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Control of Underwater Manipulators Mounted on an ROV Using Base Force Information

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Abstract

This paper presents a control scheme for obtaining high maneuverability of underwater robot manipulators mounted on a remotely operated vehicle (ROV). The motions of an underwater manipulator can affect the attitude and position of the ROV which should remain stationary in seabed operation. To compensate for the dynamic effect of the underwater manipulator on the ROV, force-torque (F/T) information between the manipulator and the vehicle is used to regulate the states of the ROV. When an F/T sensor is practically unavailable, a disturbance observer can fill the role of the F/T sensor. This paper proposes a disturbance observer for estimating the interaction forces between the ROV and the manipulator. A two-link manipulator mounted on an ROV is considered and numerical simulations are performed to demonstrate the improvement on the maneuverability of the proposed controller.

1. Introduction

Underwater manipulators, generally mounted on remotely operated vehicles (ROVs), are important equipment in shallow or deep-water missions for marine science, support of oil and gas products, exploration, and military applications [14]. However, it is difficult to control the vehicle-manipulator system as a whole, because the slowly varying motion of the vehicle generates non-linear disturbances on the base of the manipulator. On the other hand, the interaction force of the motion of the manipulators affects the attitude of ROVs. Furthermore, the hydrodynamic coefficients are often poorly known and the dynamics of the manipulator and the vehicle can change considerably according to the speed and direction of the manipulator's motion as well as that of the vehicle.

In general, an operator on the surface vessel maneuvers the manipulator in a master/slave configuration. The movement of the master arm is transmitted to the slave arm and they form a spatially correspondent system [12]. If the position and orientation of the vehicle are variable due to the vehicle-manipulator dynamic interactions, it is very difficult for the operator to make the manipulator follow a prescribed trajectory [10]. For a coupled vehicle-manipulator system, it is important to reduce the dynamic interactions to improve the maneuverability of the manipulator mounted on the ROV. However, this problem is challenging because of the dynamic and kinematic couplings that arise between the vehicle and the manipulator. Dynamic coupling, which arises from the transmission of forces and moments between the manipulator and the vehicle, varies in magnitude and direction according to the range of the manipulator trajectory specifications. These act as disturbances on the vehicle, and hence influence the end-effector position and orientation. Kinematic coupling is induced because the end-effector's position and orientation are a function of the vehicle position. This can be exploited to increase the working envelope and maneuverability of the manipulator if the vehicle's position and orientation are controllable. Some heuristic methods have been suggested for solving the dynamic coupling problem [15].

There are a number of enhanced vehicle-manipulator teleoperated schemes that have been designed to overcome kinematic and dynamic coupling problems mentioned above [3,7,8]. Improvements have been made in manipulator design and implementation of "supervisory" control systems have been pursued.

Thus far, either additional manipulators mounted on the front of an ROV or an attachment system is used to hold the ROV reasonably static relative to the work piece. This is possible either using a second manipulator or a hydraulically powered mechanism with a clamping arm that fixes itself to the work piece structure. However, both of these approaches have drawbacks. The use of the second manipulator prevents coordinated tasks involving two manipulators. To regulate ROV motion due to the reaction forces and the moments of the manipulator as well as sea current disturbances, the attachment arm must have yaw/pitch and extend/retract capabilities. So, the design of the clamping arm needs significant mechanical engineering effort. Also, It is impossible to use these methods for the unstructured environment of the seabed.

Tarn *et al.* have developed a dynamic model of an underwater vehicle with a robotic manipulator using Kane's methods [13]. This model provides a direct method for incorporating external environmental forces into the model. The main hydrodynamic effects have been included in the model. McClain *et al.* have conducted practical experiments in the coordinated control of an underwater vehicle and a single link manipulator [11]. These experiments showed that the dynamical interactions could be very significant when no vehicle control was applied. It was also noted that a coordinated-control strategy using the interaction forces acting on the vehicle due to arm motion greatly enhanced station-keeping compared to the strategy using a separate manipulator and vehicle feedback control.

Antonelli *et al.* [1] addressed the tracking method of a desired motion trajectory for an underwater vehicle-manipulator system without using direct velocity feedback. An observer is adopted to provide estimation of the system's velocity needed by a tracking control law. The combined controller-observer scheme was designed so as to achieve estimation error.

