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Disturbance Observer-Based Robust Control for Underwater Robotic Systems with Passive Joints

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Abstract

Underwater exploration requires mobility and manipulation. Underwater robotic vehicles(URV) have been employed for mobility, and robot manipulators attached to the underwater vehicle(i.e., rover) play the role of manipulation. Usually, manipulation mode happens when the rover is stationary. URV is then modeled as a passive joint and the joints of the manipulator are modeled as active joints. URV motions are determined by inherent dynamic couplings between active and passive joints. Furthermore, the control problem becomes complex since there should be considered many hydrodynamic terms as well as intrinsic model uncertainties. To cope with these difficulties, we propose a disturbance observer-based robust control algorithm for underwater manipulators with passive joints. The proposed control algorithm is able to treat an underactuated system as a pseudo active system in which passive joints are eliminated. Also, to realize a robust control method, a nonlinear feedback disturbance observer is applied to each active joint. A four-jointed underwater robotic system with one passive joint is considered as an illustrative example. Through simulation, it is shown that the proposed control algorithm has good position tracking performances even in the presence of several external disturbances and model uncertainties.

1. Introduction

Underwater robotic vehicle (URV) has been used for various underwater tasks including inspection, drilling, mine countermeasures, survey, observation, underwater cable burial, and inspection of power plant conduits. Autonomous control of URV is required in such operations. For this, dynamics and modeling issue, control issue, and system integration issue have to be simultaneously taken into account. In some of underwater operations, usage of robot manipulators is effective. In this control mode, URV is inactive. Then, the whole system can be modeled as an underactuated system which has passive joints due to motions of URV and active joints in the manipulator. The motion of the passive joints is determined by inherent dynamic couplings between the active and passive joints. Another usage of passive arm can be found in positioning Remotely Operated underwater Vehicle(ROV) in which one end of the passive arm is attached to a underwater structure and the other end is connected to a ROV[11]. The joint trajectory information of the passive arm gives the position and orientation of ROV so that it is able to maneuver its desired trajectory.

The dynamic modeling and control problems of underactuated robots have been raised during the last decade[4][5]. It is well-known that an articulated underactuated manipulator with passive joints satisfies a second-order nonholonomic constraint which forms a nonintegrable constraint on acceleration level[4][5]. Using this constraint, the dynamic equation of underactuated robot can be derived with respect to actuated joint variables[9]. Control of underwater robot with passive joints might be difficult due to several disturbances during undersea operations. Besides intrinsic model uncertainties, ROV dynamics are affected by hydrodynamic forces. Therefore, the computation of hydrodynamic forces must be accomplished first. These forces result from incompressible fluid flow determined by the Navier-Stokes (distributed fluid-flow) equations. It is here assumed that it can be represented as a sum of separately identified components for which "lumped" approximations have been used. Using these assumptions, the most significant hydrodynamic forces such as added mass, viscous drag force, buoyancy force, and force due to fluid acceleration have been identified in [1]-[3].

To deal with such systems with passive joints as well as uncertainty of dynamic model, and several external disturbances, the controller should have a robustness to achieve the desired objective. Recently, a simple robust control approach called disturbance observer was proposed by Kaneko, et.al.[6]. It does not require heavy computation or knowledge on disturbance. The disturbance observer regards the difference between the actual output and the output of nominal model as an equivalent disturbance applied to the nominal model. The disturbance observer-based robust control algorithm has been reported to compensate for modeling uncertainties as well as external disturbance[6][7][8].

In this paper, we propose a disturbance observer-based robust control algorithm and its associated dynamic model for underwater robotic vehicles. A planar four-jointed underwater robot is considered as an illustrative example. Simulation results show that the proposed control method is effective in control of general classes of underactuated robotic systems including underwater robotic vehicles in the presence of model uncertainty and several external disturbances.

