Application of Adaptive Disturbance Observer Control to an Underwater Manipulator

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Abstract
Hydrodynamics of the manipulator mounted on the vehicle are poorly known and time-varying. Furthermore, its motion is disturbed by the vehicle motion and current. This paper presents a non-regressor based adaptive control scheme with a disturbance observer for tracking the trajectory of underwater mobile platform-mounted manipulators. The presented control system does not require any information about the system. The disturbance observer regards the difference between the actual output and the output of the nominal model as an equivalent disturbance applied to the nominal model. The adaptive control law then estimates control gains defined by the combinations of the bounded constants of parameter matrices of the nominal model with disturbance error. The performance of the proposed control scheme was evaluated by a computer simulation with a two-link planar manipulator mounted on a one degree-of-freedom mobile platform. The effect of hydrodynamic forces acting on the manipulator was also considered.

1. Introduction
The manipulator control for high performance in terms of speed and accuracy is a challenging task mainly because manipulator dynamics are time-varying and nonlinear. Underwater manipulators mounted on underwater vehicles are subject to hydrodynamic uncertainties such as currents and disturbances due to the motion of the vehicle.

While dynamics and control of dry manipulators have been studied by many researchers and significant progress has been made [1-4], there are very few papers in literature [5-7], dealing with underwater manipulators and limited research progress has been made.

One effective way to deal with parameter uncertainties of the manipulator system is the use of adaptive control methods [8]. Many researchers proposed the regressor-based adaptive control approach with parameter estimation methods for unknown or time-varying system parameters [1,2,5,8,9,10]. However, the regressor-based approach usually requires large computations as the number of system parameters for estimation increases. It also assumes that the order of the dynamic model is known. Reed and Ioannou [10] showed that regressor-based adaptive controllers, relying heavily on knowledge of the dynamic system, often have degrading performances when sensor noise or other disturbances are present due to their lack of robustness.

Recently, there have been some studies to design adaptive non-regressor based adaptive control techniques for robot manipulators, addressing crucial issues with regressor-based schemes as mentioned above. One approach is to use the bound estimation method that estimates the bounds of the parameter matrices of the robot dynamic system or their combinations, and then use their estimates to adjust control gains. Among them are Choi and Yuh [11], Tarokh [12], and Song [13]. Choi and Yuh [11] used four bound combinations of system parameter matrices or disturbance terms as the new parameters for estimation. Their estimates were used to adjust the control gains. They used the Lyapunov method for stability analysis of their control system and presented experimental results for depth control of an underwater robot. Tarokh [12] proposed a decentralized adaptive controller using estimates of six parameters for each joint. These six parameters were from bounds of system parameter matrices or disturbance terms. He used the norms of the known desired joint velocity and acceleration as part of the control gains. He also used the Lyapunov method for stability analysis. Results of computer simulation with the Puma 560 robot were presented. Song [13] proposed an adaptive controller using a shape function and an estimate of one parameter that is a maximum value of bounds of all parameter matrices. His adaptive controller was based on the PD control structure for each joint. The Lyapunov method was also used for stability analysis and results of the computer simulation with the GE -P50 robot were presented. These three approaches (refs. 11, 12 and 13) discussed above were independently developed and proposed almost at the same time.

One effective approach for handling disturbance in motion control is the disturbance observer [14]. The disturbance observer regards the difference between the actual output and the output of the nominal model as an equivalent disturbance applied to the nominal model. The equivalent disturbance can be removed by the disturbance observer, and then an asymptotically stable feedback control loop can
be constructed around the nominal model. However, the disturbance observer may not be realized without introducing a low-pass filter that affects the overall performance. It is not an easy task to optimize the low-pass filter for the required performance [15]. Therefore, applying DOB with a low-pass filter to the plant results in a nominal model with disturbance error.

