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Torque Sensor based Robot Arm Control using Disturbance Observer

Hosun Lee[1], Yonghwan Oh[2] and Jae-Bok Song[3]

[1,2]Cognitive Robotics Center, Korea Institute of Science and Technology, Seoul, Korea
(Tel : +82-2-958-5759, +82-2-958-5758; E-mail: lama312@gmail.com, yonghwanoh.87@gmail.com)
[3]School of Mechanical Engineering, Korea University, Seoul, Korea
(Tel : +82-2-3290-3363; E-mail: jbsong@korea.ac.kr)

Abstract: In this paper, a robust torque control method is proposed for a robot arm which is equipped with joint torque sensor. The proposed controller is used to control the joint torque and make it to be equal with the torque controller reference input torque. A flexible joint robot model will be introduced to model the robot arm system. The disturbance observer scheme is used to reduce the disturbance effects on the system. The PI torque controller is implemented using the characteristics of disturbance observer. The performance of the proposed controller is demonstrated through experiments with a one degree of freedom robot arm.

Keywords: Torque control, Torque sensor, Disturbance Observer, Flexible joint

1. INTRODUCTION

As a result of the increased use of service robots in human life, the safety of humans have become a hot issue in recent times. One of the methods to ensure the safety is measure and control the external force of robots. Hence, the use of torque sensor on each robot joint, which would allow the measurement of external force, is an idea worth pursuing. However, the torque control of robot using torque sensor signals has some issues like the flexibility and the presence of disturbance. The flexibility is generated by pulley, timing-belt and harmonic drive. The disturbances are undesirable effects due to variation of parameters, errors in parameter identification, friction and vibration. In this study, we shall use a flexible joint robot model for a robot arm which is equipped with joint torque sensor.

'Flexible Joint Robot' is defined as a manipulator which consists of a series of rigid links interconnected by flexible joints, and this definition is first introduced in [1]. The general control algorithms, which assume a rigid model for the manipulator, are limited in their applicability to real robots where the assumption of perfect rigidity is never fully satisfied. Actually, many robots are powered by DC or AC motors and use pulleys, timing-belts and harmonic drives for speed reduction. This speed reduction part includes the torsional flexibility in the drive system, so it is named as 'Flexible Joint'. Generally, the flexibility is modeled as a torsional spring.

There have been many studies on the control of flexible joint robot and those were based on feedback linearization[5], singular perturbation[6], passive, and adaptive methods[7]. Nevertheless, disturbance remains a difficulty for controlling a flexible joints to perform its functions. The disturbance includes parameter variation during the operation, errors in system modeling, friction and vibration. Hence, there is an error between the input torque and the output torque, due to presence of disturbance.

The controller, introduced in this paper, can get the torque sensor feedback signals and cancel the disturbance which is estimated by the disturbance observer. Experiments with a one degree of flexible joint robot arm are performed in order to verify the performance of the controller.

In the following section, we shall describe the system model of one DOF(degree-of-freedom) flexible joint system and its model parameters. In section 3,the basic concept of disturbance observer will be described. In section 4,the control design methodology is proposed. In section 5,the result of torque tracking control will be shown and finally, the conclusion will be given in section 6.

2. MODELING OF ONE DOF FLEXIBLE JOINT ROBOT ARM

The dynamics of one degree of freedom flexible joint robot system[1] can be expressed as follows.

$$\tau = J_l\ddot{q} + mgl_c \sin q \quad (1)$$

$$\tau_m = J_m\ddot{\theta}_m + b_m\dot{\theta}_m + \frac{\tau}{n} + \rho_m + \tau_F \quad (2)$$

$$\tau = k_s\left(\frac{\theta_m}{n} - q\right) + k_d\left(\frac{\dot{\theta}_m}{n} - \dot{q}\right) \quad (3)$$

where q and θ_m are the link angle and the motor angle respectively. τ is the joint torque which is measured by the torque sensor. J_l and J_m are the link inertia and the motor inertia respectively, m is the link mass, g means the gravity acceleration, l_c is the link center of mass, and b_m denotes the motor friction coefficient. n is the gear ratio between the motor and the link, ρ_m is an unknown disturbance, τ_F is the motor side friction, and τ_m denotes the motor output torque. k_s and k_d are the joint stiffness and damping coefficient respectively which exist between the motor and the link.

