) in a state space form yields

$$\dot{x}=Ax+Bw \tag{12}$$

where $A=\begin{bmatrix}0 & I\\ -k_p & -k_v\end{bmatrix}$, $x=\begin{bmatrix}e\\ \dot{e}\end{bmatrix}$, $B=\begin{bmatrix}0\\ I\end{bmatrix}$,

$$w=(\Phi-U),\ \Phi=E_1(\upsilon+U)+E_2\psi_1.$$

The dimensions of A and x are $2n\times 2n$ and $2n\times 1$, respectively. Also, in (12), Φ is assumed to be bounded. If thcre exists ρ satisfying the following equation

$$\begin{aligned}\|\Phi\|&\le\|E_1\upsilon\|+\|E_2\Psi_1\|+\|E_1U\|\\&\le\|E_1\upsilon\|+\|E_2\Psi_1\|+\|E_1\|\rho=\rho\end{aligned} \tag{13}$$

then, ρ is expressed as

$$\rho=(1-\|E_1\|)^{-1}(\|E_1\upsilon\|+\|E_2\Psi_1\|) \tag{14}$$

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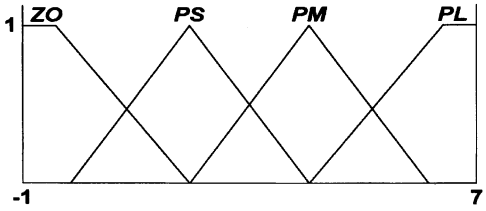


Fig. 1. Fuzzy Set for T.

In order to have $\rho > 0$, the following condition should be satisfied.

$$\max \|E_1\| < 1 \tag{15}$$

In order to establish a uniform ultimate boundedness stability result for tracking errors, a Lyapunov function is proposed as

$$V = x^T P x \tag{16}$$

where matrix P is a $2n \times 2n$ positive definite matrix such that equation (16) is assumed to be bounded for positive scalars λ_1 and λ_2 as

$$\lambda \| x \|^2 < x^T P x < \lambda_2 \| x \|^2 \tag{17}$$

Using (16) and (17), along the solution of system (12), it is shown that the derivative of V with respect to time is bounded as

$$\begin{aligned} \dot{V} &= x^T P \dot{x} + x^T P \dot{x} \\ &= -x^T Q x + 2 x^T P B w \\ &\le -x^T Q x + 2 \| x^T P B \| \rho + 2 x^T P B U \\ &\le -x^T Q x + 2 (B^T P x)^T \left(U + \frac{B^T P x}{\| B^T P x \|} \rho \right) \end{aligned} \tag{18}$$

where the Lyapunov equation (19) should be satisfied with any $2n \times 2n$ positive definite matrix Q as

$$A^T P + P A = -Q \tag{19}$$

Applying the robust controller in (7) to (18) yields the upper bounded result for $\dot{V}$ as

$$\dot{V} \le -\lambda \| x \|^2 + 2\varepsilon. \tag{20}$$

The uniform ultimate boundedness result of x is shown according to reference [4]. In this way, the end effector of robot manipulators follows the desired trajectory with uniform boundedness. However, as shown in equation (14), the magnitude of ρ depends on the magnitude of the estimation errors of uncertain system parameters and state errors. Hence, the magnitude of the robust controller composed of ρ might become very large according to the increase of parameter estimation errors and tracking errors. However, in reality, input torques are limited. Especially, in the underwater robot manipulators, the input torques of the robust controller may easily saturate owing to the large parameter uncertainties so that the stability of the system cannot be guaranteed. In the next section, a strategy is introduced to reduce the magnitude of input torques.

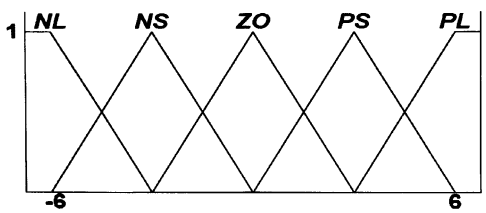


Fig. 2. Fuzzy Set for $\dot{T}$.

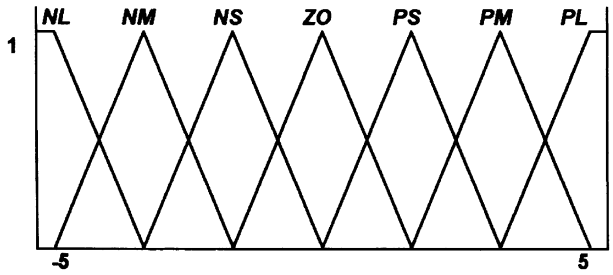


Fig. 3. Fuzzy Sets for t_{Di}.

4. TRAJECTORY CONTROL FOR THE ROBUST CONTROLLER WITH TORQUE SATURATION USING FUZZY LOGIC

As mentioned in the previous section, the robust controller guarantees bounded errors with huge control inputs. In other words, the robustness properties are guaranteed only if the control inputs do not saturate. However, the input torques for the underwater manipulators are limited, hence a way to compensate for the torque saturation should be found. To overcome this problem, a new control algorithm is devised: new trajectory planning based on fuzzy logic. A control algorithm generating new desired trajectories based on the initial desired trajectories is devised. The algorithm is fed into the robust control algorithm such that the manipulator is commanded to follow the new desired trajectories without input torque saturation.

