Comparison of Force Control Performance Based on Only Acceleration Sensor with KF/EKF

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This paper proposes two types of force control systems based only on measurements of an acceleration sensor attached on the tip position of a three-link planar redundant manipulator. To estimate the acceleration with high accuracy, a Kalman filter (KF) based on a dynamic model of the manipulator and an extended Kalman filter (EKF) based on a kinematic model of the manipulator are introduced in each system. Further, a disturbance force observer (DFOB) and a reaction force observer (RFOB) are also implemented in the force control system, and the acceleration estimated by the KF/EKF is directly utilized in those observers. Simulations and experiments are conducted to examine the characteristics of the estimation performance and compare the force control performance of the two types of systems based on the KF and the EKF.

Keywords: force control, redundant manipulator, acceleration sensor, kalman filter, work space observer

1. Introduction

In recent years, many kinds of robots have been developed and they are utilized in many fields as necessary tools in our society. In particular, they are active in the area of industrial fields, such as assembling robots in production lines. However, the roles of robots are widely expanded according to the progress of technology and the background of the times, then those are utilized in fields such as medical, welfare, nursing care and so on not only in the industrial fields. The considerable difference of control methods between in the industrial fields and the other fields mentioned above is that the former is applied “position control” and the latter is applied “force control”. The desired motion of robot with position control is prescribed in position dimension, then it is suitable for accurate positioning control such as production line and called “high stiffness control”. However, to realize a power assist robot for humans which is useful in welfare field for example, the position control is not suitable to be applied because it has possibilities that “high stiffness control” do humans injury. Therefore, the robots in such fields are often applied force control. The robots with force control move based on desired force reference, then “flexible motion” can be realized when there is interaction between humans and the robot, and secure system for humans.

The robots in any fields are usually actuated by motors attaching encoders which detect the joint angles as actuators. With the recent rapid progress in technology, encoders which have nm (10⁻⁹ m) order resolution can commonly be found in such fields. However, these sensors, which are a type of internal sensor, cannot detect motor backlash and axial torsion. Because of these errors, the accuracy in tip-positioning control of the manipulator may be deteriorated, since the end-effector position of the manipulator are geometrically calculated based on each joint angular information obtained by the encoders. Furthermore, in practical application, another sensor should be applied in case the encoders are something in trouble.

In this paper, an acceleration sensor is focused to detect the work-space information of the manipulator. Acceleration sensors are very convenient from a viewpoint of cost and its facility to attach on the robot or even human body compared with encoders. Those sensors can obtain the acceleration information of the robots directly, then its measurements can be utilized for motion control of robots, particularly for force control because force information can be obtained by the product of the mass and acceleration from a theoretical point of view.

In this paper, an acceleration sensor is attached to the tip-position of 3-link planar redundant manipulator, and absolute acceleration information is obtained by the acceleration sensor. To estimate the state of the robot and eliminate the noises included in the measurements of acceleration sensor, Kalman filter (KF) and extended Kalman filter (EKF) are introduced. Kalman filter (KF) is based on the dynamic model prescribed in work-space, and extended Kalman filter (EKF) is based on the kinematics of the manipulator. By utilizing the estimated acceleration information from those filters, force control systems based on directly obtained work-space information are realized. Furthermore, Disturbance Force Observer (DFOB) which is expanded to the work-space from joint-space disturbance observer (DOB) is introduced to compensate the disturbance in force dimension. Reaction Force Observer (RFOB) is also introduced to estimate the reaction force response on tip-position of the manipulator. Both of these observers are constructed based on the estimated acceleration information from Kalman filter and extended Kalman filter. The main purpose of this research is to realize the force control system which is not rely on the...
encoder information. Especially when applying the EKF, the state space vector is defined in joint-space, then Jacobian matrix can be generated by using estimated values, so the force control system which does not use any measurements from encoders can be realized. In this paper, two kinds of simulations are conducted to examine the accuracy of estimation by each of KF and EKF and to verify the performance of force control system. In the simulation, measurement noise and system noise, which are assumed as white noise, are added to emulate a actual acceleration sensor. In addition, experiments are also conducted to confirm the validity and compare the characteristics of the proposed control systems. The challenging issue in this paper is to realize force control based on only acceleration information by acceleration sensors.