Fig.1 describes the mechanical structure of an one degree of freedom flexible joint robot. A motor generates a driving torque, and this torque is increased by the speed

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Table 1: Dynamic parameters of robot arm

Parameters		Value	Unit
Inertia of motor	J_m	33.3×10^{-7}	kgm^2
Damping of motor	b_m	1.14×10^{-5}	-
Mass of link	m	3.6	kg
Center of mass	l_c	0.325	m
Inertia of link	J_l	0.2219	kgm^2
Stiffness of joint	k_s	52.846	Nm/rad
Damping of joint	k_d	1.312	Nms/rad

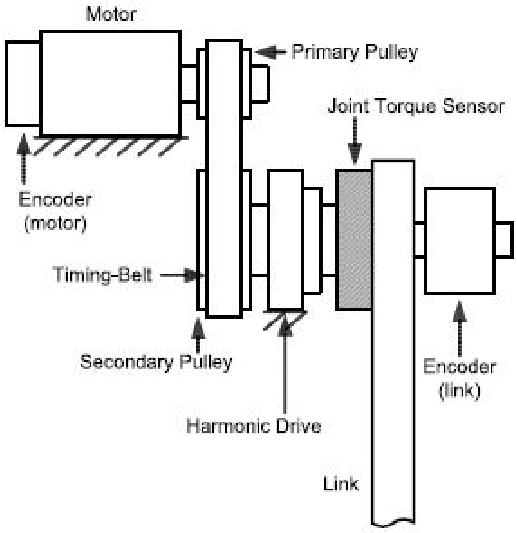


Fig. 1: One DOF flexible joint robot

reduction part: consisting of timing belt, pulley and harmonic drive. The joint torque is measured by a non-rotational type torque sensor which is attached between the harmonic drive and the link. There are two encoders to measure the motor position and the link position. The dynamic parameters of robot arm are given in Table. 1.

3. BASIC IDEA OF DISTURBANCE OBSERVER

The idea of a disturbance observer (DOB) was first proposed in [2]. The basic concept is shown in Fig. 2. In the figure, ϵ shows the control input, T_d is the unknown disturbance, μ is the reference input, y denotes the output, ζ is the measurement noise, and $P(s)$ signifies the real plant. In the observer part, $P_n(s)$ denotes the nominal plant, and $Q(s)$ is a low-pass filter to be determined. The disturbance observer regards the difference between the actual input ϵ and output of the inverse of nominal plant μ as an equivalent disturbance $\hat{T}_d$ applied to the nominal plant. It estimates the equivalent disturbance and the estimate is utilized as a cancelation signal.
From the block diagram in Fig. 2, y is expressed as

$$y = G_{uy}(s)u + G_{T_d y}(s)T_d + G_{\zeta y}(s)\zeta \quad (4)$$

where

$$G_{uy}(s) = \frac{PP_n}{P_n + (P - P_n)Q},$$

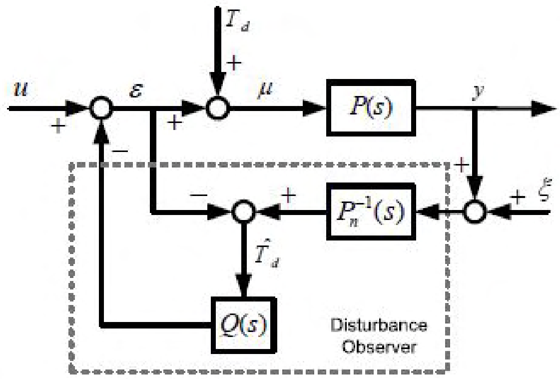


Fig. 2: Basic concept of disturbance observer

$$G_{T_d y}(s) = \frac{PP_n(1-Q)}{P_n + (P - P_n)Q},$$

$$G_{\zeta y}(s) = -\frac{PQ}{P_n + (P - P_n)Q}.$$

If $Q(s)$ is assumed to be equals 1 to see how the system based on the disturbance observer behaves, the input-output relation is characterized by the nominal model. It shows that the disturbance observer transfer the characteristic of the actual plant to that of nominal plant. On the other hand, if $Q(s)$ equals 0, the open-loop dynamics can be verified. Therefore, the low frequency dynamics of $Q(s)$ must be close to 1 for the disturbance rejection and the cancelation of model uncertainties. The high frequency dynamics of $Q(s)$ must be close to 0 to reject the sensor noise. However, the disturbance observer cannot be implemented if $Q(s) = 1$. It is also noticed that $1/Pn(s)$ is not realizable by itself but that $Q(s)/Pn(s)$ can be by realizable by letting the relative degree of $Q(s)$ be equal to or greater than that of $P(s)$. These equations show that the disturbance observer is dependent on $Q(s)$ which is the most significant parameter to determine the robustness and the disturbance suppression performance.