The main idea of this algorithm is to control the tracking time by using fuzzy logic. If the tracking time of the desired trajectory increases, it will be easier to track the trajectory since the tracking velocity slows down. Then, tracking errors and their time derivatives will be reduced. As a result, the magnitude of the robust controller will be diminished. Also, by reducing the overall tracking time, we achieve fast tracking velocity. In this way, the arriving time to the target point can be reduced. This algorithm is implemented using conventional fuzzy logic.

The fuzzy control consists of a fuzzifier, a rule base, a fuzzy inference, and a defuzzifier.[19] In this paper, the torque input error between the saturation bound and the control input is defined as $T(k) = \tau_s - \tau(k)$, and its rate is defined as $\dot{T}(k) = (\tau(k) - \tau(k-1))/\Delta t$, where Δt is the sampling time. $T(k)$ and $\dot{T}(k)$ are inputs of the fuzzy controller. The new tracking time t_D depends on $T(k)$ and $\dot{T}(k)$. The control rules for t_D are given as

$$\text{if } T(k) \text{ is } A_i, \dot{T}(k) \text{ is } B_i, \text{ then } t_{Di} \text{ is } C_i, \; i = 1, 2, \ldots m$$

where A_i and B_i are any combinations of linguistic terms such as {NL, NM, NS, ZO, PS, PM, PL}. In the rules, N represents negative, P positive, ZO zero, S small, M medium and L large. LP means Large Positive, and MN Medium Negative, and so on. C_i is combinations of seven control inputs. The control rules have 'or' operations for

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Table I. Fuzzy Rule.

$\Delta T/T$	ZO	PS	PM	PL
NL	ZO	NS	NM	NL
NS	PS	ZO	NS	NM
ZO	PM	PS	ZO	NS
PS	PL	PM	PS	ZO
PL	PL	PL	PM	PS

$i=1, 2, \ldots m$. The fuzzy sets for T, $\dot{T}$, and t_{Di} are shown in Figures 1, 2, and 3. Here, 20 fuzzy rules are employed, which are shown in Table I.

The membership functions of input variables are shown in Figure 1 where only the positive portion is applied for T. Using the membership functions, there are seven fuzzy control inputs in t_{Di}, which control the magnitude of the robust controller as

$$t_{Di}=\{\text{NL, NM, NS, ZO, PS, PM, PL}\}$$

Fuzzy inference is performed using the Max-Min inference rule. In the defuzzifier, the center of gravity method is used.

Two examples of the control strategy are as follows: if the input variables T_i becomes small and $\dot{T}_i$ large, then the desired tracking time is increased for the slow motion of the manipulator. In this way, the magnitude of the control inputs is reduced in order not to saturate. Also, if T_i becomes large and $\dot{T}_i$, small, then the desired operating time is reduced for fast trajectory tracking such that the torques are fully exploited. In this way, new desired trajectories based on the desired trajectory are generated such that the robot control input is regulated not to saturate. Since the proposed control algorithm strives to use more input torques, faster motion can be achieved. The fuzzy sets for T, $\dot{T}$, t_{Di} used in this paper are based on the author's experience. Better fuzzy algorithm can be found by an improved selection of fuzzy sets such that tracking time can be more reduced without exceeding the torque limit. The block diagram of the new robust controller structure employing new desired trajectories using fuzzy logic is shown in Figure 4.

5. NUMERICAL SIMULATION

For numerical simulation, the dynamics of a two-axis planar arm operated under the water, as shown in Figure 5, are expressed as

$$H^*(q)\ddot{q}+C^*(q,\dot{q})\dot{q}+D=\tau \tag{21}$$

where the friction term $F(q, \dot{q})$ is not considered. The matrix equation of (21) is expressed as

$$\begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}\begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{bmatrix}+\begin{bmatrix} -c\dot{q}_2 & -c(\dot{q}_1+\dot{q}_2) \\ c\dot{q}_1 & 0 \end{bmatrix}\begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix}+\begin{bmatrix} d_1 \\ d_2 \end{bmatrix}=\begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} \tag{22}$$

where

$$h_{11}=m_1^*L_{c1}^2+m_2^*(L_1^2+L_{c2}^2)+I_1^*+I_2^*+2m_2^*L_1L_{c2}\cos(q_2)$$

$$h_{12}=h_{21}=m_2^*L_{c2}^2+I_2^*+2m_2^*L_1L_{c2}\cos(q_2)$$

$$h_{22}=m_2^*L_{c2}^2+I_2^*$$

$$c=m_2^*L_1L_{c2}\sin(q_2)$$

$$d_1=\frac{1}{2}C_d\rho A_1 v_1|v_1|(L_{c1})-\frac{1}{2}C_d\rho A_2 v_2|v_2|(L_1+L_{c2})$$

$$d_2=-\frac{1}{2}C_d\rho A_2 v_2|v_2|(L_{c2})$$

In equation (22), $m_i^*=m_i+m_{iad}$, $I_i^*=I_i+I_{iad}$ for $i=1, 2$ where m_i and I_i are the measurable mass and moment of inertia, m_{iad} and I_{iad} are nonlinear and uncertain added mass and added moment of inertia. In the simulation, the mass and moment of inertia of the planar arm are assumed to be known, but not the added mass and added moment of inertia.

