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# Cartesian Trajectory Control of Humanoid Robot Arms Based on a Disturbance Observer

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**Abstract**: This paper presents an application of a disturbance observer (DOB) to the Cartesian space control of one of humanoid robot arms. Position tracking performance of the robot arm is improved by rejecting disturbance by an acceleration-based DOB(AbDOB). AbDOB utilizes an accelerometer to measure acceleration of the end-effector directly, uses that to form a conventional DOB structure, and cancels out disturbance. Experimental studies are conducted to evaluate the performance of the proposed Cartesian position control by an acceleration based DOB method.

**Keywords:** Cartesian Control, Manipulator, disturbance observer, acceleration

## 1. INTRODUCTION

Manipulation is one of the key techniques for robots to perform handling tasks. Although recent trend seems that mobility is more focused than manipulation, research on manipulation is still demanded. It is true that the manipulation technique is used most in automobile industries so that they have been developed as automobile industries are developed.

Nowadays, automobile industries are nearly saturated so that the technology for industrial robot manipulation is likely less demanded. In addition, recently, paradigm of robot research is shifted from industrial robots to service robots that require mobility and navigation more.

As for service robots, however, manipulation is an equally important technique as well as mobility in order to deliver services to humans by performing manipulation tasks. Even the manipulation technique for service robots requires more sophisticated and complicated tasks since service robots deal with humans.

Service robots with two arms have constraints in design due to the limited size and weight. Service robots with two arms belong to a category of mobile manipulators. One of popular mobile manipulators is Twendy-One that is developed as a home service robot [1]. Demonstration by Twendy-One shows that manipulation skill is still required to be improved.

Therefore, manipulation technology in service robots becomes a more important issue to consider safe, accurate, and sophisticated handling tasks under design constraints. Tracking control of robot arms is one of tasks to be tackled.

Since the workspace of service robots is defined in the Cartesian space, it is efficient to control robot arms in the Cartesian space. Considering force interaction with humans, the Cartesian space control is preferred definitely.

Therefore, in this paper, the Cartesian space control of robot arms is presented. To improve the tracking performance, a disturbance observer(DOB) based on acceleration measurements is designed to reject disturbance.

DOB has been known as a robust controller to reject disturbance and presented in the various forms. The conventional DOB structure uses the inverse model of the plant to estimate control input including disturbance. Then the disturbance is estimated by subtracting the nominal control input from the estimated control input [2]. DOB is simple and practical so that it has been used widely in industrial applications such as in motion control systems [3-5] and robot manipulator control [6,7]. The time-delayed control method is a kind of DOB control method [8-10].

Here, an acceleration-based DOB (AbDOB) is presented to control the Cartesian position of the robot arm. In the same configuration of the conventional DOB structure, the proposed DOB uses linear acceleration information. Linear acceleration is directly measured by an accelerometer mounted on the end-effector, and is used to calculate control inputs in the Cartesian controllers to estimate disturbance. In this way, an inverse model of the plant is not required.

To verify the performance of the proposed AbDOB method, experimental studies of tracking control of robot arms are performed.

## 2. CARTESIAN SPACE CONTROL

### 2.1 Manipulator Dynamics

For the Cartesian space control, controllers are designed in the Cartesian space and control input torques are specified in the joint space. Converting the

Cartesian space into the joint space holds the Jacobian relationship.

Let $q \in R^{n\times 1}$ be the joint angle vector. Joint angle vector q and Cartesian position vector $x \in R^{n\times 1}$ are related by the forward kinematic transformation.

$$x = f(q) \tag{1}$$

Derivative of (1) yields the Jacobian relationship as

$$\dot{x} = J(q)\dot{q} \tag{2}$$

where $J \in R^{n\times n}$ is the Jacobian matrix. And, the second derivative yields the acceleration

$$\ddot{x} = \dot{J}\dot{q} + J\ddot{q} \tag{3}$$

From (3), the joint acceleration term, $\ddot{q}$ can be written as

$$\ddot{q} = J^{-1}(\ddot{x} - \dot{J}\dot{q}) \tag{4}$$

Equation (4) represents the relationship between a linear control input in the Cartesian space and control input in the joint space.

The joint space robot dynamics can be described as

$$M(q)\ddot{q} + H = \tau \tag{5}$$

where the vectors $q$, $\dot{q}$, $\ddot{q}$ are the $n$ x 1 joint angle, the $n$ x 1 joint angular velocity, and the $n$ x 1 joint angular acceleration, respectively, $M(q)$ is the $n$ x $n$ symmetric positive definite inertia matrix, $H$ is the n x 1 vector of Coriolis, centrifugal torques, and gravitational torques, and $\tau$ is the $n$ x 1 vector of actuator joint torques.