2. Underwater Robot Dynamics

Generally, the dynamic equation of motion of an n-DOF manipulator can be described as

$$\tau = [I^*_{\phi\phi}]\ddot{\phi} + \dot{\phi}^T[P^*_{\phi\phi\phi}]\dot{\phi} + \tau_G, \quad (1)$$

where $[I^*_{\phi\phi}]$ is the $n \times n$ effective inertia matrix, and $[P^*_{\phi\phi\phi}]$ is the $n \times n \times n$ effective inertia power array. $\tau \equiv [\tau_1 \cdots \tau_n]^T$ represents the $n \times 1$ torque vector applied to the joint of robot manipulator. ϕ, $\dot{\phi}$ and $\ddot{\phi}$ are the $n \times 1$ vectors representing the manipulator's joint position, velocity, and acceleration, respectively. τ_G denotes the $n \times 1$ gravity torque vector. Now, the robot dynamics of Eq.(1) can be rewritten as an underwater robot dynamics in which hydrodynamic effects are added

$$\tau = [I^*_{\phi\phi}]\ddot{\phi} + \dot{\phi}^T[P^*_{\phi\phi\phi}]\dot{\phi} + \tau_G + \tau_D + \tau_B + \tau_A \quad (2)$$

where, τ_D, τ_B and τ_A represent $n \times 1$ torque vectors denoting drag force, buoyancy and fluid acceleration, and added mass, respectively.

2.1 Total Buoyancy

The buoyancy and fluid acceleration forces are described together in this section because of their similarity. Both are translational forces as illustrated in Fig.1. They are exerted through the center of buoyancy which is the center of volume of the body or equivalently the center of mass of the fluid that is displaced by the body. They are proportional to the mass of the fluid that is displaced by the body, m_f. The buoyant force, f_b is exerted on the body in the opposite direction with respect to gravity. This force results from Archimedes principle which states that a body immersed in a fluid is buoyed up with a force equal to the weight of the fluid displaced by the body. This force is specified as

$$f_b = -m_f\, a_g, \quad (3)$$

where a_g is the gravitational acceleration expressed in the link coordinate system.
A similar equation was given by Newman[1] for the fluid acceleration force, f_f, which is given by

$$f_f = m_f\, a_f, \quad (4)$$

where a_f is the acceleration of the fluid expressed in the link coordinate system. This force is exerted in the direction of the fluid acceleration and often referred to as the horizontal buoyancy force[2][3]. Both forces are combined as

$$f_B = m_f(a_f - a_g), \quad (5)$$

where f_B is called the total buoyance force. The moment resulted from f_B, is computed as

$$\tau_B = c \times f_B, \quad (6)$$

where c is the vector from the link-fixed coordinate system to its center of buoyancy.

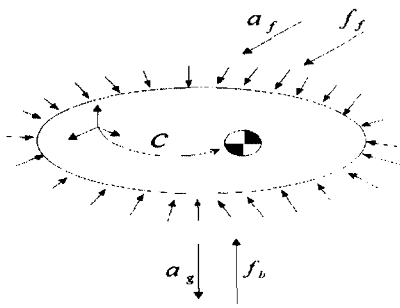

Fig. 1 Buoyancy and Fluid Acceleration

2.2 Drag Force

When an object moves through viscous fluid, drag forces are exerted on it. This force is a function of the velocity of the link relative to the fluid. Drag is a friction-like force that is in-line with the relative velocity of the body, opposite in direction, and related by the drag coefficient, C_D[2][3]. More generally, drag force is distributed over the surface of the body which can be decomposed into pressure drag which is normal to the surface of the body, and shear drag which is the tangential component[2][3]. For underwater manipulators, shear drag forces are much smaller than pressure drag forces so that the drag force is modeled with only the pressure drag, without shear drag. Pressure drag arises from non-zero normal components of relative velocity between the link's surface and the fluid. For a general body, a surface integral over the entire body is required to compute the resultant force and moment. To avoid this integration, links are approximated as cylinders shown in Fig.2, and the resulting procedure to compute a drag force is based on Sarpkaya and Isaacson [10]. With cylinders, strip theory is utilized to replace the surface integral with a line integral along the length of the cylinder[2][3]. Therefore, the cylinder is partitioned into circular disk elements with width dx, and translational velocity relative to the fluid and normal to the edge of each disk, v^n, must be determined. The translational velocity of a disk relative to the fluid at a distance d along an axis of cylinder (the x-axis in Fig. 2) is approximated, assuming its radius, r, is small compared to the length of cylinder, as follows:

$$\boldsymbol{v}^r(d) = \boldsymbol{v}_b^r + \boldsymbol{\omega}_b \times [\ d\ \ 0\ \ 0\ ], \tag{7}$$

where $\boldsymbol{\omega}_b$ is the angular velocity of the cylinder relative to the fluid, and $\boldsymbol{v}_b^r$ is the translational velocity of the cylinder relative to the fluid at the body-fixed coordinate system. The relative velocity normal to this disk, $\boldsymbol{v}^n(d)$ is the projection of the vector onto the yz-plane of the link coordinate system which is the y and z components of $\boldsymbol{v}^r(d)$.

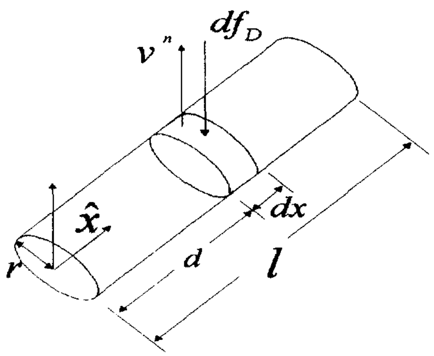

Fig. 2 Drag Force

The partial force and moment is given as follows[2,3]:

$$d f_D(d) = -\rho r C_d \| \ \boldsymbol{v}^n(d) \| \ \ \boldsymbol{v}^n(d)\, dx, \tag{8}$$

$$\tau_D(d) = -\rho r C_d \int^l \| \ \boldsymbol{v}^n(x) \| \left(\begin{bmatrix} x \\ 0 \\ 0 \end{bmatrix} \times \boldsymbol{v}^n(x) \right) dx. \tag{9}$$

2.3 Added Mass Force

When a body is accelerated through a fluid, some of the surrounding fluid is also accelerated with the body. This fluid has mass/inertia properties that can be described with a 6×6 added mass matrix, $\boldsymbol{I}^A$ [1]. A force is exerted on this surrounding fluid to achieve the acceleration, and reaction force, f_A, exerted on the body is the added mass force which is equal in magnitude and opposite in direction[1]-[3]. The most important characteristic of this force is that it is also a function of the acceleration of the rigid body. Newman derives a set of equations to compute the added mass force that is exerted on a rigid body accelerating through an unbounded, inviscid fluid undergoing steady, irrotational flow. Derived equation is rewritten in spatial notation by McMillan [2] as follows:

$$\boldsymbol{F}^A = \begin{bmatrix} \tau_A \\ f_A \end{bmatrix} = -\boldsymbol{I}^A \begin{bmatrix} \dot{\boldsymbol{\omega}}_b \\ \dot{\boldsymbol{v}}_b \end{bmatrix} - \begin{bmatrix} \hat{\boldsymbol{\omega}}_b & \hat{\boldsymbol{v}}_b \\ 0 & \hat{\boldsymbol{\omega}}_b \end{bmatrix} \boldsymbol{I}^A \begin{bmatrix} \boldsymbol{\omega}_b \\ \boldsymbol{v}_b \end{bmatrix}, \tag{10}$$

where $\boldsymbol{\omega}_b$, $\boldsymbol{v}_b$, $\dot{\boldsymbol{\omega}}_b$ and $\dot{\boldsymbol{v}}_b$ are the angular velocity, translational velocity, time derivative of the components of $\boldsymbol{\omega}_b$ and $\boldsymbol{v}_b$ with respect to the body's rotating reference frame, respectively. The hat is the cross product operator. $\boldsymbol{I}^A$ is written in terms of Newman's coefficients as[1]:

$$\boldsymbol{I}^A = \begin{bmatrix} \boldsymbol{M}_{22} & \boldsymbol{M}_{21} \\ \boldsymbol{M}_{12} & \boldsymbol{M}_{11} \end{bmatrix}. \tag{11}$$

