Force and Acceleration Sensor Fusion for Compliant Robot Motion Control

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Abstract—In this work, we present implementation and experiment of the theory of dynamic force sensing for robotic manipulators, which uses a sensor fusion technique in order to extract the contact force exerted by the end-effector of the manipulator from those measured by a wrist force sensor, which are corrupted by the inertial forces on the end-effector. We propose a new control strategy based on multisensor fusion with three different sensors—that is, encoders mounted at each joint of the robot with six degrees of freedom, a wrist force sensor and an accelerometer—whose goal is to obtain a suitable contact force estimator for the three Cartesian axes. This new observer contributes to overcome many of the difficulties of uncertain world models and unknown environments, which limit the domain of application of current robots used without external sensory feedback. An impedance control scheme was proposed to verify the improvement. The experiments were carried out on an ABB industrial robot with open control system architecture.

Keywords: Force Control, Observers, Sensor Fusion, Robot Control.

I. INTRODUCTION

It has been long recognized that multisensor-based control is an important problem in robotics. As a robotic manipulator is expected to accomplish more and more complex tasks, such as assembly and task planning in a manufacturing workcell, the need to take advantage of multiple sensors in controlling a system becomes increasingly important [1].

On the other hand, the manipulation can be controlled only after the interaction forces are controlled properly. That is why force control is required in manipulation robotics. For force control to be implemented, information regarding forces at the point contact has to be fed back to the controller. Force sensors are getting that information. An important problem arises when we have only a force sensor. That is a dynamic problem; in the dynamic situation, not only the interaction forces and moments at the contact point but also the inertial forces are measured by the wrist force sensor [2]. Since the inertial forces are undesirable forces to be measured in the robot manipulation, we need to process the force sensor signal in some way in order to extract the contact force exerted by the robot.

In order to overcome this problem, Uchiyama proposed to use the trajectory error in a computed torque servo as signals for the external forces and moments [3]. Fujita and Inoue applied a similar idea to the measurement of forces by a strain gage [4]. In their method, the external forces are extracted from the forces measured by the strain gage by subtracting the inertial forces to be estimated by the trajectory reference [4]. Those methods, however, can be applied only to the cases where planned trajectories are known beforehand. To avoid this drawback, Uchiyama proposed an optimal filter to extract the external forces and moments from the forces and moments measured by a force sensor [2]. His method includes dynamic modeling of the process of force sensing and estimation of the external forces and moments by an optimal filter—i.e., the extended Kalman filter.

Following this idea, Lin developed a controller consisting basically in a position controller and a compensator in the contact force feedback loop [5]. For this controller, if the manipulator is in free motion, the contact force estimate becomes zero and the controller is automatically reduced to a position controller. On the other hand, if the manipulator is in contact motion, the compensator in the force feedback loop is designed to reshape the overall transfer function so that the closed-loop system can reach the desired target. To estimate the contact force, an observer was developed which used the dynamic information of the tool where some of these dynamic variables, like the acceleration of the tool, were simply estimated by means of the kinematic model of the robot. As the tool acceleration estimate does not reflect the real acceleration of the tool, high accuracy cannot be expected.

To solve this problem, a new fusion of force and acceleration sensors was proposed in [6], which combines the mentioned sensors using an observer based in a Kalman Filter, with the goal of obtaining a suitable
Environmental force estimator. This observer was applied successfully in an impedance control loop to control the force exerted by a six-DOF robotic manipulator to its environment.

The main contribution of this paper is to develop a new force observer that fuses the data from three different sensors—that is, resolvers mounted at each joint of the robot with six degrees of freedom, a wrist force sensor and an accelerometer—with the goal of obtaining a suitable contact force estimator. In contrast to the observer proposed in [6], the new observer includes the dynamic of the robotic manipulator, which improves the properties of the observer, and moreover, it was extended to the three Cartesian task-space axes.

The rest of the paper is organized as follows. Firstly, the problem formulation is presented in Sec. II. In Sec. III, we describe the new observer. The Setup of the system is described in Sec. IV. Section V describes the Modeling and Control. Results are shown in Sec. VI. Finally, the conclusions are presented in Section VII.