A disturbance observer-based robust control algorithm has been proposed for underwater robotic systems with passive joints [4]. An ROV was modeled as a passive joint and the joints of the manipulator were modeled as *active joints*.

In this paper, a new control scheme is proposed to achieve high maneuverability of underwater robot manipulators mounted on an ROV. A base F/T sensor is attached between a manipulator and an ROV, and the signal is used to regulate the states of the ROV. For the case when a base F/T sensor is unavailable, a disturbance observer is used instead of the base F/T sensor. The new control law proposed here is inspired by the work of Geffard *et al.* [5] where a base F/T sensor is used for passive force-feedback teleoperation.

This paper considers a two-link manipulator mounted on an ROV, where the ROV is modeled as 3-DOF in the vertical plane of motion. With the model of the underwater robotic system, numerical simulations are performed to demonstrate the improvement on the maneuverability of the proposed controller.

2. Base F/T Sensor-Based Method

When the vehicle-manipulator system is considered as two separate systems, the interaction forces caused by the motion of the manipulator can be regarded as a disturbance of each system. It is these interaction forces in the ROV that cause the undesirable motion.

If the interaction forces are measured, the undesirable motion of the ROV, which is caused by the movement of the manipulator, can be compensated using a feed-forward control law. In the present work, in order to measure the interaction forces, an F/T sensor is mounted between the ROV and the manipulator.

In this paper, a control law is developed for the vehicle-manipulator system in the vertical plane, where the ROV and the manipulator can be modeled as 3 and 2-DOF, respectively. Figure 1 shows interaction forces between the ROV and the manipulator, where the manipulator is mounted on the forefront of the ROV. The motion of the manipulator causes the interaction forces.

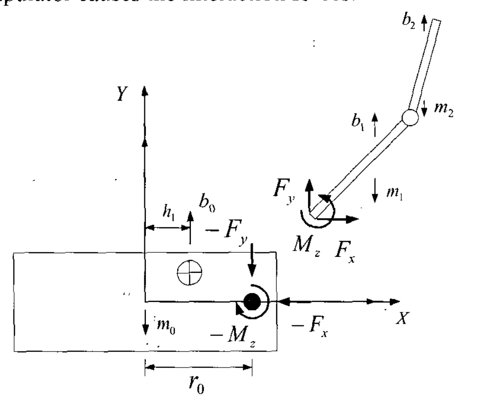

Fig. 1 Interaction forces between the ROV and the manipulator.

In Figure 1 the measured signals of the F/T sensor are denoted as

$$\zeta = \begin{bmatrix} F_x \\ F_y \\ M_z \end{bmatrix}. \quad (1)$$

m_0, m_1 and m_2 are the mass of the ROV and the first and second link, respectively; and b_0, b_1 and b_2 indicate the buoyancy of the ROV, the first and the second link, respectively. r_0 is the distance between the base of the manipulator and the center of rotation, which is set to be the origin. h_1 is the horizontal distance between the center of buoyancy and the center of rotation.

When the manipulator folds its arm and has the configuration shown in Figure 2, the vehicle-manipulator system remains stationary. The mass of the vehicle-manipulator system should be equivalent to the buoyancy of the system in order to control the ROV in the sea:

$$m_0 + m_1 + m_2 = b_0 + b_1 + b_2 . \quad (2)$$

The manipulator is designed so as to be attached at the position r_0 from the origin, and the following equation should be satisfied to remove the moment caused by the weight of the manipulator:

$$(m_1 + m_2 - b_1 - b_2)r_0 = b_0 h_1 . \quad (3)$$

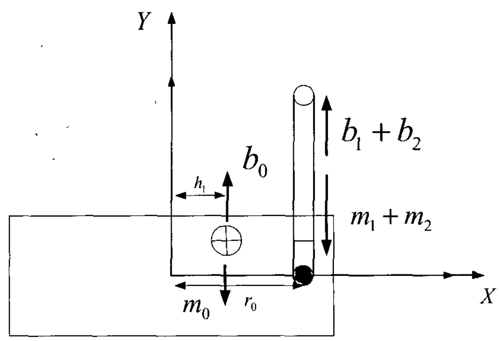

Fig. 2 Equilibrium posture of the vehicle/manipulator system.