The paper is organized as follows. In Sect. 2, the dynamic model of 3-link manipulator in joint-space and work-space are introduced, and the dynamic model is represented as two type of state-space model which are based on dynamic model of the manipulator (for KF) and the kinematic model of that (for EKF) respectively. The kinematic model is described as non-linear model, then it is linearized by Taylor series expansion. Each model is discretized to be applied Kalman filter and extended Kalman filter. In Sect. 3, the force controller is introduced, and the structure of DFOB and RFOB are also represented. In addition to that, extended Kalman filter is briefly explained, and finally the whole force control systems based on KF and EKF are shown. In Sect. 4, two kinds of simulations are conducted, first one is to examine the estimation accuracy of acceleration information with KF and EKF. The second one is to verify the performance of force control system which utilizes the estimated acceleration information from KF and EKF. In Sect. 5, experiments are conducted to confirm the validity and compare the characteristics of the proposed control systems. Finally, conclusions are described in Sect. 6.

2. Modeling

In this section, both of kinematics and dynamic model of a 3-DOF planar redundant manipulator are described. The dynamics of the manipulator is translated to that in work-space, to utilize work-space information obtained by acceleration sensor. Figure 1 shows a kinematic model of a 3-link manipulator.

2.1 Modeling of Kinematics

In this sub-section, kinematics of the robot is described. The joint-space coordinates is defined as \( q = [q_1, q_2, q_3]^T \). The tip-position of the manipulator in work-space is represented as 2-dimensional vector \( x = [x, y]^T \). Here the robot is regarded as a redundant manipulator. Forward and inverse kinematics can be derived as follows.

\[
\dot{x} = J_{aco}(q)\dot{q}
\]

\[
\ddot{x} = J_{aco}(q)\ddot{q} + J_{aco}(q, q)q
\]

\[
\dot{q} = J_{aco}^+(q)\dot{x}
\]

Table 1. Parameters for manipulator

<table>
<thead>
<tr>
<th>variables</th>
<th>unit</th>
<th>explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>( q_1, q_2, q_3 )</td>
<td>rad</td>
<td>angle of each joint</td>
</tr>
<tr>
<td>( l_1, l_2, l_3 )</td>
<td>m</td>
<td>length of each link</td>
</tr>
</tbody>
</table>

where \( J_{aco} \) and \( J_{aco}^+ \) denote the Jacobian matrix and the pseudo-inverse matrix \( (11)(12) \) of the manipulator respectively, and these matrices are defined as follows.

\[
J_{aco}(q) = \begin{bmatrix} J_{11} & J_{12} & J_{13} \\ J_{21} & J_{22} & J_{23} \end{bmatrix}
\]

\[
J_{aco}^+(q) = J_{aco}^T(J_{aco}J_{aco}^T)^{-1}
\]

2.2 Modeling of Dynamics in Joint-Space

With the assumption of the mass of each link is concentrated at the end of the link, the dynamic model in joint-space of the redundant manipulator using Lagrange equation is described as follows.

\[
\tau = I\dot{q} + H(q, \dot{q})
\]

where \( I \) and \( H \) denote inertia matrix in joint-space and the vector of Coriolis and centrifugal force respectively. \( \tau \) is joint torque vector.

2.3 Modeling of Dynamics in Work-Space

In this sub-section, the dynamics in work-space is introduced from (12) to utilize work-space information obtained by an acceleration sensor. The relation between torque vector \( \tau \) in joint-space and force vector \( F \) in work-space is defined by considering virtual work principle as follows.

\[
\tau = J_{aco}^T(q)F
\]

In general, joint-space energy of a redundant manipulator will be the same or more than work-space one. However, by considering only joint-space kinetic energy which has influence to work-space, (14) can be obtained.

\[
\frac{1}{2}q^T I_n \dot{q} = \frac{1}{2} x^TMx
\]

Here, subscript “\( n \)” means nominal value, and \( M \) is called equivalent mass matrix. The nominal matrix of \( M_n \) is a diagonal matrix, and actually used in the force controller. The difference between actual equivalent mass matrix and nominal.
one is compensated in work-space sufficiently since the difference becomes not so large when conducting force control. The motion of the manipulator in force control is assumed not so dynamic, thus non-diagonal elements of the $M_n$ does not make harm about stability in this force control system. By considering (1) and (14), $M$ is defined as follows:

$$
M = (J_{acc}I_n^{-1}J_{aco})^{-1} \quad (15)
$$

Substituting (2), (13) and (15) into (12), motion equation in work-space is obtained as follows:

$$
\begin{align*}
M \dot{x} &= F_{ref} - F_{dis} \quad (16) \\
F_{dis} &= (M - M_n) \dot{x} - MJ_{aco}q + MJ_{aco}I_n^{-1} \tau_{dis} \quad (17)
\end{align*}
$$

where subscript "reb" means reference value and $\tau_{dis}$ is torque disturbance in joint-space. $F_{dis}$ denotes force disturbance in work-space including parameter fluctuation of the equivalent mass matrix $M$.