II. PROBLEM FORMULATION

Assume that the robot dynamic for each axis \( i \) can be modelled by the following space state system (Fig. 1)

\[
\begin{align*}
\dot{\xi}_i &= A_R \xi_i + B_R \text{Ref}_i \\
y_i &= C_R \xi_i + D_R \text{Ref}_i
\end{align*}
\]  

(1)

where \( \xi = (\xi_1, \xi_2, \xi_3)^T \) is \( (p_{\text{pos}}, v_{\text{el}}, a_{\text{cc}})^T \) and \( \text{Ref}_i \) represents the position reference for axis \( i \). Matrices \( A_i, B_i, C_i \) and \( D_i \) have the following structure:

\[
\begin{align*}
A_R &= \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix}, & B_R &= \begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix} \\
C_R &= \begin{pmatrix} c_{11} & c_{12} & c_{13} \end{pmatrix}, & D_R &= \begin{pmatrix} d_{1} \end{pmatrix}
\end{align*}
\]  

(2)

This model represents the dynamic of the manipulator for each axis \( i \) without considering the force interaction—that is, inertial and contact forces—on its tip. On the other hand, when contact manipulation with a surface using the end-effector of a robotic manipulator (Fig. 1), the wrist force sensor measures two kinds of forces: the environmental or contact force \( (F_i) \) and the inertial force produced by acceleration \( (m_\text{ref}_i) \), that is:

\[
m_\text{ref}_i = u_i - F_i
\]  

(4)

being \( m \) the tool mass.

Then, considering Eqs. (1) and (4), the whole dynamics of the manipulator can be represented by

\[
\begin{align*}
\dot{\xi}_i &= A_R \xi_i + B_R \text{Ref}_i + B_u u_i + B_F F_i \\
y_i &= C_R \xi_i + D_R \text{Ref}_i + B_F F_i
\end{align*}
\]  

(5)

where

\[
B_u = \begin{pmatrix} 0 \\ 0 \\ m \end{pmatrix}, & B_F = \begin{pmatrix} 0 \\ -\frac{1}{m} \\ 0 \end{pmatrix}
\]  

(6)

III. FORCE OBSERVER

Sensor fusion is a method of integrating signals from multiple sources. It allows extraction of information from several different sources to integrate them into a single signal or information. In our case, the final information corresponds to the contact force that a manipulator exerts to its environment while the sources of information are three different sensors, namely: resolvers mounted at each joint of the robot with six degrees of freedom, a wrist force sensor and an accelerometer.

To our purpose, a force observer based on Kalman filter technique was developed to estimate the environmental force \( (F_i) \) for the three Cartesian axes \( (x, y \text{ and } z) \), that is, to separate the external forces and distal end-effector inertia forces in the measurement given by the force sensor.

From Eqs. (5) and (6) and, as position, position reference, force and acceleration for each axis \( i \) are assumed to be available to measurement, the outputs \( y_i \) of our system...
description may be arranged as
\[
y_i = \begin{pmatrix} c_1 \xi_i \\ c_2 \tilde{F}_i \tilde{F}_i + c_4 F_i \tilde{F}_i \\ c_5 b_i \end{pmatrix} = \begin{pmatrix} c_1 & 0 & 0 \\ 0 & c_2 & 0 \\ 0 & 0 & c_4 \end{pmatrix} \begin{pmatrix} \xi_i \\ p_{ref,i} \\ F_i \end{pmatrix} \tag{8}
\]

or
\[
y_i = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \frac{c_3 - c_5}{m} \\ 0 & \frac{c_3 - c_5}{m} & -c_5 \end{pmatrix} \begin{pmatrix} p_{ref,i} \\ u_i \\ F_i \end{pmatrix} \tag{9}
\]

where all outputs are multiplied by a configurable gain \( c_{ji} \) to be calibrated and \( 0_{3x3} \) is a zero matrix of \( 3x3 \) dimensions. In brief notation, we have
\[
y_i = C_i \tilde{\xi}_i + D_i \begin{pmatrix} p_{ref,i} \\ u_i \\ F_i \end{pmatrix} \tag{10}
\]

Static Force Observers

A force observer suggested from these relationships would be
\[
\tilde{F}_i = D_i^T y_i = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \begin{pmatrix} c_1 & 0 & 0 \\ 0 & c_2 & 0 \\ 0 & 0 & c_4 \end{pmatrix} \begin{pmatrix} 0 \\ c_3 - c_5 \\ -c_5 \end{pmatrix} y_i \tag{11}
\]

where \( D_i^T \) is the pseudo-inverse of \( D_i \).