This paper is an extension of the adaptive control system developed by Yuh [16] and experimentally tested for an underwater robot by Choi and Yuh [11]. The disturbance observer is used to simplify the nonlinear underwater manipulator system with uncertainties into a simple model with disturbance error. Using this simple model, the adaptive control system is designed. By introducing the disturbance observer, the adaptive controller becomes much simpler than the previous ones [11, 16, 17]. At the same time, the adaptive controller adapts to any changes in performance due to disturbance error resulted from a low-pass filter in the observer and provides better performance than other linear control approaches with the disturbance observer.

The proposed controller has a very simple structure and is computationally efficient. The only information required to implement this scheme is the number of joints and actuator inputs of the system. The adaptive control law estimates parameters defined by combinations of bounded constants of the parameter matrices of the nominal model with disturbance error, instead of each unknown parameter of the actual system model. No computation for updating the robot dynamic model is needed. Therefore, it is easy to implement the control scheme to a class of dynamic systems. The tracking errors can asymptotically converge to zero by the Lyapunov method, without requiring high gain values or assuming that the dynamic system is slowly time varying. Effectiveness of the presented control system was investigated by computer simulation with a 2 d.o.f manipulator system whose output is \( q \) and \( \dot{q} \).

If \( Q \) is an identity matrix, from equations (1-3), the system inside the dotted line becomes the nominal model:

\[
q = s^{-1} P_n u^* \quad (4)
\]

However, the disturbance observer cannot be implemented with \( Q=I \) since \( P_n^{-1} \) is not realizable by itself. Therefore, the relative degree of \( Q \) must be equal or greater than that of \( P_n \).

For \( Q \neq I \), the filtered estimate can be expressed by

\[
\hat{d} = \hat{d} + \Delta \hat{d} \quad (5)
\]

where \( \Delta \hat{d} \) is the difference between \( \hat{d} \) and \( \hat{d} \), due to a time delay of the low-pass filter.

Therefore, from equations (1, 3, and 5),

\[
q = s^{-1} P_n (u^* + \Delta \hat{d}) \quad (6)
\]

The n-joint robot manipulator mounted on a mobile platform having a translation motion can be described by the following vector equation:

\[
M(q) \ddot{q} + C(q, \dot{q}) \dot{q} + G + u_d = u \quad (7)
\]

where \( q \) is the joint angle vector, \( u \) is the \( n \times 1 \) input torque vector, \( M(q) \) is the \( n \times n \) inertia matrix including added mass effect, \( C(q, \dot{q}) \) is the \( n \times n \) matrix representing centrifugal and Coriolis terms as well as drag terms, \( G \) is the \( n \times 1 \) vector of gravity and buoyancy terms, \( u_d \) includes effects of un-modeled hydrodynamics as well as disturbances due to the current and base motion.

If one chooses \( P_n^{-1} = sM_n \) in Eq. (6), where \( M_n \) is a constant diagonal matrix, the dotted block in Fig. 1 can be represented by the following simple model:

\[
M_n \ddot{q} + h = u^* \quad (8)
\]

where \( h = -\Delta \hat{d} \)


diagram

2. Controller Design

![Diagram of controller design](image)

Figure 1 shows the overall control system that has the inner loop compensator of the disturbance observer inside the dotted line and has the outer loop of the adaptive controller. The system with the disturbance observer inside the dotted box becomes a simple nominal model with disturbance error, which is controlled by the adaptive controller.

A. Disturbance Observer

As shown in Fig. 1, the control input \( u \) is computed by

\[
u = u^* + \hat{d} \quad (1)
\]

where \( u^* \) is the output of an adaptive controller and \( \hat{d} \) is the filtered estimate of \( d \):

\[
\hat{d} = Q \hat{d} \quad (2)
\]

where \( Q \) is a low-pass filter, and \( \hat{d} \) is the estimate is the sum of the external disturbance \( d \) and the modeling error:

\[
\hat{d} = u - sP_n^{-1} q \quad (3)
\]

where \( P_n \) represents a nominal model of the underwater manipulator system whose output is \( q \) and \( \dot{q} \).