### 2.4 State-Space Model for Kalman Filters

To eliminate the noise effect in the measurement value of acceleration sensor and estimate the state of the manipulator, two kinds of Kalman filters (linear Kalman filter (KF)/extended Kalman filter (EKF)) are utilized. In this sub-section, state-space models are introduced for each filter.

#### I). Workspace motion equation based state space model for KF

Here, by defining state space vector as (18), equation-of-state and observation equation are represented as (19) and (20) based on (16). The vector $\mathbf{u}$ denotes state-input into Kalman filter.

$$
\begin{align*}
x_f &= [ \dot{\mathbf{x}}, \dot{\mathbf{y}} ]^T F_{dis(x)} F_{dis(y)} \quad (18) \\
\dot{x}_f &= A \dot{x}_f + B \mathbf{u} \quad (19) \\
y &= [ \mathbf{x}, \mathbf{y} ]^T = c^T x_f \quad (20)
\end{align*}
$$

where

$$
\begin{align*}
\mathbf{u} &= F_{ref} \quad (21) \\
A &= \begin{bmatrix}
0 & 0 & \frac{1}{M_{aco}} & 0 \\
0 & 1 & 0 & -\frac{1}{M_{aco}} \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix} \quad (22) \\
B &= \frac{1}{M_{aco}} \\
c^T &= \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix} \quad (24)
\end{align*}
$$

To implement the linear Kalman filter to this system, the state-space model has to be discretized. By taking forward difference method, (19) and (20) are discretized as follows.

$$
\begin{align*}
x_f(k+1) &= A_d x_f(k) + B_d \mathbf{u}(k) + \mathbf{w}(k) \quad (25) \\
y(k) &= c^T x_f(k) + \mathbf{w}(k) \quad (26)
\end{align*}
$$

where

$$
\begin{align*}
A_d &= \begin{bmatrix} 1 & 0 & \frac{\Delta t}{M_{aco}} & 0 \\
0 & 1 & 0 & -\frac{\Delta t}{M_{aco}} \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix} \quad (27) \\
B_d &= \begin{bmatrix} \frac{\Delta t}{M_{aco}} \\
0 \\
0 \\
0
\end{bmatrix} \quad (28)
\end{align*}
$$

$\Delta t$ denotes sampling time. $\mathbf{w}(k)$ and $\mathbf{v}(k)$ are measurement noise and system noise respectively. These are assumed as a white noise in the simulation which is shown in Sect. 4.

#### II). Kinematics based state space model for EKF

Here, by defining state space vector as (29), equation-of-state and observation equation are represented as (30) and (31) based on (2).

$$
\begin{align*}
x_{II} &= [ \mathbf{q}, \mathbf{q}, \mathbf{q} ]^T \quad (29) \\
\dot{x}_{II} &= A' \dot{x}_{II} + B \mathbf{v} \quad (30) \\
y &= \mathbf{h}(\mathbf{q}, \mathbf{q}, \mathbf{q}) = J_{aco}(\mathbf{q}) \mathbf{q} + J_{aco}(\mathbf{q}, \mathbf{q}) \mathbf{q} \quad (31)
\end{align*}
$$

where

$$
\begin{align*}
A' &= \begin{bmatrix} 0 & 1 & 0 \\
0 & 0 & 1 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix} \quad (32) \\
B &= \begin{bmatrix} 0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 1
\end{bmatrix} \quad (33) \\
V &= \mathbf{q} = [ \mathbf{q}_1, \mathbf{q}_2, \mathbf{q}_3 ]^T \quad (34) \\
\mathbf{h}(\mathbf{q}, \mathbf{q}, \mathbf{q}) &= J_{aco}(\mathbf{q}) \mathbf{q} + J_{aco}(\mathbf{q}, \mathbf{q}) \mathbf{q} \quad (35)
\end{align*}
$$