The numerical values used for the parameters of the two-link planar manipulator are shown in Table II.

The shape of the links is a circular cylinder. The inertias of the links are calculated based on $I_1=(1/12)m_1(3r_1^2+l_1^2)$ and $I_2=(l/12)m_2(r_2^2+l_2^2)$. The values of the added mass and added moment of inertia are assumed as

$$m_{ad1}=2(Kg), m_{ad2}=1.5\cos(q_2)(Kg),\ I_{ad1}=0.1(Kg-m^2),$$

$$I_{ad2}=0.04\cos(q_2)(Kg-m^2).$$

Since the projected areas of robot links vary according to the direction of movement of the links, they are assumed to be $b_1=1.17$, $b_2=0.34\cos(q_2)$. In this simulation, the currents and wave effects are neglected. The control gains for the computed torque scheme are set as

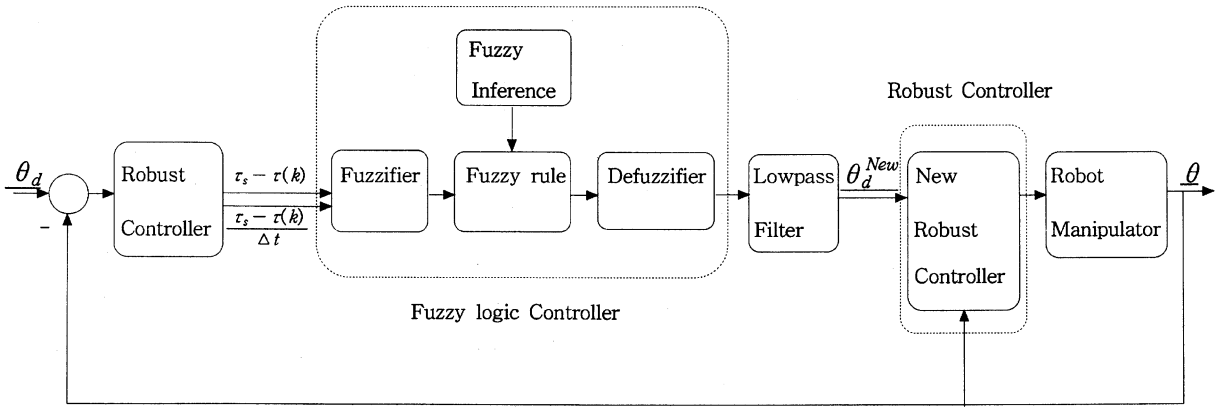


Fig. 4. The block diagram of the fuzzy robust controller structure.

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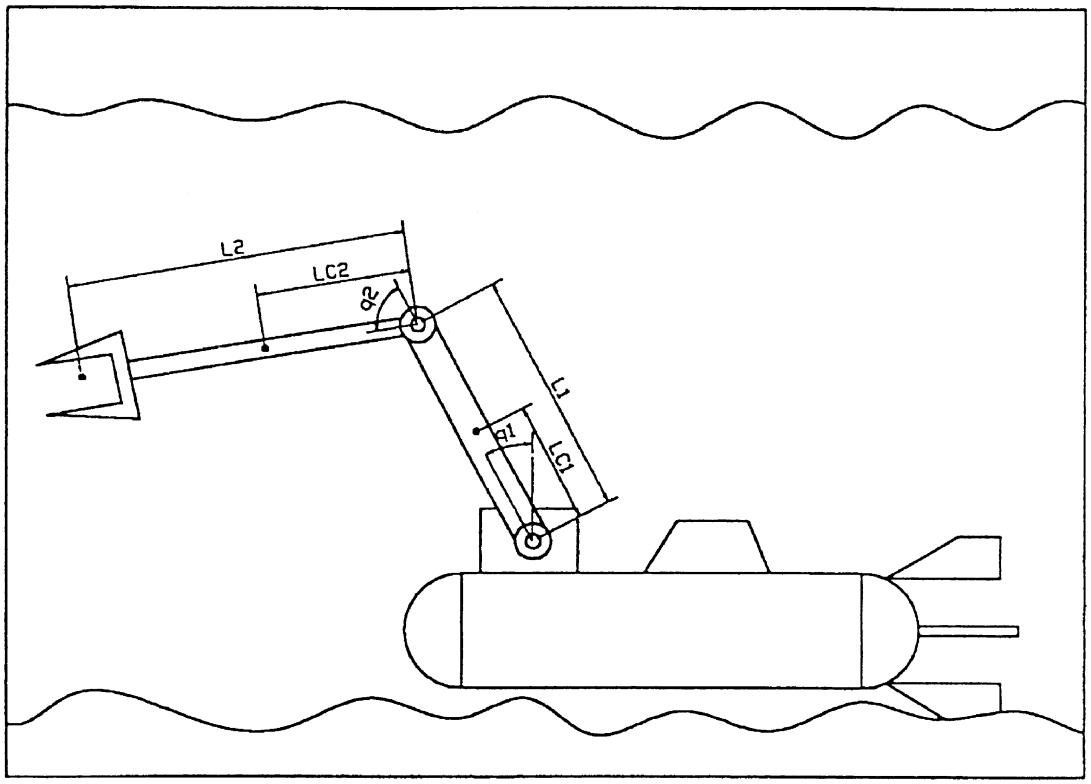