The n-joint robot manipulator mounted on a mobile platform having a translation motion can be described by the following vector equation:

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M(q) \ddot{q} + C(q, \dot{q}) \dot{q} + G + u_d = u \quad (7)
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where \( q \) is the joint angle vector, \( u \) is the \( n \times 1 \) input torque vector, \( M(q) \) is the \( n \times n \) inertia matrix including added mass effect, \( C(q, \dot{q}) \) is the \( n \times n \) matrix representing centrifugal and Coriolis terms as well as drag terms, \( G \) is the \( n \times 1 \) vector of gravity and buoyancy terms, \( u_d \) includes effects of un-modeled hydrodynamics as well as disturbances due to the current and base motion.

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\]

where \( h = -\Delta \hat{d} \)
B. Adaptive Controller
We now design an adaptive controller for the nominal model of equation (8) with the tracking error vector $e$ defined as
\[ e = q_d - q \]  
(9)
where $q_d$ is a desired value of $q$.

The parameter matrices of the nominal model are assumed to be bounded as
\[ \| M_n^{-1} \| \leq \alpha, \quad \| h \| \leq \beta_f / \kappa, \quad \lambda_{\min}(M^{-1}) \geq \gamma \]  
(10)
where $\| \cdot \|$ represents Euclidean norm, and $\alpha, \beta_f, \kappa$ and $\gamma$ are positive constants.

Instead of mathematically proving (10), we will present how to estimate new parameters defined by
\[ \theta_i = \frac{\alpha \beta_f}{\gamma} i = 1, 2, 3 \]  
(11)
where $\beta_2 = \beta_3 = \eta / \alpha$ and $\eta$ is a constant $\geq 1$.

Consider the following control law
\[ u^i = K_0 \bar{q}_d + K_1 \kappa + K_2 \bar{e} + K_3 e = \sum_{i=0}^{3} K_i \Phi_i \]  
(12)
where $\Phi_0 = \bar{q}_d$, $\Phi_1 = \kappa$, $\Phi_2 = \bar{e}$, $\Phi_3 = e$, and $K_i$ are control gain matrices with $K_0 = M_n$.

From equations (8) and (12), the error equation can be obtained as follows:
\[ \dot{e} = M_n^{-1} \{ (h / \kappa - K_i) \kappa - K_2 \bar{e} - K_3 e \} 
= M_n^{-1} \sum_{i=0}^{3} (P_i - K_i) \Phi_i \]  
(13)
where $P_1 = h / \kappa$, $P_2 = P_3 = 0$.

**Theorem**: The tracking error $e$ asymptotically converges to zero and the estimate of the parameters converge to a certain bounds with the following adaptive controller:
\[ K_i = \frac{\dot{\theta} \bar{e} \Phi_i^T}{\| \bar{e} \| \| \Phi_i \|}, \quad i = 1, 2, 3 \]  
(14)
\[ \dot{\theta}_i = f_i \| \bar{e} \| \| \Phi_i \| \]  
(15)
where $f_i$ are positive constants, $\dot{\theta}_i$ are estimates of $\theta_i$'s, and
\[ \bar{e} = \dot{e} + \sigma e \]  
(16)
where $\sigma$ is a positive constant satisfying $\sigma \leq \eta$.