Substituting (2) and (4) into (5) and using the relationship of $\tau = J^T F$ yield the Cartesian dynamics equation

$$M(q)J^{-1}(\ddot{x} - \dot{j}\dot{q}) + H = J^T F \tag{6}$$

Multiplying both sides by $J^{-T}$ yields the Cartesian dynamics equation

$$M^*\ddot{x} + H^* = F \tag{7}$$

where $M^* = J^{-T}M(q)J^{-1}$ and $H^* = J^{-T}H - J^{-T}MJ^{-1}\dot{j}\dot{q}$.

2.2 Cartesian Space Control Scheme

In the Cartesian space control, the controller is specified in the Cartesian space. The model–based control law is specified as

$$F = M^*u + H^* \tag{8}$$

where $u$ is PD control input as

$$u = K_d\dot{e} + K_p e \tag{9}$$

where $e = x_d - x$ , and $K_d, K_p$ are control gain matrices.

Here we assume that models are not available such that $M^* = I, H^* = 0$ in (8). Fig. 1 shows the non-model based Cartesian PD control block diagram.

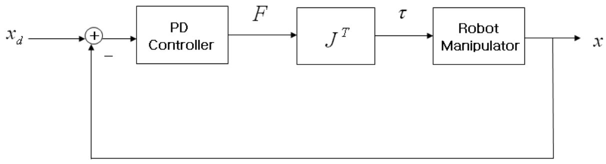


Fig. 1 Cartesian position control of robot manipulator by PD control method

2.3 Disturbance Observer for Non-model Based Case

Fig. 2 shows the Cartesian position control structure with an acceleration-based disturbance observer (AbDOB). Instead of using the inverse model of the plant, acceleration is directly measured by a sensor.

Measurement of linear acceleration produces the estimate of control input torque, $\hat{\tau}$ through the force input, $\hat{F}$ .

The estimate of the disturbance $\hat{D}$ is obtained from the difference between the nominal torque input and the estimated torque input as shown in Fig. 2.

$$\hat{D} = \hat{\tau} - \bar{\tau} \tag{10}$$

where $\hat{\tau} = J^T\hat{F} = J^T\hat{M}^*\ddot{X}$ and $\ddot{X}$ is the acceleration measurements from an accelerometer sensor.

The control input torque, $\tau$ including disturbance is described as

$$\tau = \bar{\tau} + D \tag{11}$$

Substituting the nominal torque input, $\bar{\tau} = J^T F - \hat{D}$ into (11) yields

$$\tau = J^T F - \hat{D} + D \tag{12}$$

If we get an exact disturbance estimation such as $\hat{D} = D$, then a disturbance-free control input torque is achieved as

$$\tau = J^T F \tag{13}$$

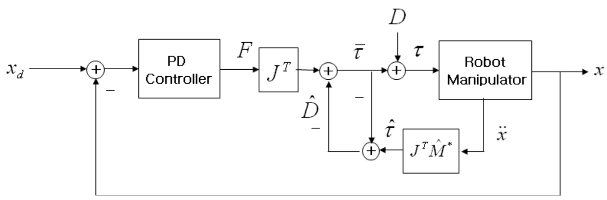


Fig. 2 Cartesian position control of robot manipulator with AbDOB method

Therefore, performance of disturbance rejection depends upon the exact estimation of torque input, $\hat{\tau}$, of which calculation is dependent upon the information of Jacobian, $J^T$ and inertia matrix, $\hat{M}^*$.

## 3. ROBOT ARM CONTROL

3.1 Real Robot

A mobile manipulator is developed for serving humans as shown in Fig. 3. The robot has two arms of 5 D.O.F each. One of arms is tested for control performance.

Flat motors and harmonic drives are used to actuate each joint to give high performance by minimizing backlash.

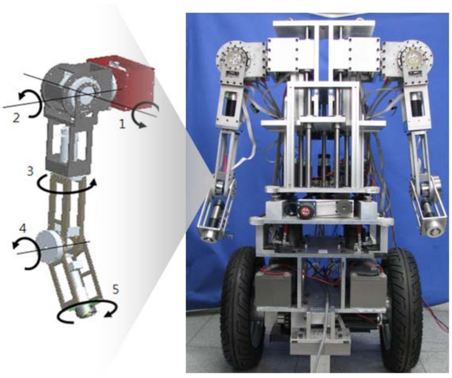

Fig. 3 5 DOF robot manipulator

3.2 Overall Hardware

DSP28335 is used as a main controller and a PC is used as an auxiliary controller. Control sampling time is set to 10 *msec*. Calculation of inverse kinematics is realized in the DSP chip to extract the angle of each joint from the Cartesian space trajectories.