4. CONTROLLER DESIGN

For the control of joint torques, the motor side dynamic equation, Eq. 2 can be used to assume the nominal plant $P_n(s)$. The following transfer function is obtained by taking the Laplace transformation of Eq. 2 which the disturbance and joint torque terms are removed.

$$P_n(s) = \frac{1}{(\hat{J}_m s^2 + \hat{b}_m s)} \quad (5)$$

With the aid of this nominal plant and measured position, the disturbance observer estimates the input of the nominal plant. The difference between the actual input and the input of the nominal model is regarded as the equivalent disturbance, $\hat{\rho}$.

$$\hat{\rho} = \tau_m - \hat{J}_m \ddot{\theta}_m - \hat{b}_m \dot{\theta}_m. \quad (6)$$

The equivalent disturbance, which is estimated by disturbance observer, is used to cancel the actual disturbance.

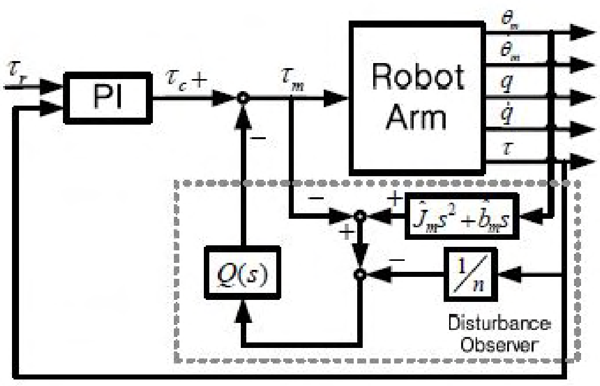


Fig. 3: Block diagram of proposed controller.

The design of Q-filter, $Q(s)$, is one of the important steps in the implementation of disturbance observer. One of the popular choice of the Q-filter is a binomial model as suggested in [3], [4]. where N is the order of $Q(s)$, f_c is a filter time constant, and r is the relative degree of $Q(s)$. The relative degree of Q should be greater than or equal to that of the transfer function describing the nominal plant to satisfy the causality. In this paper, $Q_{31}(s)$, which is a third-order binomial filter, is chosen to design the disturbance observer as suggested in [3]

$$Q_{31}(s) \quad = \quad \frac{3f_c s+1}{(f_c s)^3+3(f_c s)^2+3(f_c s)+1} \tag{7}$$

where f_c is the time constant of the filter.
The whole control algorithm is shown in Fig. 3. The PI controller can be described by Eq. 8.

$$\tau_c \quad = \quad K_P(\tau_r-\tau)+K_I\int_0^t(\tau_r-\tau)dt. \tag{8}$$

And the torque controller computes the motor control torque, τ_m, with the help of the PI controller output, τ_c, and the estimated torque, τ_e.

$$\tau_m \quad = \quad \tau_c+\tau_e \tag{9}$$

$$\quad = \quad K_P(\tau_r-\tau)+K_I\int_0^t(\tau_r-\tau)dt+\tau_e. \tag{10}$$

The disturbance observer compensates the disturbance and the PI controller makes the output torque follow the desired input torque.

5. EXPERIMENTAL RESULT

Proposed controller will be compared with the PI controller with friction compensator in order to show the torque tracking performance. A reference torque trajectory,τ_r is obtained by a simple PD position controller of the form

$$\tau_r \quad = \quad K_{PP}(q_r-q)+K_{PD}(\dot{q}_r-\dot{q}). \tag{11}$$

Herein, K_{PP} and K_{PD} are the proportional feedback and derivative gains respectively. The reference torque is computed using link position and velocity. The friction compensator gives friction torque which is estimated by the following equation

$$\hat{\tau}_F \quad = \quad \hat{\tau}_C\tanh(\alpha\dot{\theta}_m)+\hat{\tau_V}\dot{\theta}_m \tag{12}$$

where $\hat{\tau}_C$ is the Coulomb friction coefficient and $\hat{\tau}_V$ is the viscous friction coefficient. α is taken as 70 in this experiment. Table. 2 lists the selected gain values for each experiment. The comparison results of the experiments of each controller are shown in Fig. 5. Both the torque controllers show reasonable tracking control performance, but the torque controller with disturbance observer shows that the oscillation is reduced during its working. Fig. 6 shows the torque error comparison. It clearly shows the better performance of the disturbance observer based controller.