**Proof**: Consider the following Lyapunov function candidate:
\[ V = \frac{1}{2} \bar{e}^T \bar{e} + \frac{1}{2} e^T e + \frac{1}{2} \sum_{i=0}^{3} f_i^{-1} \gamma (\theta_i - \dot{\theta}_i)^2 \]  
(17)
Differentiating equation (17) along equation (13) with respect to time yields
\[ V = \bar{e}^T \dot{e} + \sigma \bar{e}^T \bar{e} + e^T \dot{e} - \sum_{i=0}^{3} f_i^{-1} \gamma (\theta_i - \dot{\theta}_i)^2 \]
\[ = \left[ \bar{e}^T (M_n^{-1} \sum_{i=1}^{3} P_i \Phi_i) + \sigma \bar{e}^T \bar{e} + e^T \dot{e} - \sigma e^T e \right. \]
\[ - \sum_{i=0}^{3} f_i^{-1} \gamma \theta_i \dot{\theta}_i + \left. \left[ -\bar{e}^T M_n^{-1} \sum_{i=1}^{3} K_i \Phi_i + \sum_{i=0}^{3} f_i^{-1} \gamma \theta_i \dot{\theta}_i \right] \right] \]  
(18)
With the adaptive controller (14), (15) and $\sigma \leq \eta$, the equation in the first bracket of (18) becomes
\[ \bar{e}^T (M_n^{-1} \sum_{i=1}^{3} P_i \Phi_i) + \sigma \bar{e}^T \bar{e} + e^T \dot{e} - \sum_{i=0}^{3} f_i^{-1} \gamma \theta_i \dot{\theta}_i \]
\[ = \bar{e}^T M_n^{-1} \sum_{i=1}^{3} P_i \Phi_i - \alpha F \| \Phi_i \| + \sigma \bar{e}^T \bar{e} - \eta (\| F \| + \| \bar{e} \|) \]
\[ + e^T \dot{e} - \sigma e^T e \]
\[ \leq (\| M_n^{-1} \| \| P_i \| - \alpha \| F \| \| \Phi_i \| + (\sigma - \eta) (\| F \| + (\eta - 1) (\| \bar{e} \| \| \Phi_i \| - \sigma e^T e \]
\[ \leq -\sigma e^T e \]  
(19)
and the equation in the second bracket becomes
\[ -\bar{e}^T M_n^{-1} \sum_{i=1}^{3} K_i \Phi_i + \sum_{i=0}^{3} f_i^{-1} \gamma \theta_i \dot{\theta}_i \]
\[ = \sum_{i=1}^{3} \bar{e}^T M_n^{-1} \sum_{i=0}^{3} f_i^{-1} \gamma \theta_i \dot{\theta}_i \]
\[ \leq \sum_{i=1}^{3} (\lambda_{\min}(M_n^{-1}) + \gamma) \| \bar{e} \| \| \Phi_i \| \| \dot{\theta}_i \| \]
\[ \leq 0 \]  
(20)
From (18), (19), and (20), $\dot{V}$ is reduced to
\[ \dot{V} \leq -\sigma e^T e \]  
(21)
which is negative for all $e \neq 0$. Therefore, the tracking error will asymptotically go to zero.

It is noted that the direct use of the controller of (14) would generate large control input signals and extreme chattering phenomena at near zero value of denominator. To avoid this problem, the following controller is used instead of equation (14):
\[ K_i = \frac{\dot{\theta} \bar{e} \Phi_i^T}{\| \bar{e} \| \| \Phi_i \|} \text{ for } \| \bar{e} \| \| \Phi_i \| > \delta_i \]  
\[ \frac{\dot{\theta} \bar{e} \Phi_i^T}{\delta_i} \text{ for } \| \bar{e} \| \| \Phi_i \| \leq \delta_i \]  
(22)
where $i = 1, 2, 3$ and $\delta_i$ is a positive constant. The control gain described by equation (22) may not guarantee the asymptotic stability but tracking errors are bounded by small numbers depending on $\delta_i$. 
3. Case Study

The performance of the proposed adaptive disturbance observer controller was compared with that of a PD disturbance observer controller by computer simulation with a two-link planar, underwater manipulator vertically mounted on a mobile platform having a horizontal motion. The PD disturbance observer controller has the same disturbance observer but uses a PD controller instead of the adaptive controller as shown in Figure 1. For simplicity, the link mass is treated as a point mass at the distal end of each link; added inertia forces are estimated; and drag forces are calculated along the link with constant hydrodynamic coefficients. It is assumed that the center of gravity of each link coincides with its center of buoyancy, and the platform’s motion is measured by on-board sensors.