Fig. 5. A two-link planar arm operating under the water.

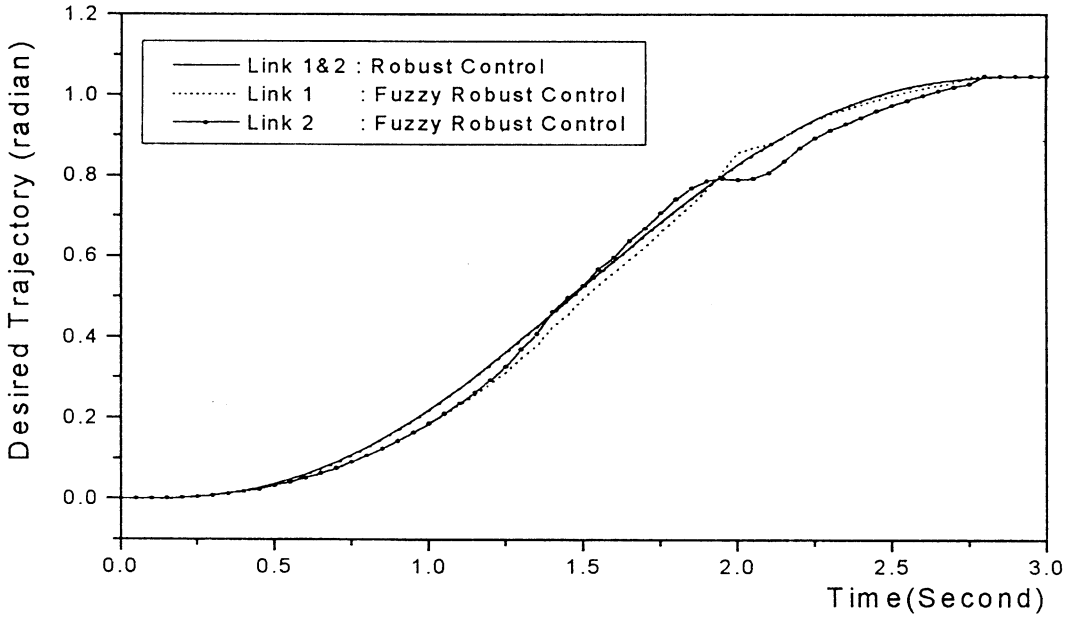


Fig. 6. Generation of New Desired Trajectories.

Table II. Link parameters for numerical simulation.

No. of Link	Mass m_1, m_2(Kg)	Moment of inertia I_1, I_2(Kgm^2)	Radius r_1, r_2(m)	Length L_1, L_2(m)	Centroid L_{c1}, L_{c2}(m)
Link 1	8	0.172	0.05	0.5	0.25
Link 2	5	0 067	0.03	0.4	0.2

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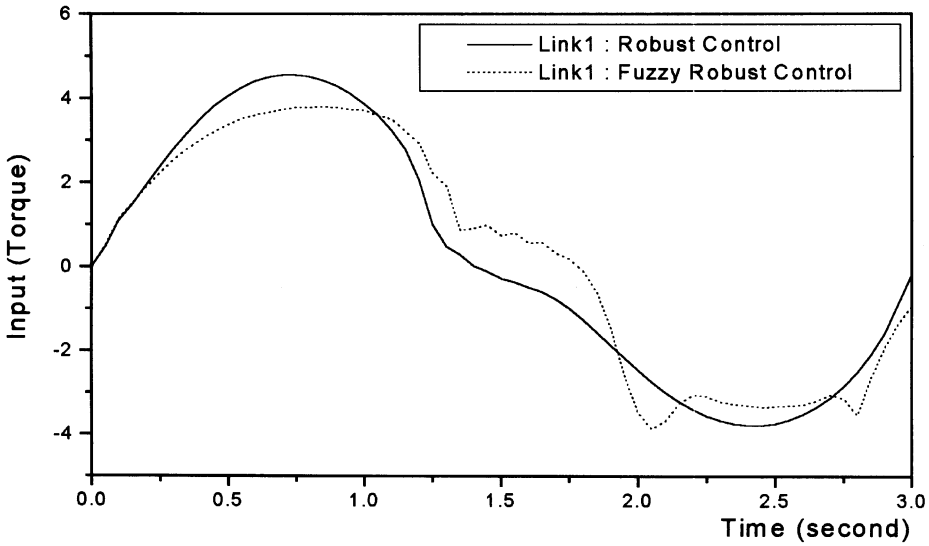


Fig. 7. Comparison of Torque Inputs for Link 1.