Provided that the calibration constants \( \{c_{ji}\}_{j=1}^5 \) are known and non-zero, the observers will offer an exact measurement of the force \( F_i \) without any observer dynamics. A direct calculation gives
\[
\tilde{F}_i = \frac{1}{c_4 c_5} \begin{pmatrix} 0 \\ 0 \\ c_5 \end{pmatrix} y_i = F_i \tag{12}
\]

Dynamic Force Observers

Converting the equations of motion into a standard state space formulation we have
\[
\begin{align*}
\dot{\tilde{\xi}}_i &= A_i \tilde{\xi}_i + B_i p_{ref,i} + B_{u} u_i + B_F F_i \\
\tilde{y}_i &= C_i \tilde{\xi}_i + D_i p_{ref,i} + D_{u} u_i + D_F F_i \tag{13}
\end{align*}
\]

where the matrices \( A_i, B_i, B_F, C_i, D_{pi}, D_{ui} \) and \( D_F \) can be obtained from Eqs. (1) and (9) as
\[
A_i = \begin{pmatrix} a_{11,i} & a_{12,i} & a_{13,i} \\ a_{21,i} & a_{22,i} & a_{23,i} \\ a_{31,i} & a_{32,i} & a_{33,i} \end{pmatrix}, B_i = \begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix} \tag{14}
\]
\[
B_u = \begin{pmatrix} 0 \\ 0 \\ 1/m \end{pmatrix}, B_F = \begin{pmatrix} 0 \\ -1/m \end{pmatrix}, C_i = \begin{pmatrix} c_{11} \\ c_{12} \\ 0_{2x3} \end{pmatrix}, D_{pi} = \begin{pmatrix} 0 \\ 0 \\ -c_{33}/m \end{pmatrix}, D_{ui} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}, D_F = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \tag{15}
\]

As previously mentioned, a Kalman filter is proposed to estimate the environmental force in system (13). In this context, an observer where the input \( F \) has not been considered is useful and the resultant bias between data and Kalman filter output is instrumental for estimation of external forces acting on the system
\[
\begin{align*}
\dot{\tilde{\xi}}_i &= A_i \tilde{\xi}_i + B_i p_{ref,i} + B_{u} u_i + K_i (y_i - \tilde{y}_i) \\
\tilde{y}_i &= C_i \tilde{\xi}_i + D_{pi} p_{ref,i} + D_{ui} u_i + D_F F_i \tag{16}
\end{align*}
\]

The dynamics of the estimation error \( \tilde{\xi}_i = \xi_i - \tilde{\xi}_i \) for axis \( i \) are obtained as
\[
\begin{align*}
\dot{\tilde{\xi}}_i &= (A_i - K_i C_i) \tilde{\xi}_i - (B_F + K_i D_F) F_i \\
\tilde{y}_i &= y_i - \tilde{y}_i = C_i \tilde{\xi}_i + D_{pi} p_{ref,i} + D_{ui} u_i + D_F F_i \tag{17}
\end{align*}
\]

Then, if matrix \((A_i - K_i C_i)\) is designed to have eigenvalues with negative real part so that the observers be stable, observer-based dynamic force observers may be suggested as
\[
\tilde{F}_i = D_F^T (\tilde{y}_i - C_i \tilde{\xi}_i) \tag{18}
\]

with the property
\[
\tilde{F}_i = D_F^T (-C_i \tilde{\xi}_i + \tilde{y}_i) = D_F^T D_F F_i = F_i \tag{19}
\]

In the case studied here where \( D_F^T C = 0 \), a particularly simple form of an unbiased force observer is obtained as
\[
\tilde{F}_i = D_F^T \tilde{y}_i \tag{20}
\]

Stochastic Force Estimation Error Dynamics

In the case where stochastic disturbances are present, we consider the system dynamics for each axis \( i \)
\[
\begin{align*}
\dot{\tilde{\xi}}_i &= A_i \tilde{\xi}_i + B_i p_{ref,i} + B_{u} u_i + B_F F_i + v_{\tilde{\xi}}_i \\
y_i &= C_i \tilde{\xi}_i + D_{pi} p_{ref,i} + D_{ui} u_i + D_F F_i + v_{y_i} \tag{21}
\end{align*}
\]
with uncorrelated stochastic disturbance processes \( v_{s,i} \) and \( v_{y,i} \) such that

\[
\mathcal{E}'\left(\begin{bmatrix} v_{s,i} \\ v_{y,i} \end{bmatrix}\right) = 0, \quad \mathcal{E}'\left(\begin{bmatrix} v_{s,i} \\ v_{y,i} \end{bmatrix}\right)^T = Q_i = \begin{bmatrix} Q_{s,i} & Q_{y,i} \\ Q_{y,i}^T & Q_{y,y,i} \end{bmatrix}
\]