3. Underactuated Robot Dynamics

For a n-link underactuated underwater robot with r actuated joints and p unactuated joints, the dynamic equations can be written as follows :

$$\begin{pmatrix} \tau_a \\ 0_p \end{pmatrix} = \begin{pmatrix} I_{aa} & I_{ap} \\ I_{pa} & I_{pp} \end{pmatrix} \begin{pmatrix} \ddot{\phi}_a \\ \ddot{\phi}_p \end{pmatrix} + \begin{pmatrix} F_a \\ F_p \end{pmatrix}, \tag{12}$$

where $\phi = (\phi_a^T\ \phi_p^T)^T \in R^{(n=r+p)}$ is the joint variable, $\phi_a \in R^r$ is the r-actuated joints, $\phi_p \in R^p$ is the p-unactuated joints. Input torque vector, $F(\phi\ \dot{\phi}) = (F_a^T\ F_p^T)^T$, is $\dot{\phi}^T[\ P\ _{\dot{\phi}\phi\phi}]\ \dot{\phi} + \tau_{G} + \tau_D + \tau_B + \tau_A$. $\tau = (\tau_a^T\ 0_p^T)^T \in R^n$. $\tau_a \in R^r$ is the actual input torque applied to the active joints, and $0_p \in R^p$ is the zero input vector applied to the passive joints. Eq.(12) can be described as two separate equations given by

$$I_{pa} \ddot{\phi}_a + I_{pp} \ddot{\phi}_p + F_p = 0_p \in R^p, \tag{13}$$

and

$$I_{aa} \ddot{\phi}_a + I_{ap} \ddot{\phi}_p + F_a = \tau_a \in R^r. \tag{14}$$

From Eq.(13), if I_{pp} is nonsingular, the acceleration of the unactuated joints can be described in terms of the acceleration of the actuated joints as follows:

$$\ddot{\phi}_p = -I_{pp}^{-1}(I_{pa}\ddot{\phi}_a + F_p). \quad (15)$$

Substituting (15) into (14) yields

$$\tau_a = I_{aa}^{*}\ddot{\phi}_a + F^{*}, \quad (16)$$

which is the dynamic equation described by a function of the active joints variables. $I_{aa}^{*} \in R^{r\times r}$ in (16) denotes the effective inertia matrix given by

$$I_{aa}^{*} \in R^{r\times r} = [I_{aa} - I_{ap}(I_{pp}^{-1} I_{pa})],$$

and

$$F^{*} \in R^{r\times 1} = F_a - I_{ap} I_{pp}^{-1} F_p.$$

The velocity vector of the end-effector ($\dot{u}$) can be expressed directly in terms of the joint velocity vector ($\dot{\phi}$) as

$$\dot{u} = G_{\phi}^{u}\dot{\phi}, \quad (17)$$

where G_{ϕ}^{u} denotes the first-order kinematic influence coefficient(KIC) matrix (or Jacobian) relating the end-effector velocity vector to the joint velocity vector. The acceleration vector can be obtained by differentiating (17) with respect to time as [9]

$$\ddot{u} = G_{\phi}^{u}\ddot{\phi} + \dot{\phi}^{T} H_{\phi\phi}^{u}\dot{\phi}, \quad (18)$$

where $H_{\phi\phi}^{u}$ is the second order kinematic influence coefficient (KIC). Using (15), the acceleration vector of the joint variable can be represented as

