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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 currents 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 feed 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)

$$\begin{cases} \dot{\xi}_i = A_{R_i}\xi_i + B_{R_i}p_{ref_i} \\ y_i = C_{R_i}\xi_i + D_{R_i}p_{ref_i} \end{cases} \tag{1}$$

where $\xi_i = (\xi_{1_i}, \xi_{2_i}, \xi_{3_i})^T = (pos_i, vel_i, acc_i)^T$ and p_{ref_i} represents the position reference for axis i. Matrices A_i, B_i, C_i and D_i have the following structure:

$$A_{R_i} = \begin{pmatrix} a_{11_i} & a_{12_i} & a_{13_i} \\ a_{21_i} & a_{22_i} & a_{23_i} \\ a_{31_i} & a_{32_i} & a_{33_i} \end{pmatrix}, B_{R_i} = \begin{pmatrix} b_{1_i} \\ b_{2_i} \\ b_{3_i} \end{pmatrix} \tag{2}$$

$$C_{R_i} = \begin{pmatrix} c_{11_i} & c_{12_i} & c_{13_i} \end{pmatrix}, D_{R_i} = \begin{pmatrix} d_{1_i} \end{pmatrix} \tag{3}$$

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 ($m\ddot{\xi}_{1_i}$), that is:

$$m\ddot{\xi}_{1_i} = u_i - F_i \tag{4}$$

being m the tool mass.

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

$$\begin{cases} \dot{\xi}_i = A_{R_i}\xi_i + B_{R_i}p_{ref_i} + B_u u_i + B_F F_i \\ y_i = C_{R_i}\xi_i + D_{R_i}p_{ref_i} \end{cases} \tag{5}$$

where

$$B_u = \begin{pmatrix} 0 \\ \frac{1}{m} \\ 0 \end{pmatrix}, B_F = \begin{pmatrix} 0 \\ -\frac{1}{m} \\ 0 \end{pmatrix} \tag{6}$$
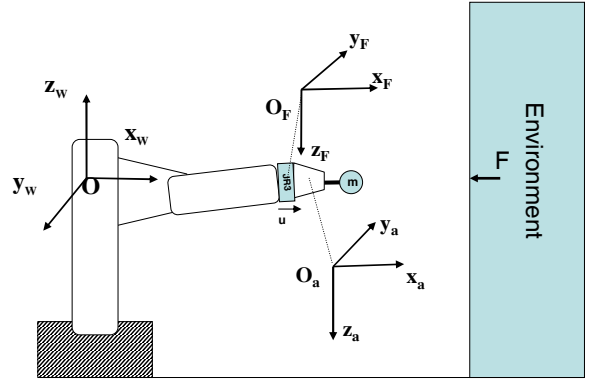

Fig. 1. Coordinate frames of the system and interaction with the environment.

Since the task undertaken requires the control of the environmental force (F_i), an observer, which fuses information from a force sensor and an accelerometer and, that takes into account the manipulator dynamics, is proposed to estimate this environmental force.

Description of coordinate frames and motion

As shown in Fig. 1, $O_F X_F Y_F Z_F$ and $O_A X_A Y_A Z_A$ correspond, respectively, with the force sensor coordinate frame and the accelerometer frame. The world frame is represented by $O_W X_W Y_W Z_W$ and coincides with the robot frame. To our purpose, the force observer will be developed in the three axes OX_F, OY_F and OZ_F.

Let R_A^F denote the rotation matrix that relates accelerometer frame to the force sensor frame. Assume that the force sensor is rigidly attached to the robot tip, the accelerometer is placed on the tool and that

$$R_A^F = I_{3x3} \tag{7}$$

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 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

$$y_i = \begin{pmatrix} c_{1_i}\xi_{1_i} \\ c_{2_i}p_{ref_i} \\ c_{3_i}\ddot{\xi}_{1_i} + c_{4_i}F_i \\ c_{5_i}\ddot{\xi}_{1_i} \end{pmatrix} = \begin{pmatrix} c_{1_i} & 0 & 0 & 0 \\ 0 & c_{2_i} & 0 & 0 \\ 0 & 0 & c_{4_i} & c_{3_i} \\ 0 & 0 & 0 & c_{5_i} \end{pmatrix} \begin{pmatrix} \xi_{1_i} \\ p_{ref_i} \\ F_i \\ \ddot{\xi}_{1_i} \end{pmatrix} \tag{8}$$