A feed-forward controller that allows the ROV to have no movement can be designed if the interaction force is measured. To maintain the attitude of the ROV, the compensating control force can be obtained using the base F/T sensor signals as follows:

$$\tau_c = -\begin{bmatrix} F_x \\ F_y - (m_1 + m_2 - b_1 - b_2)g \\ M_z + r_0(F_y - (m_1 + m_2 - b_1 - b_2)g) \end{bmatrix} \quad (4)$$

It is noted that because F_y contains a gravitational force of the manipulator, F_y has a static value $((m_1 + m_2 - b_1 - b_2)g)$, even though the manipulator is in equilibrium posture (Figure 2). Therefore, the net disturbance force in the y-direction is $(F_y - (m_1 + m_2 - b_1 - b_2)g)$. Because the base of manipulator is at a distance r_0 from the center of rotation, the net disturbance force in y-direction $(F_y - (m_1 + m_2 - b_1 - b_2)g)$ causes the additional moment $(r_0(F_y - (m_1 + m_2 - b_1 - b_2)g))$.

It is easy to extend this approach to a higher DOF system, although only the 5-DOF system has been considered in this paper. However, attaching the F/T sensor between the ROV and the manipulator is difficult in practice, and ineffective in cost.

3. Disturbance Observer Based Method

A control structure known as a disturbance observer has been used to improve the robustness and to simplify both force and position robotic control algorithms [2,6,9]. In this paper, a disturbance observer is applied to estimate the interaction forces between the ROV and the manipulator without any base F/T sensors, and the effectiveness of the disturbance observer is investigated for improving the maneuverability of the underwater manipulators mounted on the ROV.

Figure 3 depicts the structure of the controller based on the disturbance observer, which has been applied to estimate the interaction force and to compensate the undesirable movement of the ROV caused by the motion of the manipulator.

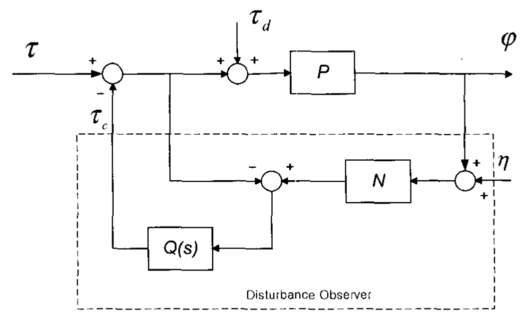

Fig. 3 Disturbance observer based control scheme of the ROV.

In Figure 3, P is the real dynamics of the ROV and τ_d is an external disturbance having low frequency, such as hydraulic drag and dynamic effect of the underwater manipulator. N is the nominal model when it is in the equilibrium posture. The disturbance observer (DO) used in this paper is different from the one developed in previous research [2,6,9]. Unlike previous disturbance observer, the nominal model that the system needs to track is a nonlinear ROV model in the equilibrium posture, which is given as

$$M\ddot{\varphi} + F + G = \tau , \quad (5)$$

where $\varphi \in R^{n\times 1}$ is the states of the ROV, n is the degree-of-freedom of the vehicle-manipulator system, $M \in R^{n\times n}$ is a symmetric positive definite inertia matrix, $F \in R^{n\times 1}$ is a coriolis and centrifugal matrix and $G \in R^{n\times 1}$ is a gravity and buoyancy matrix of the ROV in the equilibrium posture. $Q(s)$ is a low-pass filter which is employed to realize the nominal model and to reduce the effect of measurement noise (η). This work used a 3rd order binomial low-pass filter as follows:

$$Q(s)=\begin{bmatrix} Q_1(s) & & \\ & \ddots & \\ & & Q_n(s) \end{bmatrix} \quad (6)$$

where $Q_i(s)=\frac{3\left(\tau_{ci}s+\frac{1}{3}\right)}{(\tau_{ci}s+1)^3}$ and $i=1,2,\cdots,n.$

The disturbance observer shown in Figure 3 is used to enforce a robust desired input/output behavior of the ROV by canceling disturbances (hydraulic drag and dynamic effect of the manipulator et al.,) and plant/model mismatch. With this disturbance observer, the ROV can remain stationary while the manipulator tracks the desired path.

4. Simulation Example

A. Simulation Model

In this paper, an ROV that has 3-DOF and a manipulator that has 2-DOF are used to evaluate the proposed control algorithm. Figure 4 shows the vehicle/manipulator system.