$$\ddot{\phi} = \begin{bmatrix} \ddot{\phi}_a \\ \ddot{\phi}_p \end{bmatrix} = \begin{bmatrix} I \\ -I_{pp}^{-1} I_{pa} \end{bmatrix} \ddot{\phi}_a + \begin{bmatrix} [0]_{r\times r} \\ -I_{pp}^{-1} F_p \end{bmatrix}, \quad (19)$$

where I denotes an $r\times r$ identity matrix.
Substituting (19) into (18), we can obtain the acceleration vector at the end-effector

$$\ddot{u} = G_{a}^{u}\ddot{\phi}_a + G_{\phi}^{u}\begin{bmatrix} [0]_{r\times r} \\ -I_{pp}^{-1} F_p \end{bmatrix} + \dot{\phi}^{T} H_{\phi\phi}^{u}\dot{\phi}, \quad (20)$$

where $G_{a}^{u} = G_{\phi}^{u}\begin{bmatrix} I \\ -I_{pp}^{-1} I_{pa} \end{bmatrix}$ denotes an effective first-order kinematic influence coefficient (KIC) matrix relating the end-effector velocity vector to the actuated joint velocity vector. If G_{a}^{u} is nonsingular and the acceleration vector of the end-effector is given, the acceleration of the actuated joint variables can be obtained as

$$\ddot{\phi}_a = G_{a}^{u^{-1}}\left(\ddot{u} - G_{\phi}^{u}\begin{bmatrix} [0]_{r\times r} \\ -I_{pp}^{-1} F_p \end{bmatrix} - \dot{\phi}^{T} H_{\phi\phi}^{u}\dot{\phi}\right). \quad (21)$$

4. Robust Control

When the dynamics of the underwater manipulator with passive joints is given as a function of the actuated joint variables, strictly speaking, it is not exact, but merely an estimate of the real dynamics of the underwater underactuated manipulator. Thus, the actual dynamics of the robot should be represented as

$$\tau_a = I_{aa}^{*}\ddot{\phi}_a + F^{*} + \varepsilon, \quad (22)$$

where ε denotes the unmodeled dynamics of the robot. Eq.(22) can be rewritten as a fixed inertia term plus an equivalent disturbance torque as[7][8]

$$\tau_a = \bar{I}_{aa}^{*}\ddot{\phi}_a + \tau_d(\phi, \dot{\phi}, \ddot{\phi}_a), \quad (23)$$

where $\bar{I}_{aa}^{*} \equiv \text{diag}\{\bar{I}_{11}^{*}, \cdots, \bar{I}_{rr}^{*}\}$ is a $r\times r$ diagonal matrix. Here, $\bar{I}_{ii}^{*}$ is the constant-valued nominal inertia term for the ith joint axis. Then, the dynamics of the ith joint axis is treated as $\tau_i = \bar{I}_{ii}\ddot{\phi}_i$, where $\bar{I}_{ii}$ can be experimentally measured by using a frequency response for the torque input and the velocity output. In Eq.(23), $\tau_d(\phi, \dot{\phi}, \ddot{\phi}_a) \equiv [\tau_{d1} \cdots \tau_{dr}]^{T}$ is the $r\times 1$ vector implying an equivalent disturbance including all the unmodeled dynamics and hydrodynamic forces. τ_d can be represented as

$$\tau_d = (I_{aa}^{*} - \bar{I}_{aa}^{*})\ddot{\phi}_{aa} + F^{*} + \varepsilon. \quad (24)$$

Dynamics of each axis can be decoupled by eliminating the equivalent disturbance given in (24). The equivalent disturbance can be estimated by disturbance observer and can be suppressed by adding the estimated disturbance signal to the control input. Its basic concept is shown in Fig.3 which shows a structure of the disturbance observer for the ith single axis which is based on inverse model of nominal plant.