The jerk term in (34) is assumed as Gaussian white noise with zero mean. This means that there is no control input signal in this system represented by (30). The discretized model of this state-space equation is represented as follows.

$$
\begin{align*}
x_{II}(k+1) &= A_d' x_{II}(k) + B_d \mathbf{v}(k) \quad (36) \\
y(k) &= \mathbf{h}(x_{II}(k)) + \mathbf{w}(k) \quad (37)
\end{align*}
$$

where

$$
\begin{align*}
A_d' &= \begin{bmatrix} 1 & 0 & \Delta t \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix} \quad (38) \\
B_d &= \begin{bmatrix} 0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix} \quad (39)
\end{align*}
$$

Furthermore, since (37) is non-linear function of $x_{II}(k)$, the function has to be linearized to be applied extended Kalman filter (EKF). At the time $k$, under assumption that a priori estimated value $\hat{x}_{II}$ is available, non-linear function of (37) is linearized with Taylor series expansion as follows.

$$
\mathbf{h}(x_{II}(k)) = \mathbf{h}(\hat{x}_{II}(k)) + c^T(k)(x_{II}(k) - \hat{x}_{II}(k)) \quad (40)
$$

where

$$
\begin{align*}
c^T(k) &= \frac{\partial \mathbf{h}(x_{II})}{\partial x_{II}} \bigg|_{x_{II}=\hat{x}_{II}(k)} \quad (41)
\end{align*}
$$
Substituting (40) to (37), (42) is obtained.

\[ y(k) = e^{T}(k)x_{II}(k) + w(k) + h(\hat{x}_{II}(k)) - e^{T}(k)\hat{x}_{II}(k) \]

(42)

From (42), non-linear observation function \( y(k) \) is linearized as follows.

\[ z(k) = e^{T}(k)x_{II}(k) + w(k) \]

(43)

where

\[ z(k) = y(k) - h(\hat{x}_{II}(k)) + e^{T}(k)\hat{x}_{II}(k) \]

(44)

By the above process, it can be seen that has been linearized as shown in (43). However, it is necessary to be taken care that the vector \( e^{T} \) is time varying term. The whole control structure based on Kalman filter (KF) and extended Kalman filter (EKF) are explained in Sect. 3.

3. Control System

In this section, first, force control system based on disturbance observer (DFOB) and reaction force observer (RFOB) is explained. Second, Kalman filter (KF) and expanded Kalman filter (EKF) are shown. The whole block diagrams of force control system based on KF and EKF are represented in the end of this section.

3.1 Force Controller

In the manipulator based on the disturbance force observer (DFOB), the dynamical disturbance and the variation of the equivalent mass matrix are suppressed at the same time. Here, force reference value \( F_{\text{ref}} \) is given as follows.

\[ F_{\text{ref}} = F_{\text{cmd}} - F_{\text{res}} \]

(45)

where \( F_{\text{cmd}} \) is the force command value, and \( F_{\text{res}} \) is the force response value which is estimated by reaction force observer (RFOB). To realize the decoupling force controller, arbitrary joint inertia matrix \( I_{n}^{-1} \) in (15) is selected as follows:

\[ I_{n}^{-1} = \{ J_{\text{aco}}(q)^{T} \} M_{\text{en}}^{-1} \{ J_{\text{aco}}(q) \} \]

(46)

Here, \( M_{\text{en}} \) is the virtual diagonal mass matrix in the workspace and which is set as unit matrix in simulations and experiments. Substituting (46) into (15), the equivalent mass matrix is fixed to the virtual one and decoupled in redundant manipulator. Then, the force reference value can be determined as follows.

\[ F_{\text{ref}} = M_{\text{en}}^{-1}(F_{\text{cmd}} - F_{\text{res}}) \]

(47)

Finally, the joint torque reference vector \( \tau_{\text{ref}} \) is given as follows.

\[ \tau_{\text{ref}} = J_{\text{aco}}(q)^{T}(M_{\text{en}}^{-1}F_{\text{ref}} + F_{\text{dis}}) \]

(48)