The resulting total drag is calculated by

$$\vec{F}_D = \int_0^1 1/2 \rho \nabla \cdot U^2 \, d\vec{c} \, dx$$

(23)

and the drag force induced torque \(u_D\) for each link is calculated as

$$u_D = \int_0^1 1/2 \rho \nabla \cdot U^2 \, d(\vec{r} \times \vec{c}) \, dx$$

(24)

where \(\nabla = \nabla_{D,basic} \sin^2 \alpha_d\) is the drag coefficient, \(\alpha_d\) is the angle between the current direction and the link’s longitudinal axis direction, \(U\) is the relative velocity of the link to the current, \(d\) is the diameter of the link, \(\vec{r}\) is the position vector of the element \(dx\) from the link’s origin and \(\vec{c}\) is the unit vector representing the direction of the resulting drag force on the link, which is perpendicular to the link’s axis and in the plane formed by \(\vec{r}\) and \(\vec{U}\).

Matrices of equation (7) for this manipulator are as follows:

$$M(q, \dot{q}) = \begin{bmatrix} l_2^2 m_{s2} + 2(1 - l_2^2 m_{s2} c_2 + l_2^2 (m_{a1} + m_{a2})) \, l_2^2 m_{s2} + l_1 l_2 m_{s2} c_2 \\ l_2^2 m_{s2} + l_1 l_2 m_{s2} c_2 \\ l_2^2 m_{a2} \end{bmatrix}$$

$$C(q, \dot{q}) = \begin{bmatrix} -m_{a2} l_2^2 s_2 \dot{q}_2 - m_{s2} l_2 s_2 (\dot{q}_1 + \dot{q}_2) \\ m_{s2} l_3 s_2 \dot{q}_1 \\ 0 \end{bmatrix}$$

$$G = \begin{bmatrix} (m_2 - \rho v_1) l_2 g c_{1z} + (m_1 + m_2 - \rho v_1 - \rho v_2) l_1 g c_{1z} \\ (m_2 - \rho v_2) l_2 g c_{1z} + (m_1 + m_2 - \rho v_1) l_1 g c_{1z} \end{bmatrix}$$

$$u_d = \begin{bmatrix} -l_{a2} (s_{a1} + m_{a2} (l_{a2} s_{a1} + l_{a2} s_{a2})) \vec{x}_0 + u_{d1} \\ -m_{a2} l_{a2} s_{a2} \vec{x}_0 + u_{d2} \end{bmatrix}$$

where \(q_i\) is the joint angular position of joint \(i\); \(l_i\) is the length of link \(i\); \(m_i\) is the point mass of link \(i\); \(m_{ai}\) is the total mass of link \(i\) including added mass; \(v_i\) is the volume of link \(i\); \(\vec{x}_0\) is the horizontal acceleration of the platform; \(\rho\) is the water density; \(g\) is the gravitational constant; \(u_{d2} = u_{D2} + u_{d1}\); \(u_{d1} = u_{d1} + u_{d2} + l_1 \times \vec{F}_{D2}\); \(c_i = \cos \theta_i\), \(s_i = \sin \theta_i\); \(c_{iy} = \cos(\theta_i + \theta_j)\) and \(s_{iy} = \sin(\theta_i + \theta_j)\).