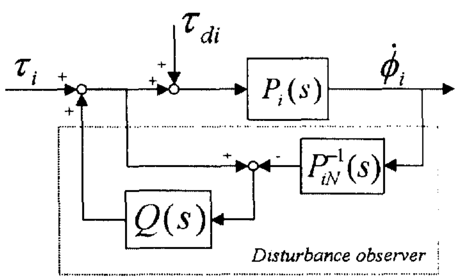

Fig. 3 Disturbance Observer

In this Figure, $P_{iN}(s)$ is the nominal plant of the ith real system $P_i(s)$. $P_{iN}(s)$ is given as $\frac{1}{\bar{I}_{ii}^{*} s}$, and $Q_i(s)$ is a low pass filter which is

employed to realize $P_{iN}^{-1}(s)$ and reduce the effect of measurement noise. Discussion on the design of Q-filter can be found in [12].
From Fig. 3, the transfer function is obtained as follows:

$$\dot{\phi}_i = G^{\phi}_{\tau_i}(s)\,\tau_i + G^{\phi}_{\tau_{di}}(s)\,\tau_{di}, \qquad (25)$$

where

$$G^{\phi}_{\tau_i}(s) = \frac{P_i(s)\,P_{iN}(s)}{P_{iN}(s) + (P_i(s) - P_{iN}(s))Q_i(s)} \qquad (26)$$

and

$$G^{\phi}_{\tau_{di}} = \frac{P_i(s)\,P_{iN}(s)(1 - Q_i(s))}{P_{iN}(s) + (P_i(s) - P_{iN}(s))Q_i(s)}. \qquad (27)$$

If $Q_i(s) \approx 1$, Eqs. (26) and (27) are reduced to

$$G^{\phi}_{\tau_i} \approx P_{iN}(s), \quad \text{and} \quad G^{\phi}_{\tau_{di}} \approx 0. \qquad (28)$$

This implies that the real plant behaves as a nominal plant in spite of the presence of disturbances within a specified frequency range. In this control method, the system is treated as a pseudo active system in which the passive joint is eliminated. Therefore, if such a disturbance observer is employed for every actuated joint of the manipulator, then the robot dynamics can be considered as simple equivalent dynamic system given by

$$\tau_a = \bar{I}^*_{aa}\,\ddot{\phi}_a, \qquad (29)$$

where the acceleration given in (21) is simplified as

$$\ddot{\phi}_a = G_a^{u\,-1}(\bar{u} - \dot{\phi}^T H^u_{\phi\phi}\dot{\phi}). \qquad (30)$$

5. Simulation

Consider a planar underwater vehicle system consisting of an underwater robotic vehicle(URV) and a manipulator attached to the underwater robotic vehicle. Underwater exploration requires mobility and manipulation. URV has been employed for mobility, and robot manipulators attached to the URV have the role of manipulation. Usually, the manipulation mode happens when the rover is stationary.

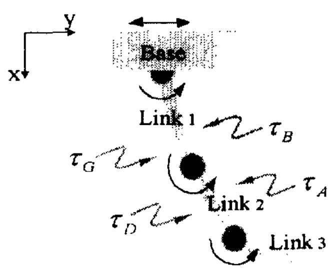

Fig. 4 Simulation Model

URV is then modeled as a passive joint and the joints of the manipulator are modeled as active joints. The motion of URV is determined by the dynamic coupling between the active and passive joints. Fig. 4 shows a four jointed manipulator which has one linear passive joint and three active revolute joints. The base denotes the underwater robotic vehicle such as underwater rover. The dynamic and kinematic parameters for the system are represented in Table 1. With loss of generality, it is assumed that the fluid is steady and each link has cylinder structure.