The controller outputs are also calculated in the DSP to drive the motor. The DSP communicates with actuators through the CAN interface. A PC is used for the storage of data and monitoring the status of the robot. Fig. 4 shows the overall framework between control hardware.

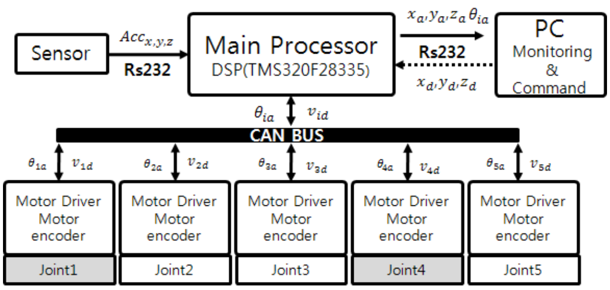

Fig. 4 Overall control hardware structure

## 4. EXPERIMENTAL RESULTS

4.1 Desired Trajectory

In order to generate linear motion, a two link structure of joint 1 and joint 4 of a robot arm shown in Fig. 3 is used. The robot arm is required to follow the straight line in the *y* axis. There is no desired *x* axis trajectory specified. The desired Cartesian trajectory is given as

$$y_d = y_0 + 0.1\cos\left(\Delta t \frac{\text{pi}}{600}\right) - 0.1, \quad (14)$$
$$\Delta t = 10\text{ms}, \quad y_0 = 0.196m$$

The desired trajectory is shown in Fig. 5. The robot is required to move 0.2 *m* in *y* axis twice back and forth.

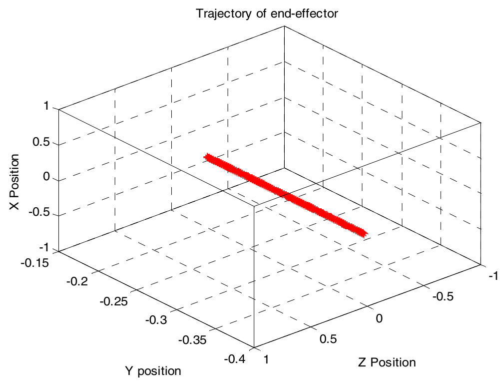

Fig. 5 Trajectory for the experiment

4.2 Filter Design

Performance of DOB depends upon accurate sensing of linear acceleration. To extract accurate acceleration signals, filter design becomes important. Noise of sensor data is eliminated by a low-pass filter. A filter is designed as

$$\text{H(s)} = \frac{0.004}{S^2 + 0.089S + 0.004} \quad (15)$$

where cut-off frequency is 2 Hz and sampling frequency is 100 Hz. A digital filter by bilinear transformation is described as

$$\frac{Y(z)}{X(z)} = \frac{0.0036\,Z^2 + 0.0072\,Z + 0.0036}{Z^2 - 1.8227\,Z + 0.8372} \quad (16)$$

The difference equation becomes

$$\text{y[n]} = a_1\text{y[n}-1] + a_2 y[n-2]$$
$$+ b_0\text{x[n]} + b_1 x[n-1] + b_2 x[n-2]$$

where
$a_1 = 1.8227$, $a_2 = -0.837$ , $b_0 = 0.0036$, $b_1 = 0.0072$, $b_2 = 0.0036$.

4.3 Tracking Control Performance

Two control methods are tested. Firstly, PD control is tested. PD controller gains are selected by trial and error procedures so that gains are quite optimized. Fig. 6 shows the end-effector trajectory controlled by the PD control method. The robot follows the desired trajectory well although models are not given in the controller.

Another reason of good tracking results of Fig. 6 is that there is no typical disturbance to the system. The robot arm moves in free space.

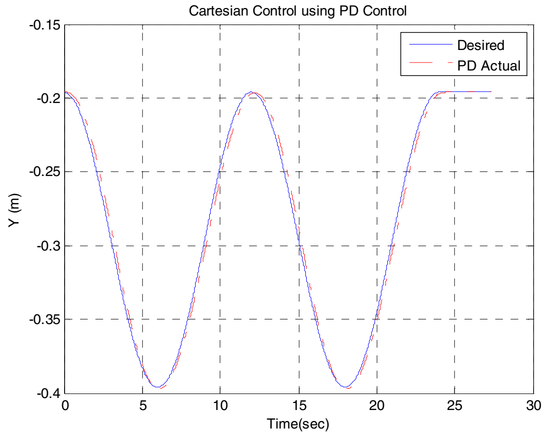


Fig. 6 Y axis tracking result of PD control method

The same experiment is performed for the AbDOB structure. Fig. 7 shows the tracking result. Comparing with Fig. 6, performances of tracking results are quite comparable for PD and AbDOB control methods. Table 1 shows the numerical difference that AbDOB performs better.