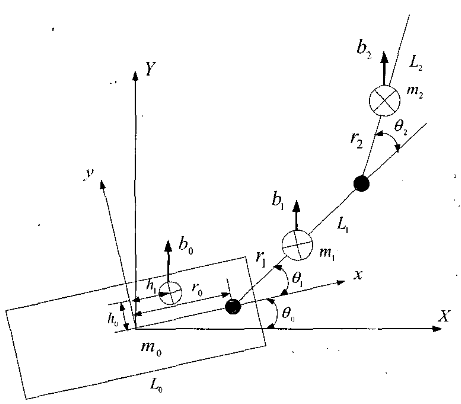

Fig. 4 A vehicle/manipulator system.

Where m_0 : mass of the ROV
m_1 : mass of the first link
m_2 : mass of the second link
b_0 : buoyancy of the ROV
b_1 : buoyancy of the first link
b_2 : buoyancy of the second link
L_0 : length of the ROV
L_1 : length of the first link
L_2 : length of the second link.

The ROV has two translational motions x_0 and y_0 and one rotational motion θ_0. The manipulator has two serially connected revolution links, which are attached to the ROV at a distance r_0 from the origin of the ROV. The center of the buoyancy of the ROV is given by (h_1, h_0) according to the local coordinate $x-y$ plane fixed to the ROV. The dynamic and kinematic parameters for the system are given in Table 1.

Table 1 Kinematic/Dynamic parameters of vehicle-manipulator system.

Description	ROV	Link 1	Link 2
Length (m)	2	0.7	0.5
Mass (kg)	300	50	30
Buoyancy (kg)	330	30	20
Distance from mass center (m)	$r_0=0.6$ $h_0=0.05$ $h_1=0.0545$	0.35	0.25

To obtain the dynamics of the vehicle/manipulator system, the Lagrange-Euler method is applied.

B. Simulation Results

To illustrate the performance of the proposed control method, numerical simulation is performed using the previously presented vehicle-manipulator system.

A simple PD controller is used to regulate the ROV, and each joint also has a PD controller to track the desired joint trajectory. The controller gains used in the simulation are presented as follows:

$$\text{Manipulator}: K_P=\begin{bmatrix}1000 & 0\\ 0 & 300\end{bmatrix},\ K_D=\begin{bmatrix}70 & 0\\ 0 & 50\end{bmatrix}$$

$$\text{ROV}: K_P=\begin{bmatrix}100 & 0 & 0\\ 0 & 100 & 0\\ 0 & 0 & 100\end{bmatrix},\ K_D=\begin{bmatrix}20 & 0 & 0\\ 0 & 20 & 0\\ 0 & 0 & 20\end{bmatrix}.$$

The desired trajectory of the end-effector is a circle whose radius is 0.3 (m).

Figure 5 shows the trajectory of the end-effector without a base F/T sensor. Even though the PD gain of the ROV is very large, the end-effector cannot track the desired trajectory, because the movements of the manipulator cause undesirable motion of the ROV. The undesirable motion of the ROV is shown in Figure 6.

Figure 7 shows the trajectory of the end-effector in the case when the base F/T sensor signal is used to measure the disturbance force and compensate the undesirable motion using the controller presented in Section 2.

Control performance of the base F/T sensor based method is highly superior to the simple PD control. The motion of the ROV that caused by the movement of the manipulator is shown in Figure 8. The magnitude of the undesirable motion is reduced significantly.

For the case when there are no base F/T sensors, the disturbance observer based control scheme is tested. We set $\tau_{ci}\ (i = 1,2,\cdots,n)$ as *100 (rad/sec)*. Figure 9 shows the trajectory tracking capability of the disturbance observer based approach. The performance is almost the same as the result of the controller with the base F/T sensor, and the movement of the ROV due to the motion of the manipulator is negligible (Fig. 10). Therefore, the control scheme can obtain high maneuverability of vehicle-manipulator systems.

If the filtering frequencies τ_{ci} are infinite, the performance will be exactly same as that of the controller with the base F/T sensor. However, these magnify the effect of measurement noise. Therefore, we should compromise between performance and the noise problem.

5. Conclusion

This paper demonstrates the effectiveness of a base F/T sensor in regulating the states of the ROV. It is useful to use an F/T sensor installed between the ROV and the manipulator to compensate the dynamic effects of the underwater manipulator to the ROV. A disturbance observer based controller is proposed for the case in which the base F/T sensor is practically unavailable. These two approaches can increase the maneuverability of the underwater manipulator significantly and do not require a dynamic model to be identified.