Table 1 Kinematic/Dynamic Parameters

Description	length(m)	Radius(m)	mass(Kg)
Base	-	-	1000
Link 1	0.7	0.08	23.75
Link 2	0.5	0.06	9.54
Link 3	0.3	0.04	2.54

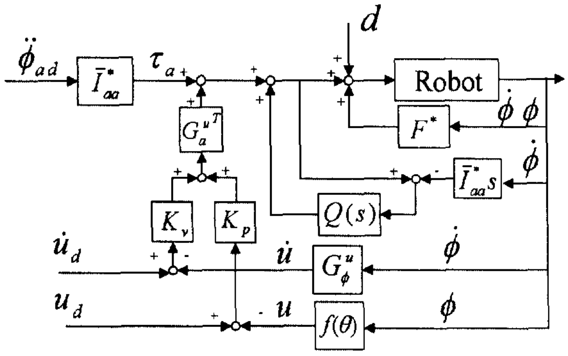

Fig. 5 Simulation Block Diagram

Fig. 5 shows the block diagram for the disturbance observer plus PD control scheme. A nonlinear feedback corresponding to the nonlinear dynamic term is included, and a simple linear PD control is added to improve the position tracking performance. The parameters used in simulation are presented in Table 2. The desired trajectory of the end-effector is a circle whose radius is 0.08(m) as shown Fig.6 and the orientation of the last link keeps a constant angle(i.e., 0°). Fig. 6 and Fig. 7 show the desired and actual paths of the end-effector of the robot for disturbance observer plus PD control algorithm and simple Kinematics-based trajectory planning given in (30), and PID controller plus complex Dynamics-based trajectory planning in Eq.(21) without disturbance observer, respectively.
It is shown that the trajectory tracking performance of the disturbance observer-based robust control plus PD control scheme is much superior to that of simple PID based control scheme. Besides the tracking performance, PID control scheme requires very large PID gains, and also it needs fast sampling

time since sensitivity to external disturbances is shown to be very large. Thus, employing PID scheme seems to be impractical since there is a hardware limitation due to high sampling time.

Table 2. Simulation Parameters

$Q(s)$	$\frac{1}{(s+0.01)^2}$
$\bar{I}^*_{aa}$	$\begin{bmatrix} 14.95 & 0 & 0 \\ 0 & 1.655 & 0 \\ 0 & 0 & 0.07638 \end{bmatrix}$
$f(\theta)$	forward kinematics
K_v	8000(x), 8000(y), 250(ϕ)
K_p	5000(x), 5000(y), 500(ϕ)

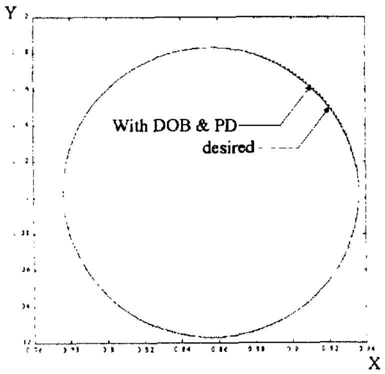

Fig. 6. Simulation Result for DOB plus PD control and simple kinematic-based trajectory planning in Eq.(30)

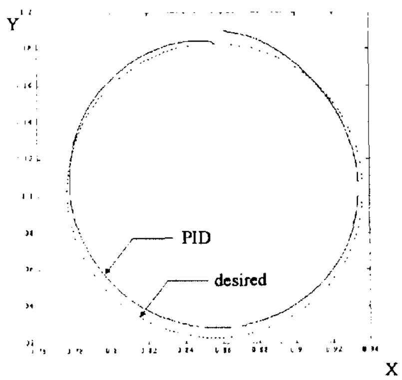

Fig. 7. Simulation Result for PID control and complex dynamics-based trajectory planning in Eq.(21)

6. Conclusion

The underactuated underwater robot is subject to external disturbances together with model uncertainties, which make the control task challenging. In this paper, a disturbance observer based independent joint control scheme plus PD control scheme was employed. The presented control scheme is not only robust to model uncertainty, but also external disturbances such as hydrodynamic forces. The feasibility of the proposed control scheme has been shown through simulation study for a four-linked model of a planar underactuated underwater vehicle system. Experimental verification of the proposed control algorithm will be our future work.

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