The disturbance force in (48) is estimated by disturbance force observer (DFOB) which block diagram is shown in Fig. 2. The dynamical disturbance including and the variation of the equivalent mass matrix is compensated by implementing DFOB which input of acceleration information is obtained from Kalman filter. Furthermore, force response in the force controller (47) is estimated by RFOB which block diagram is shown in Fig. 3. The parameters \( F_{\text{int}} \) and \( F_{\text{fric}} \) in this diagram represent inner interference force and friction force respectively. Generally, the parameter \( F_{\text{int}} \) is always ignored since the value is really small. The parameter \( F_{\text{fric}} \) is often identified previously through identification test, however, that value is also ignored in this paper under assumption that the value is very small with small motion of the manipulator when force control. These observers include 1st order LPF, then measurement noise may be sufficiently eliminated when that is input directly into these observers. However, LPF with too low its cut-off frequency contributes the system instability, so it is necessary to eliminate noise previously before inputting observers. In addition to that, Kalman filter can also estimate the system state based on prescribed system model, not only eliminate noise of the acceleration sensor measurement.

3.2 Calculation Algorithm of Extended Kalman Filter

Kalman filter is a set of mathematical equations that provides an efficient computational solution of the least-squares method. The filter is very powerful in several aspects. For example, it supports estimation of past, present, and even future states, and it can do so even when the precise nature of the modeled system is unknown. It is basically a statistical method that combines knowledge of the statistical nature of system errors with knowledge of system dynamics, as represented by a state space model, to provide an estimate of the state of a system.

In this paper, Kalman filter is utilized to estimate the acceleration information of the manipulator’s end-effector from the measurements of the acceleration sensor including noises. Concretely speaking, Kalman filter (KF) is applied to the
linear system based on work-space dynamics represented by (25) and (26), and extended Kalman filter (EKF) is applied to the linearized system based on kinematics represented by (36) and (43). EKF is one of Kalman filter which algorithm is expanded to be applied the non-linear system as shown in (36). The algorithm ofKF and EKF are almost the same, and that of EKF can be considered it is a generalized Kalman filter, then in this paper, only EKF algorithm is explained.

Basically, Kalman filter algorithm has two steps. First step is called prediction step, and second step is called filtering step. Each step is represented as follows.

1) Prediction Step
\[
\hat{x}_{t|k-1} = A\hat{x}_{t|k-1} + B_{a}u_{k-1}
\]
\[
P_{t|k-1} = AP_{t|k-1}A^{T} + \sigma^2_{e}I
\]
where subscript “-” indicates the a priori values of the variables (before the information in the measurement is used). \(P\) is the error covariance matrix.

2) Filtering Step
\[
g(k) = P^{-}(k)e^{T}(k)(e^{T}(k)P^{-}(k)e(k) + \sigma^2_{w})^{-1} \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot 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KF and EKF, ordinary tip-position control based on encoder information is conducted in this section.

### 4.1.1 Simulation Specifics

The force reference for tip-position control is generated as follows.

\[
F_{\text{ref}} = M_{\text{en}} \left[ K_p (x_{\text{cmd}} - x_{\text{res}}) + K_v (\dot{x}_{\text{cmd}} - \dot{x}_{\text{res}}) + \ddot{x}_{\text{cmd}} \right]
\]  

(54)

where \( K_p \) and \( K_v \) are position gain and velocity gain respectively. The position command \( x_{\text{cmd}} \) is given to follow circular orbit. Two different following speeds of circular commands, QUICK and SLOW modes are tried, and those specifics are shown in Table 2. The parameters set in the simulations are given as Table 3. The values of position gain \( K_p \) and velocity gain \( K_v \) are determined to make this position control system critical damping. Generally speaking, it is difficult to identify the covariance of measurement noise of sensors, then the suitable initial condition of KF and EKF are determined by try and error, and specified as follows in this simulation.

- **KF**

\[
\hat{x}_k(0) = [0 \ 0 \ 0 \ 0]^T \quad \text{....................... (55)}
\]

\[
diag P(0) = 0.05 \quad \text{....................... (56)}
\]

\[
diag \sigma_w^2 = 3.5 \quad \text{....................... (57)}
\]

\[
diag \sigma_v^2 = 1.8 \quad \text{....................... (58)}
\]

- **EKF**

\[
\hat{x}_{\text{est}}(0) = [q_{\text{init}}^{\text{init}} \ q_{\text{init}}^{\text{init}} \ q_{\text{init}}^{\text{init}} \ 0 \ 0 \ 0 \ 0 \ 0]^T \quad \text{..................... (59)}
\]

\[
diag P(0) = 0.00005 \quad \text{....................... (60)}
\]

where the subscript “init” denotes the value in initial condition of the manipulator.