The stochastic properties of the static and dynamic force estimation errors \( \hat{F}_i \), respectively, will be

\[
\mathcal{E}\{\hat{F}_i\} = \begin{bmatrix} F_i - \hat{F}_i = F_i - D_i^T \hat{y}_i = -D_i^T v_{y,i} \\ F_i \end{bmatrix} = 0, \quad \mathcal{E}\{\hat{F}_i \hat{F}_i^T\} = D_i^T Q_i (D_i^T)^T
\]

and

\[
\hat{F}_i = F_i - \hat{F}_i = F_i - D_i^T (\hat{y}_i - C_i \hat{\xi}_i) = -D_i^T v_{y,i}
\]

\[
\mathcal{E}\{\hat{F}_i\} = 0, \quad \mathcal{E}\{\hat{F}_i \hat{F}_i^T\} = D_i^T Q_i (D_i^T)^T
\]

Using transfer function notation, we have

\[
\hat{F}_i(s) = D_i^T (-C_i (sI - A_i + K_i C_i)^{-1} (B_F + K_i D_F)) F_i(s) + D_i^T D_F F_i(s) + D_i^T v_{y,i}(s)
\]

\[
= F_i(s) + D_i^T v_{y,i}(s)
\]

Whereas these force estimators are unbiased, they are sensitive to accelerometer noise and it is worthwhile to consider other force observer structures with low-pass properties.

**Low-pass Force Observer Structures**

As the unbiased force estimators are sensitive to accelerometer noise, it is worthwhile to consider other force observer structures with low-pass properties. In search of such observer structures, from Eqs. (13) and (15) the dynamics of the estimation error \( \hat{\xi}_i \) can be obtained as

\[
\dot{\hat{\xi}}_i = (A_i - K_i C_i) \hat{\xi}_i + K_i C_i \hat{\xi}_i + B_F F_i + k_i D_F p_{ref,i}(27)
\]

where \( y_i \) are the outputs of our system (Eq. 9). Then, component-wise application of the observer (Eq. 28) gives

\[
\dot{\hat{\xi}}_{1,i} = (a_{11} - k_{11} c_{11}) \hat{\xi}_{1,i} + a_{12} \hat{\xi}_{2,i} + a_{13} \hat{\xi}_{3,i}
\]

\[
+ k_{11} c_{11} \hat{\xi}_{1,i} - k_{12} \hat{\xi}_{2,i} + k_{13} c_{13} \hat{\xi}_{3,i} + a_{11} y_i + a_{12} \hat{\xi}_{2,i} + a_{13} \hat{\xi}_{3,i}
\]

\[
\dot{\hat{\xi}}_{2,i} = (a_{21} - k_{21} c_{11}) \hat{\xi}_{1,i} + a_{22} \hat{\xi}_{2,i} + a_{23} \hat{\xi}_{3,i}
\]

\[
+ k_{21} c_{11} \hat{\xi}_{1,i} - k_{22} \hat{\xi}_{2,i} + k_{23} c_{23} \hat{\xi}_{3,i} + a_{21} y_i + a_{22} \hat{\xi}_{2,i} + a_{23} \hat{\xi}_{3,i}
\]

\[
\dot{\hat{\xi}}_{3,i} = (a_{31} - k_{31} c_{11}) \hat{\xi}_{1,i} + a_{32} \hat{\xi}_{2,i} + a_{33} \hat{\xi}_{3,i}
\]

\[
+ k_{31} c_{11} \hat{\xi}_{1,i} - k_{32} \hat{\xi}_{2,i} + k_{33} c_{33} \hat{\xi}_{3,i} + a_{31} y_i + a_{32} \hat{\xi}_{2,i} + a_{33} \hat{\xi}_{3,i}
\]

where

\[
\alpha_{11} = k_{13} c_{13} + k_{14} c_{14} m
\]

\[
\alpha_{21} = k_{23} c_{23} + k_{24} c_{24} m
\]

\[
\alpha_{31} = k_{33} c_{33} + k_{34} c_{34} m
\]

Deriving Eq. (29) and using Eqs. (30) and (31), an expression for the dynamics of \( \hat{\xi}_i \), can be found as

\[
\dot{\hat{\xi}}_i = \dot{\hat{\xi}}_{1,i} - \Lambda_{1,i} \hat{\xi}_{1,i} - (a_{12} \Lambda_{2,i} + a_{13} \Lambda_{3,i}) \hat{\xi}_{3,i} = \beta_i - \frac{a_{12}}{m} F_i
\]
which included the robot dynamic and the tool, was
later, a movement in constrained space.