Table 2: Gain value used in the experiments

Gain	PI with Disturbance Observer	PI with Friction compensator
K_{PP}	8.0	7.0
K_{PD}	0.4	0.4
K_P	420.0	320.0
K_I	40.0	35.0

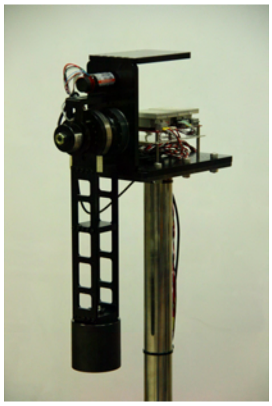
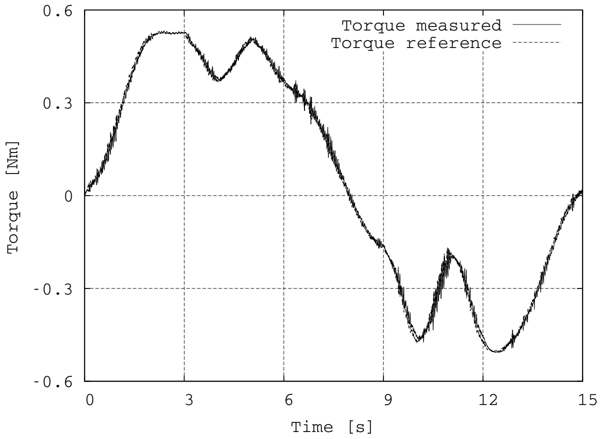


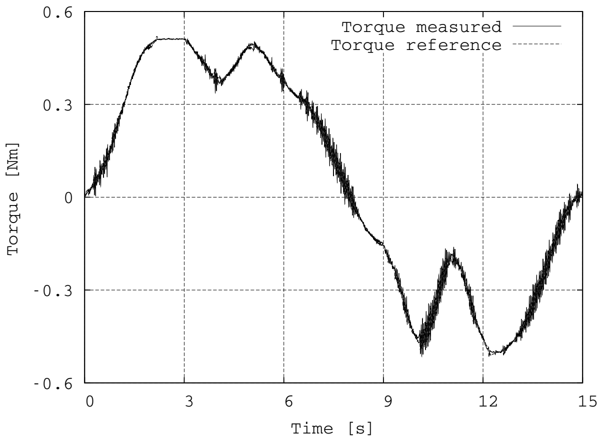
Fig. 4: One DOF flexible joint robot arm.

6. CONCLUSION

In this paper, we suggested a torque controller which utilizes the robot joint torque sensor signals for controlling a robot arm whose joints are modeled as flexible joints. The flexible joint is a joint model which consider the flexibility in speed reduction part. The flexibility and the disturbance are problems to control the joint torque. The objective of the controller is to control the joint torque such that it is equal to the controller input torque. The disturbance observer scheme is used to cancel the actual disturbance of system. It is shown that a simple PI controller could improve its performance with disturbance observer. It is further verified by experiments using a one DOF robot arm equipped with joint torque sensor. The proposed controller shows better performance than the friction compensator based torque controller.

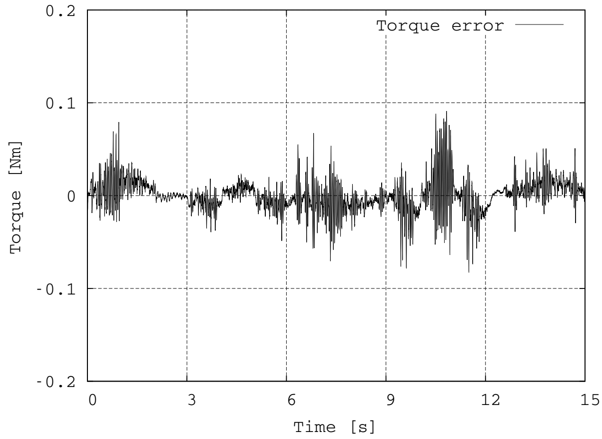


(a) PI controller with DOB

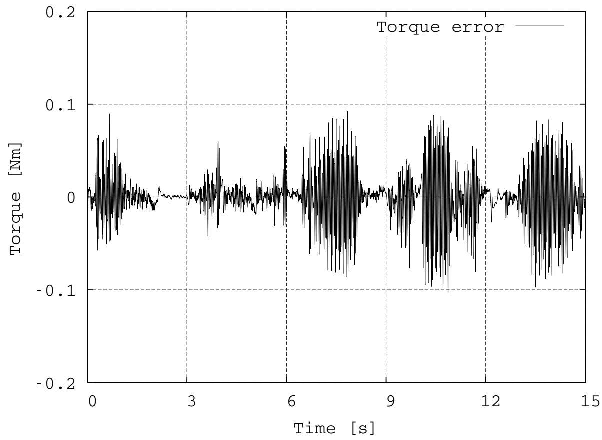


(b) PI controller with friction compensator

Fig. 5: Experimental result: reference torque vs measured torque



(a) PI controller with DOB



(b) PI controller with friction compensator

Fig. 6: Experimental result: torque error

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