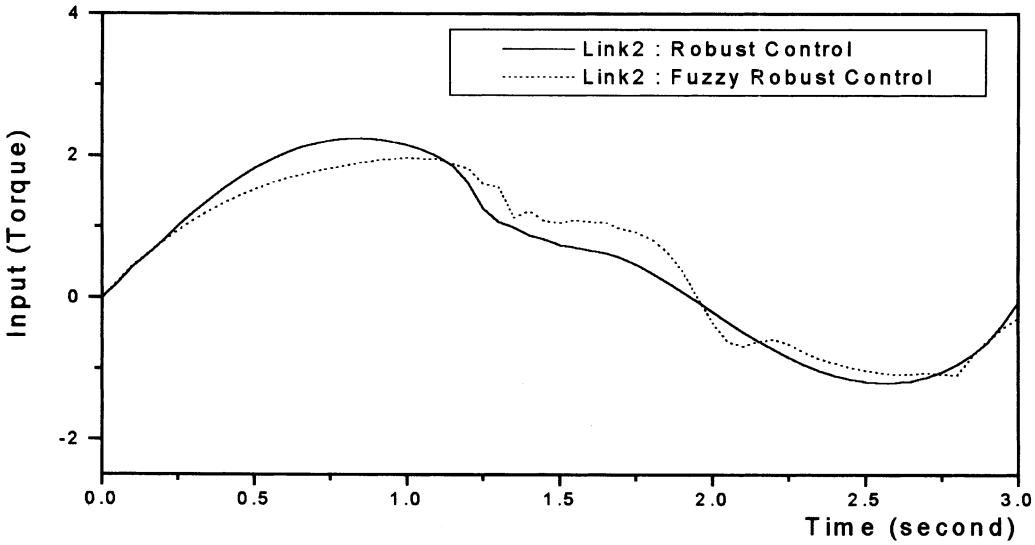


Fig. 8. Comparison of Torque Inputs for Link 2.

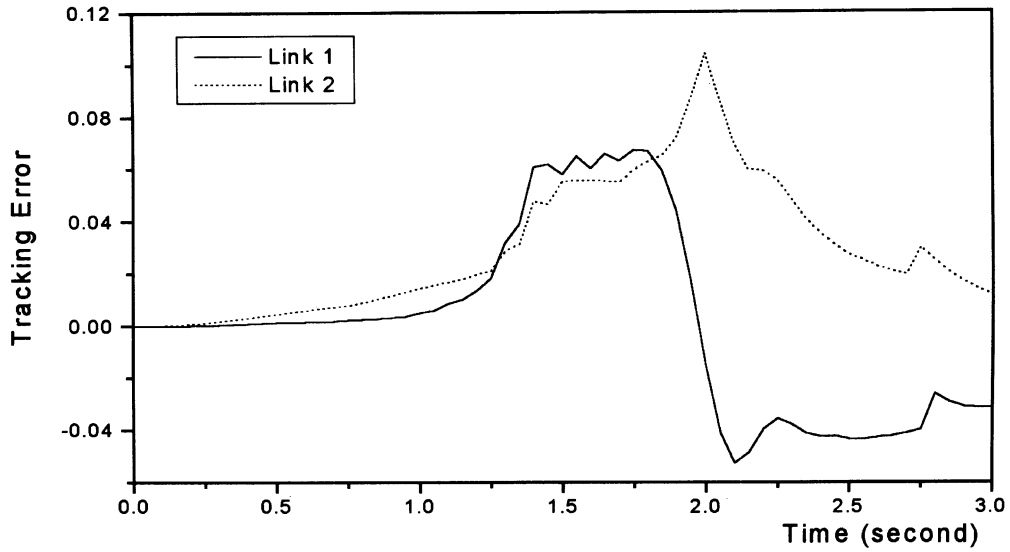


Fig. 9. Trajectory Tracking Errors.