During the simulation, the following numerical values were used: \(l_1 = 0.7m\), \(l_2 = 0.5m\), \(m_1 = 10kg\), \(m_2 = 5kg\), \(m_{a1} = 15.64kg\), \(m_{a2} = 9.03kg\), \(c_{D,basic} = 1.1\), and \(\rho = 1025 kg/m^3\). It is assumed that the links are cylindrically shaped and \(d = 0.1m\). In the adaptive disturbance observer control laws, Eqs. (1), (2), (3), (14), (15), (16) and (22), the following values were used: \(\kappa = 20\), \(f = [25 10 10]^T\), \(\sigma = 10\), \(M_n = 1\), and \(Q = g_1 / (s + g_1)\). Here \(g_1\) is the inverse of the time delay of the low-pass filter. \(\sigma\) affects the overall time constant of the system as seen in equation (16), while \(f_i\) affects the adaptation speed. \(\kappa\) could be any reasonable constant, comparable to other signals in size. \(\delta_i\) can be chosen depending on the size of the allowable errors and actuator performance such as chattering and saturation limits. The effects of these parameters were discussed in ref. 18.

During the simulation, the manipulator’s end effector was required to track the trajectory, \(x = 0.6\) and \(y = 0.5 + 0.2 \sin(2\pi / T)\) meters with \(T = 4\) seconds, while the vehicle moved horizontally \(x_0 = 0.4 \sin(2\pi / T_0)\), where \(T_0 = 8\) seconds. The sampling frequency was 500Hz. Figure 2 shows the desired planar motion of the manipulator mounted on the underwater vehicle every 0.5 seconds. PD control gains were tuned as \([1000 500]^{T}\) for each link and the initial estimates of parameters in the adaptive controller (Eq. 15) were arbitrarily chosen as \([10 1600 1600]^{T}\).

![Figure 2: Desired trajectory of the 2-link arm mounted on a horizontally moving platform used in simulation](image-url)

Effects of disturbance and the low-pass filter \(Q(s)\) on each control system were investigated with the following four cases:

- Case 1: no current and \(g_1 = 300\).
- Case 2: 0.3 m/s current in x direction and \(g_1 = 300\).
- Case 3: no current and \(g_1 = 30\).
- Case 4: 0.3 m/s current in x direction and \(g_1 = 30\).
4. Results
Figures 3.a.1, 3.a.2, 3.a.3, and 3.a.4 show results of the PD disturbance observer control system for four cases, respectively, while figures 3.b.1, 3.b.2, 3.b.3, and 3.b.4 show results of the adaptive disturbance observer control system for four cases, respectively. As shown in the following sets of figures: (3.a.1, 3.a.2), (3.a.3, 3.a.4), (3.b.1, 3.b.2), (3.b.3, 3.b.4), for the same value of $g_1$, there is no significant difference in performance of each control system between case 1 and case 2 and between case 3 and case 4 even though there is a difference in disturbance due to the current. These results show that the disturbance observer controller effectively minimizes the effect of disturbance. However, it is observed in figures (3.a.1 and 3.a.3) or (3.a.2 and 3.a.4) that the effect of different values of $g_1$ on the PD disturbance observer control system is significant. The linear PD controller cannot effectively handle the effect of different low-pass filters and the overall control performance varies depending on the low-pass filter. Unlike the PD controller, the adaptive controller effectively handles the effect of different low-pass filters and there are no significant changes in the overall control performance regardless of changes in the low-pass filter. In fact, the adaptive disturbance observer control system is robust with respect to disturbance and the low-pass filter except the initial adaptation period as shown in figures 3.b.1, 3.b.2, 3.b.3, and 3.b.4.

5. Conclusions
This paper presents a robust control scheme for underwater manipulators, which consists of a disturbance observer controller and a non-regressor based adaptive controller. It provides robustness with respect to disturbance and different low-pass filters. The presented control system, the adaptive disturbance observer control system is quite simple to implement as it does not require any information about the system. The disturbance observer controller, which is used as the inner loop controller, compensates for the difference between the actual output and the output of the nominal model, and thus makes the actual system act as a nominal system with disturbance error. The adaptive controller that is used as the outer loop controller estimates control gains defined by the combinations of the bounded constants of parameter matrices of the nominal model with disturbance error. It self-tunes its control gains to compensate for tracking errors due to disturbance error.

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References
Figure 3: Joint angular errors with (a) PD disturbance observer controller and (b) adaptive disturbance observer controller.