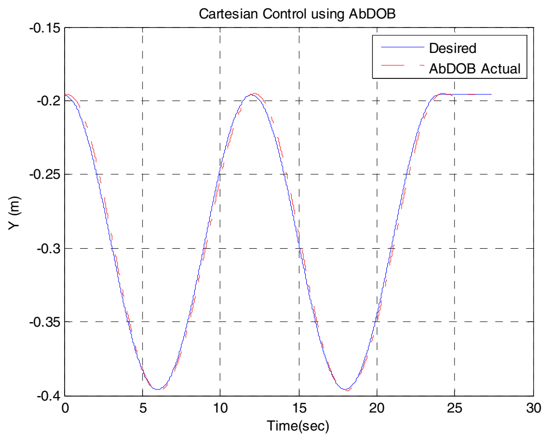


Fig. 7 Y axis tracking result of AbDOB method

However, we can clearly see the notable errors in the *x* axis between a PD control method and a DOB method. Fig. 8 shows the tracking errors of *x* axis by PD and AbDOB control method together. Although there is no specified trajectory in *x* axis, notable tracking errors occur as shown in Fig. 8.

This is due to the transformation from the joint space to the Cartesian space. In the Cartesian control, Cartesian tracking errors are controlled by conversion of Cartesian control input to joint torque through Jacobian as indicated in (13). This causes indirect control of each joint that leads to the x axis error.

The magnitude of a tracking error is about 0.004m. The tracking error in x axis is not wanted. The tracking error of AbDOB control method is reduced. Fig. 9 shows the corresponding acceleration data sensed by an accelerometer for the AbDOB.

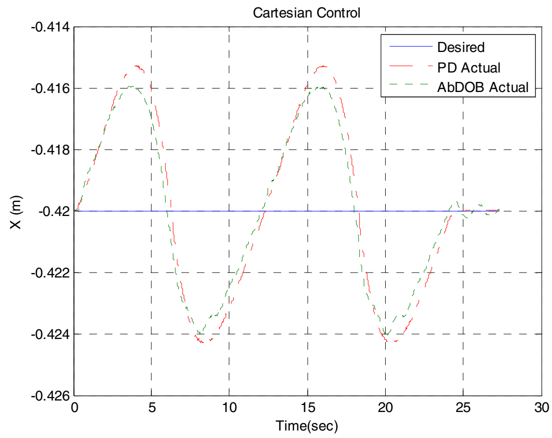


Fig. 8 X axis tracking errors of PD and AbDOB

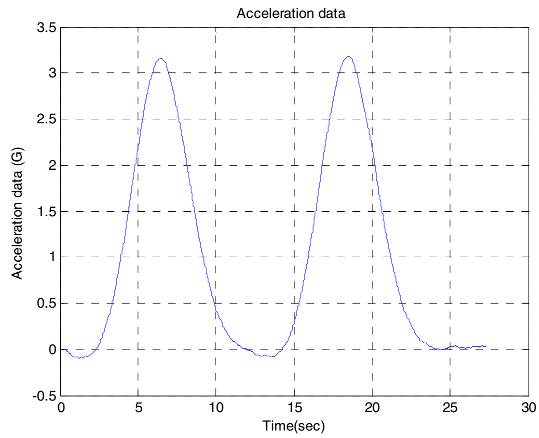


Fig. 9 Acceleration signal

Table 1 shows RMS errors of PD control and DOB control method. We clearly distinguish better performances by the AbDOB control method.

Table 1. RMS error of X ,Y axis tracking result

| RMS error | PD control | AbDOB |
|---|---|---|
| X axis | 0.1537 | 0.1250 |
| Y axis | 0.2912 | 0.2342 |


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## 5. Conclusion

In this paper, performance of the acceleration-based DOB control method is verified by empirical studies on robot arms developed for service robots. The feasibility of the controller has been tested on a robot arm with two joints. We clearly demonstrated that the proposed Cartesian AbDOB controller outperforms over the conventional PD control method with paying measurement of acceleration in linear motions. However, notable $x$ axis tracking errors due to the space transformation are observed.

To improve the performance of AbDOB further, several issues should be taken into consideration.

1) An accurate model of the robot manipulator is required.
2) Acceleration signal is filtered to reject noise.
3) Q filter can be introduced.
4) Coupled errors need to be minimized.

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