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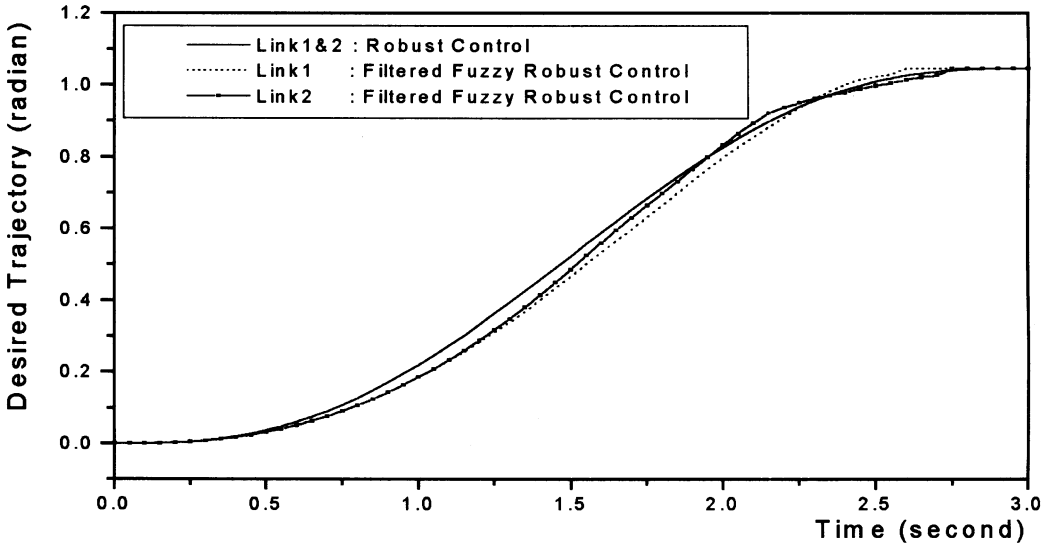


Fig. 10. Generation of New Trajectories.

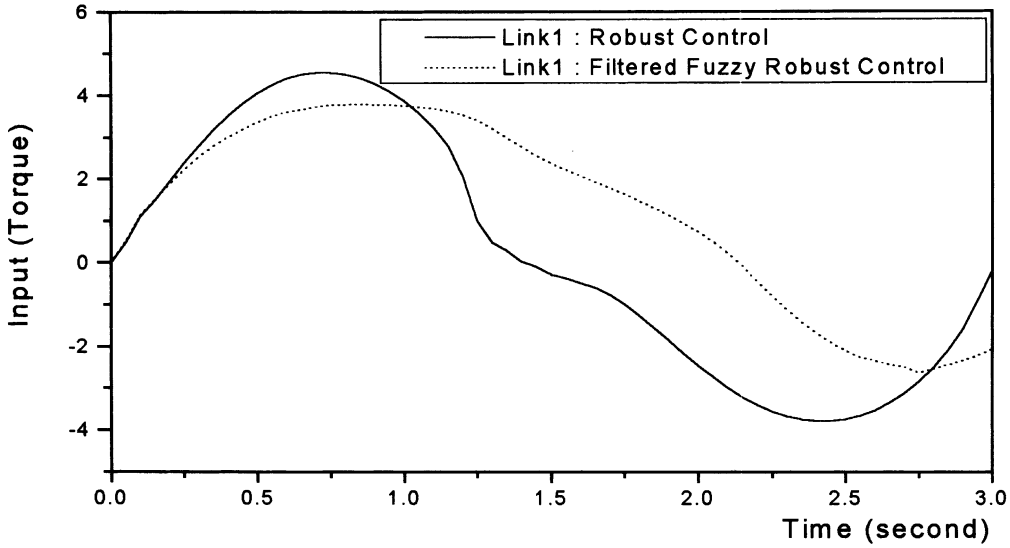


Fig. 11. Comparison of Torque Inputs for Link 1.

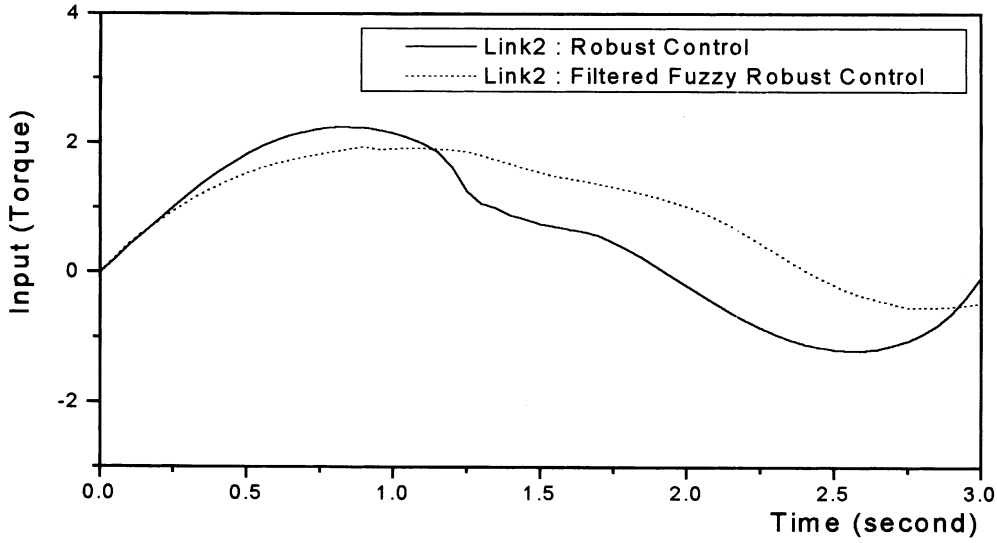


Fig. 12. Comparison of Torque Inputs for Link 2.