### 4.1.2 Simulation Results

The simulation results of estimated acceleration information by KF and EKF when following QUICK motion are shown in Fig. 8 and Fig. 9 respectively. From these figures, it can be said that the estimation performance of acceleration of KF is better than that of EKF, while the former has still larger noises than the latter. It is considered that the worse estimation of EKF is induced by approximation of jerk joint-angular term in (34) as Gaussian white noise with zero mean. The accelerations vary in time during the arm motion, and the zero mean assumption is not valid, particularly during fast acceleration periods.

Fig. 10 and Fig. 11 show the simulation results of estimated acceleration information by KF and EKF when following SLOW motion. From Fig. 10, it can be said that the S/N ratio is worse with low acceleration. By taking a comparison between Fig. 9 and Fig. 11, it is thought that the EKF with slow motion of the manipulator shows relatively better estimation performance than that with fast motion.

In the end of this simulation, EKF will be better choice when conducting force control with small motion of the manipulator.

### 4.2 Force Control Based on KF/EKF

In this subsection, estimated acceleration values from KF/EKF are feed-backed for the force control system shown in Fig. 4 and Fig. 5, and examined the performance of each control system.

#### 4.2.1 Simulation Specifics

The reaction force from environment is assumed as spring-damper system given by (63).

\[
F_{\text{env}} = -M_{\text{en}} (x_{\text{res}} - x_{\text{cmd}}) + D_{\text{en}} \dot{x}_{\text{res}} \quad \text{................ (63)}
\]
Force Control Based on Acceleration Sensor

Nobuhiro Kobayashi et al.

Fig. 10. Estimated acceleration by KF in simulation (LOW)

Fig. 11. Estimated acceleration by EKF in simulation (LOW)

Table 4. Parameters of environmental force

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_{env} )</td>
<td>1.0</td>
<td>Environment virtual mass</td>
</tr>
<tr>
<td>( k_{env} )</td>
<td>500.0</td>
<td>Environment stiffness</td>
</tr>
<tr>
<td>( d_{env} )</td>
<td>10.0</td>
<td>Environment damping</td>
</tr>
</tbody>
</table>

Fig. 12. Force control result with KF in simulation

where each parameters are set as shown in Table 4. The observer gains and the initial conditions of Kalman filter and extended Kalman filter are set as the same with the former simulation. The force reference is generated by (47), and force command \( F^{\text{cmd}} \) is given as linear function to make pushing motion along to \( x \)-axis in \( t = 5.0 - 7.0 \) [sec], and sinusoidal wave is given as force command after that period.

4.2.2 Simulation Results

Figure 12 and Fig. 13 show the results when force control of pushing motion is conducted with feedback of estimated acceleration information from KF and EKF respectively. From these figures, KF based force control shows worse performance than EKF based one because of remaining noise effect in estimated acceleration information as shown in previous simulations. Though this noise effect could be eliminated by setting the cut-off frequency of DFOB lower, it is generally known that the lower cut-off frequency is unlikable since bandwidth of the observer becomes narrower.

5. Experiments

In this section, experiments are carried out using proposed force control system, and the validation is confirmed in actual environment.

5.1 Experiment Specifics

Figure 14 shows overview of experimental setup, and this system is operated by RT-Linux. All parameters and initial conditions of KF and EKF are set as the same with in simulations. The values of cut-off frequency \( g_{d/ob} \) and \( g_{r/ob} \) are determined by try and error. In general, cut-off frequency of observers should be increased as possible from perspectives of estimation accuracy, however, in actual situation, those values cannot be too big to avoid instability of the system with bad effect of sensor noise. Then those values are often determined by try and error in practical situation. The Table 5 shows each specification of experimental setup. Force commands are also given like simulations, and accuracy of force control is examined. It has to be noticed that \( F_{int} \) and \( F_{fric} \) in Fig. 3 are ignored since those values are thought to be small with slow contact motion in this experiment. Output of the RFOB calculated based on encoder information is assumed as the actual force response in this experiment. Table 5 shows the specification of the acceleration sensor adopted in experiments, and Fig. 15 shows the raw data of \( x \)-axis acceleration from the sensor. As shown in Fig. 15, an acceleration sensor with higher resolution would be preferable from the viewpoint of accuracy, since S/N ratio is bad in relatively small motion of the manipulator when conducting force control. In addition to that, as shown in Table 5, any acceleration sensor has bias error more or less when it stops, thus adequate processing is necessary to eliminate it before moving the manipulator. In this paper, average value of bias error which is measured during stopping motion is simply subtracted from actual sensor data during force control.