As for the experiments carried out to verify
automatic calibration procedure,
impedance control
observer performance and in consequence, the proposed
was used to represent the physical constraint. To verify the
experiments was a grinding tool with a weight of 13 kg.

The accelerometer was placed on the tip of the tool to
measure its acceleration. The accelerometer signals were
read by the robot controller in real time via an analog input.

The model used for our experiment had the
following features:
- Type: Triaxial capacitive accelerometer.
- Model: PCB Piezotronics 3703D3FD20G.
- Sensitivity: 100mV/g (10.2mV/(m/s)).
- Measurement Range: 20g pk (196m/s pk).
- Frequency Range: 0 to 500Hz.

V. MODELING AND CONTROL

For the environment, a vertical screen made of cardboard
was used to represent the physical constraint. To verify the
observer performance and in consequence, the proposed
automatic calibration procedure, impedance control was
used [7] [9]. As for the experiments carried out to verify the
automatic procedure, they consisted of three phases:
an initial movement in free space, a contact transition, and
later, a movement in constrained space.

The model used to design the impedance controller, which included the robot dynamic and the tool, was
considered for the three Cartesian task-space axes.

A linear dynamic model showing the relation between
the position reference (\(p_{ref_i}\)) and the current position of
the robot tip (\(\xi_i\)) was identified. An output-error model
was calculated using the System Identification Toolbox of
Matlab, the resulting model being as follows:

\[
G_1(q) = \frac{1.2348q^{-1} - 1.5084q^{-2} + 0.3011q^{-3}}{1 - 1.0494q^{-1} + 0.0775q^{-2} - 0.0006q^{-3}}
\]

(39)

The state space equations of the system were:

\[
\begin{align*}
\dot{X}_i &= A_d X_i + B_d x_{p_{ref_i}} \\
y_i &= C_d X_i
\end{align*}
\]

(40)

where \(X_i = [\xi_i, \dot{\xi}_i, \ddot{\xi}_i]^T\) and

\[
A_d = \begin{bmatrix}
49.6 & -55.8 & 0.4 \\
658 & 641 & 4.8 \\
-8022 & 9077.2 & -1263
\end{bmatrix}
\]

(41)

\[
B_d = \begin{bmatrix}
214 \\
-444 \\
7578
\end{bmatrix}, C_d = \begin{bmatrix} 1.2348 & -1.5084 & 0.3011 \end{bmatrix}
\]

(42)

for \(i = x, y, \) and \(z\). The impedance control approach was
chosen as the control law to verify the properties of the
new force observer. In this sense, a LQR controller was
used to make the impedance impedance relation variable
go to zero [9] for the three axes \((x, y, z)\). The control law
applied was

\[
u_i = -Lx_i + c_i \hat{F}_i + l_i \hat{p}_{ref_i}
\]

(43)

with \(c_i\) as the force gain in the impedance control, \(\hat{F}_i\)
the estimated environmental force, which in our case it
was estimated using the force observer, \(p_{ref_i}\) the position
reference for axes \((x, y, z)\) and \(l_i\) the position gain constant,
\(L\) being calculated considering Eq. (40).

VI. RESULTS

The experiments carried out on the real robot to verify
the performance of the observer consisted of three phases
for all axes \((x, y, z)\): an initial movement in free space, a
contact transition, and later, a movement in constrained space.

The experiments for axis \(x\) are shown in Fig. 3, which
depicts, at the top, the force measurement from the JR3
sensor (left) and the force observer output (right) while
at the bottom, the acceleration of the tool getting into
contact with the environment (left), and the observer
compensation (right) are shown. Note that the observer
eliminates the inertial effects.

Fig. 4 depicts the force sensor output for axis \(y\) and the
force observer output for the same axis (left). Note that
the observer eliminates the inertial effects and how the
transition of contact phase \((t = 4s)\) is improved since the
observer eliminates the perturbations introduced by the
VII. CONCLUSIONS

A new contact force observer that fuses the data from three different sensors—that is, resolvers mounted at each joint of the robot with six degrees of freedom, a wrist force sensor and an accelerometer—with the goal of obtaining a suitable contact force estimator has been developed. The new observer includes the dynamics of the robotic manipulator, which improves the properties of the observer. Moreover, it is extended to the three Cartesian task-space axes.

On the other hand, the observer helps to improve the performance as well as stability and robustness for the impact transition phase since it eliminates the perturbations introduced by the inertial forces. To verify the behavior of the observer, experiments were done on an industrial robot applying an impedance control approach.

REFERENCES