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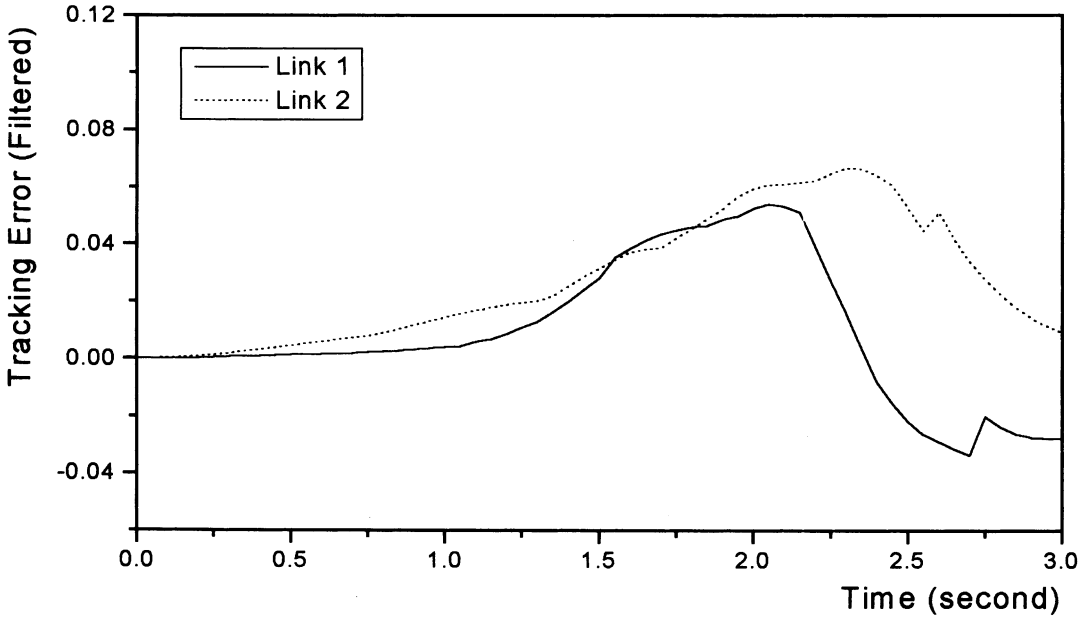


Fig. 13. Trajectory Tracking Errors.

$$k_v=\begin{bmatrix}25 & 0\\ 0 & 25\end{bmatrix},\quad k_p=\begin{bmatrix}10 & 0\\ 0 & 10\end{bmatrix}$$

A 4×4 identity matrix for Q is used such that P matrix is decided by solving equation (19). ε for the robust controller is chosen as 10^{-3}. The starting and arriving point of the desired trajectories of the link 1 and 2 are [0, π/3] and [0, π/3], where the desired trajectories are composed of the 5th order polynomial. The velocities and accelerations are obtained by differentiating the trajectory function once and twice with respect to time, respectively. The initial desired trajectory tracking is performed for 3 seconds. The fuzzy logic for the robust controller introduced in section 4 is applied. The inputs for the fuzzy algorithm are $T(k)=\tau_s-\tau(k)$ and its time derivative $\dot{T}(k)$ where τ_s are assumed to be 3.8 and 1.8 for the 1st and 2nd links, respectively.

Substituting all the numerical values for the parameter, and control gains into Equation (6) and applying the controller to the two-axis underwater robot manipulator, one obtains the results shown in the Figures 6, 7, 8, and 9. Figure 6 shows the desired trajectory and new generated desired trajectories for robot manipulators. The solid line represents the initial desired trajectory, and the dotted and dot on solid lines represent new desired trajectories generated by the fuzzy algorithm. The new trajectories are near to the initial desired one since they are modified from the initial one. In Figure 6, the initial trajectory was designed to arrive at the target point in 3 seconds, but, the new trajectories are generated to hit the target in around 2.7 seconds. This indicates that the fuzzy algorithm can shorten the traveling time by controlling input torques. Figures 7 and 8 represent the input torques of the robust controller and fuzzy robust controller for the link 1 and link 2, respectively. In Figures 7 and 8, the torque saturation bounds were assumed to be ±3.8 and ±1.8, respectively. According to Figures 7 and 8, the calculated input torques of the robust controller exceed the saturation bounds, but those of the fuzzy robust controller stay within the torque saturation bounds. In addition to this, actions striving to apply more torques are shown without exceeding the torque bounds. By this action, the torques of robot manipulators are fully exploited to expedite trajectory tracking. Figure 9 shows the tracking errors along the new trajectories when the fuzzy robust controller is applied. The solid and dotted line represent the errors of the 1st and 2nd links, respectively.

The output of the fuzzy control algorithm causes chattering. As shown in Figure 5, the new desired trajectories based on the fuzzy algorithm contain high frequcncy chattering modes. To get rid of these, the 5-point moving average which is a simple low pass filter was applied to filter out the high frequency of the fuzzy algorithm outputs, t_{Di}. Related simulation results are shown in Figures 9 through 12. The simulation was performed in the same condition as in Figures 6 through 9. As shown in Figure 10, new smooth desired trajectories were generated by the filtering algorithm. Also, in Figures 11 and 12, related input torques of the fuzzy robust controller are shown. In Figure 13, tracking error results are shown. The filtering action yields smooth trajectories easy to follow so that it reduces tracking errors.