5.2 Experiment Results

Figure 16 and Fig. 17 show
Table 5. Specification of experimental setup

<table>
<thead>
<tr>
<th>Constant</th>
<th>Value</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>(J_i(1,2,3))</td>
<td>(810 \times 10^{-4}, 430 \times 10^{-4}, 150 \times 10^{-4})</td>
<td>inertia moment of (i)-th motor [kg·m²]</td>
</tr>
<tr>
<td>(G_i(1,2,3))</td>
<td>100, 100, 100</td>
<td>gear ratio of (i)-th motor</td>
</tr>
<tr>
<td>(K_i(1,2,3))</td>
<td>5.76, 4.91, 4.2</td>
<td>torque constant of (i)-th motor [Nm/A]</td>
</tr>
<tr>
<td>(l_i(1,2,3))</td>
<td>0.15, 0.15, 0.15</td>
<td>length of (i)-th link [m]</td>
</tr>
<tr>
<td>(m_i(1,2,3))</td>
<td>0.42, 0.52, 0.18</td>
<td>weight of (i)-th link [kg]</td>
</tr>
</tbody>
</table>

Table 6. Specification of acceleration sensor

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>500[mV/G]</td>
</tr>
<tr>
<td>Band frequency</td>
<td>0 - 100 [Hz]</td>
</tr>
<tr>
<td>Zero-point offset</td>
<td>±3.75×10[-4] [VDC]</td>
</tr>
</tbody>
</table>

Fig. 15. Raw acceleration sensor data

Fig. 16. Force control result with KF in experiment

Fig. 17. Force control result with EKF in experiment

As possible by Kalman filter before inputting the observer. From this point of view, EKF is suitable about eliminating noise in acceleration sensor measurement especially in relatively static state of manipulator’s motion with bad S/N ratio. Though Fig. 17 also shows a little oscillation and error in force control, the EKF based force control system utilizing only an acceleration sensor measurements could be a back up or alternative system of ordinary encoder based force control system in practical application if the accuracy could be compromised at some extent. Generally speaking, oscillation of response in force control could be suppressed by force feedback, thus oscillating response in 16 is considered not from the structure but from the force controller and estimation performance of Kalman filter. In the proposed approach, as one of remarkable features, only the feasibility of kinematics estimation in MDOF manipulator by acceleration sensors without joint encoders is shown and its application to force control is described. To achieve high performance force control, there are some important issues. In particular, the determination of optimal location of acceleration sensors and additional modeling of mechanical system including two-mass resonant system are key issues for achieving significant improvement of force control performance. They are subjects for future studies and development.

6. Conclusion

Two types of force control system based on measurements of an acceleration sensor attached on the tip-position of a 3-link planar redundant manipulator were proposed in this paper. The planar redundant manipulator is adopted to consider severer condition than non-redundant one and to avoid gravity effect as a first step of this research. To estimate the acceleration information, Kalman filter (KF) based on dynamic model and extended Kalman filter (EKF) based on kinematic model were introduced and implemented. Furthermore, Disturbance Force Observer (DFOB) and Reaction Force Observer (RFOB) were also implemented to eliminate the error of force control and to estimate the force response without force sensor respectively in the force control system, and the estimated acceleration information obtained by KF/EKF was directly utilized in those observers. Simulations and experiments evaluate estimation performance and compare the force control performance based on each of KF and EKF. From simulation and experiment results, EKF based force control system is thought to be more adequate to construct the system utilizing only an acceleration sensor measurements than KF based one, and this system could be taken advantage as a back up or alternative system of ordinary encoder based force control system in practical application if the accuracy could be acceptable at some extent. To consider more general condition, non-planar manipulator with gravity effect should be adopted as a future work. The same method in this paper is considered to be available by including the gravity effect in the model.

References

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