Acknowledgements

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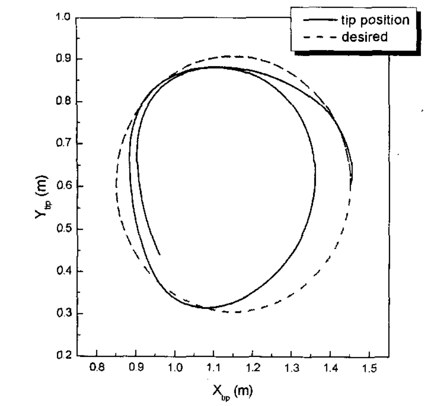

Fig. 5 Trajectory tracking performance of the end-effector without the base F/T sensor and the disturbance observer (DO).

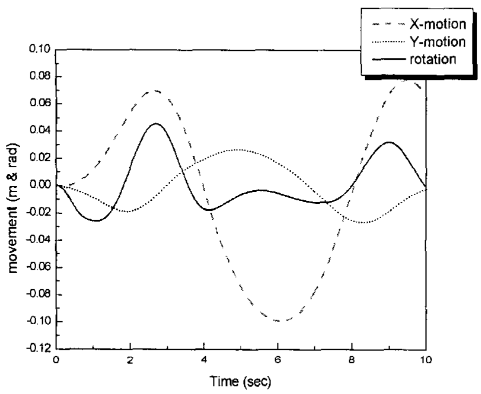

Fig. 6 States of the ROV without the base F/T sensor and the DO.

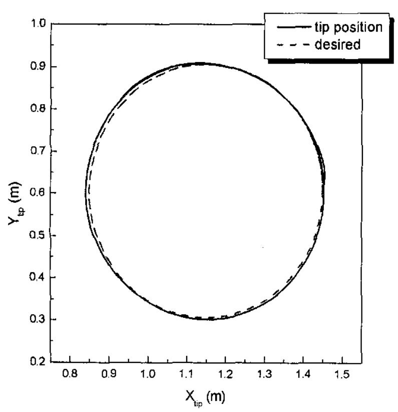

Fig. 7 Trajectory tracking performance of the end-effector with the base F/T sensor.

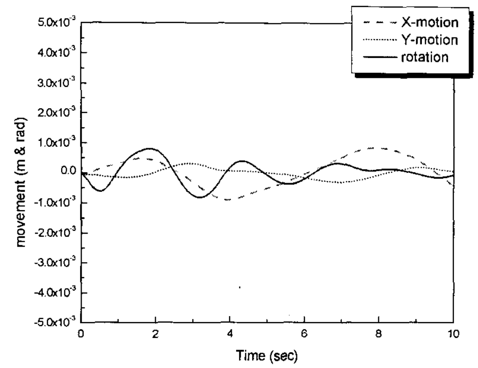

Fig. 8 States of the ROV with the base F/T sensor.

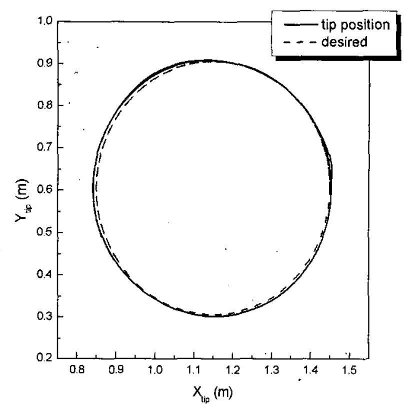

Fig. 9 Trajectory tracking performance of the end-effector with the DO.

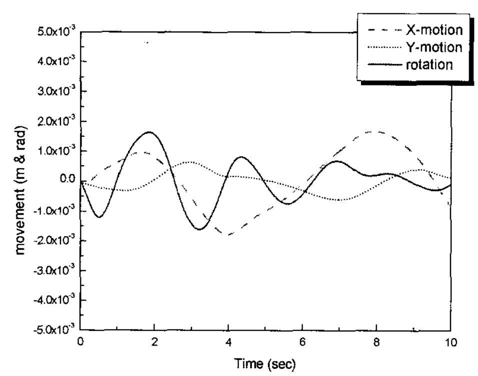

Fig. 10 States of the ROV with the DO.