According to the simulation results, the fuzzy robust controller shows two improvements: one is that it prevents the exceeding of the torque saturation bounds by a software approach, which implies that the stability of the proposed robust controller is guaranteed; the other is that it can reduce the tracking time of robot manipulators. In addition to these, the moving average filter helps to yield improved trajectory generation and tracking error reduction.

6. CONCLUSION

The robust controller for the highly nonlinear and uncertain robot manipulators may require infinite input torques such

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that it may face torque saturation. In this case, the stability of the robust controller cannot be guaranteed. To solve this problem, a new robust controller, which does not saturate, was devised by using an algorithm based on fuzzy logic. By this algorithrm, a new desired trajectory close to the initial one is generated. The devised control algorithm was applied to the underwater robot manipulator with highly uncertain parameters, such as the added mass, added moment of inertia, drag, and frictional forces. According to the simulation results, the proposed robust controller expedites trajectory tracking of the underwater robot manipulator within torque limits. Also, to reduce chattering of the fuzzy algorithm outputs, a simple low pass filter was applied, which resulted in an improvement of trajectory tracking.

References

1. J.J.E. Slotine and S.S. Sastry, "Tracking Control of Nonlinear Systems Using Sliding Surfaces With Applications to Robot Manipulators" *Int. J. Control*, **39**(2), 465–492 (1983).
2. J.J.E. Slotine, "Sliding Controller Design for Nonlinear Systems" *Int. J. Control*, **40**(2), 421–434, (1984).
3. S. Gutman, "Uncertain. Dynamical Systems – A Lyapunov min-max approach" *IEEE Trans. Aut. Contr*, **AC-24**, 437–443 (Mar., 1979).
4. M. Corless and G. Leitmann, "Continuous State Feedback Guaranteeing Uniform Ultimate Boundedness for Uncertain Dynamic Systems" *J. Automatic Controls*, **AC-26**, 1139–1143 (1979).
5. D.M. Dawson, F.L. Lewis and J.F. Dorsey, "Robust Force Control of a Robot Manipulator" *Int. J. Robotics Research*, **11**, 312–319 (1992).
6. L. Cai and A.A. Goldenberg, "Robust Control of Unconstrained Maneuver and Collision for a Robot Manipulator with Bounded Parameter Uncertainty" *Proc. IEEE Int. Conf. on Robotics and Automation*, 1010–1015 (1988).
7. K.J. Astrom and B. Wittenmark, *Computer Controlled System – theory and design*, 2nd ed. (Prentice Hall, 1990).
8. J.H. Kim and Z. Bien, "Robust Stability of Uncertain Linear Systems with Saturating Actuators" *IEEE Trans. Automat. Contr.*, **39**(1) 202–207 (1994).
9. P.O. Gutman and S. Gutman, "A Note on the Control of Uncertain Linear Dynamical Systems with Constrained Control Inputs" *IEEE Trans. Automat. Contr.*, **30**, 484–486 (1985).
10. N.J. Krikelis and S.K. Barkas, "Design of Tracking Systems subject to Actuator Saturation and Integrator Wind-up" *Int. J. Contr.*, **39**(4), 667–682 (1984).
11. J.J.E. Slotine and M.W. Spong, "Robust Robot Control with Bounded Input Torques" *J. Robotic Systems*, **2**(4), 329–352 (1985).
12. M.W. Spong, J.S. Thorp and J.M. Kleinwas, "The Control of Robot Manipulators with Bounded Input" *IEEE Trans. on Automatic Contr.*, **31**(6), 483–490 (1986).
13. W. Kaewprom and K. Ohishi, "Robust Manipulator Control Considering Saturation of Joint Torque and Joint Servo System" *2nd Asian Control Conference*, 617–620. (1977)
14. B. Levesque and M. J. Richard, "Dynamic Analysis of a Manipulator in a Fluid Environment" *Int. J. Robotic Research*, **13**(3), 221–231 (1994).
15. H.S. Choi, "Modeling of robot manipulators working under the sea and the design of a robust controller" *Robotica*, **14**, 213–218 (1996).
16. V.F. Filaretov and E.V. Koval "Autonomous Stabilization of Underwater Robots in the Time Manipulation Operations" *Proc. Int. O.P.E.C., Osaks, Japan*, 382–388 (1994).
17. Inge Spangelo and Olav Egeland, "Generation of energy-optimal trajectories for an autonomous underwater vehicle" *IEEE Int. Conf. Robotics and Automation*, 2107–2112 (1992).
18. J. Yuh, *Underwater Robotic Vehicles: Design and Control*, (TSI Press, 1995).
19. E.H. Mamdani and S. Appilian, "An Experiment in Linguistic Synthesis with a Fuzzy Logic Controller" *Int. J. Man-Machine Stud.*, **7**, 1–13 (1975).

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