or

$$y_i = \begin{pmatrix} c_{1_i} & 0 & 0 \\ & 0_{3x3} & \end{pmatrix} \begin{pmatrix} \xi_{1_i} \\ \xi_{2_i} \\ \xi_{3_i} \end{pmatrix} +$$
$$+ \begin{pmatrix} 0 & 0 & 0 \\ c_{2_i} & 0 & 0 \\ 0 & \dfrac{c_{3_i}}{m} & c_{4_i} - \dfrac{c_{3_i}}{m} \\ 0 & \dfrac{c_{5_i}}{m} & \dfrac{-c_{5_i}}{m} \end{pmatrix} \begin{pmatrix} p_{ref_i} \\ u_i \\ F_i \end{pmatrix} \tag{9}$$

where all outputs are multiplied by a configurable gain c_{j_i} to be calibrated and 0_{3x3} is a zero matrix of $3x3$ dimensions. In brief notation, we have

$$y_i = C_i\xi_i + D_i \begin{pmatrix} p_{ref_i} \\ u_i \\ F_i \end{pmatrix} \tag{10}$$

Static Force Observers

A force observer suggested from these relationships would be

$$\widehat{F}_i = D_i^{\dagger}y_i = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}^T \begin{pmatrix} c_{2_i} & 0 & 0 \\ 0 & \dfrac{c_{3_i}}{m} & \dfrac{c_{4_i}m - c_{3_i}}{m} \\ 0 & \dfrac{c_{5_i}}{m} & \dfrac{-c_{5_i}}{m} \end{pmatrix}^{-1} \cdot$$
$$\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} y_i = \dfrac{1}{c_{4_i}c_{5_i}} \begin{pmatrix} 0 & 0 & c_{5_i} & -c_{3_i} \end{pmatrix} y_i \tag{11}$$

where $D_i^{\dagger}$ is the pseudo-inverse of D_i.

Provided that the calibration constants $\{c_{j_i}\}_{j=1}^5$ 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

$$\widehat{F}_i = \dfrac{1}{c_{4_i}c_{5_i}} \begin{pmatrix} 0 & 0 & c_{5_i} & -c_{3_i} \end{pmatrix} y_i = F_i \tag{12}$$

Dynamic Force Observers

Converting the equations of motion into a standard state space formulation we have

$$\begin{cases} \dot{\xi}_i = A_i\xi_i + B_ip_{ref_i} + B_uu_i + B_FF_i \\ y_i = C_i\xi_i + D_{p_i}p_{ref_i} + D_{u_i}u_i + D_{F_i}F_i \end{cases} \tag{13}$$

where the matrices $A_i, B_i, B_{u_i}, B_F, C_i, D_{p_i}, D_{u_i}$ and D_{F_i} can be obtained from Eqs. (1) and (9) as

$$A_i = \begin{pmatrix} a_{11_i} & a_{12_i} & a_{13_i} \\ a_{21_i} & a_{22_i} & a_{23_i} \\ a_{31_i} & a_{32_i} & a_{33_i} \end{pmatrix}, B_i = \begin{pmatrix} b_{1_i} \\ b_{2_i} \\ b_{3_i} \end{pmatrix} \tag{14}$$

$$B_u = \begin{pmatrix} 0 \\ \dfrac{1}{m} \\ 0 \end{pmatrix}, B_F = \begin{pmatrix} 0 \\ \dfrac{-1}{m} \\ 0 \end{pmatrix}, C_i = \begin{pmatrix} c_{1_i} & 0 & 0 \\ & 0_{2x3} & \end{pmatrix},$$

$$D_{p_i} = \begin{pmatrix} 0 \\ c_{2_i} \\ 0 \\ 0 \end{pmatrix}, D_{u_i} = \begin{pmatrix} 0 \\ 0 \\ \dfrac{c_{3_i}}{m} \\ \dfrac{c_{5_i}}{m} \end{pmatrix}, D_{F_i} = \begin{pmatrix} 0 \\ 0 \\ c_{4_i} - \dfrac{c_{3_i}}{m} \\ \dfrac{-c_{5_i}}{m} \end{pmatrix}.$$

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 used and the resultant bias between data and Kalman filter output is instrumental for estimation of external forces acting on the system

$$\begin{cases} \dot{\widehat{\xi}}_i = A_i\widehat{\xi}_i + B_ip_{ref_i} + B_uu_i + K_i(y_i - \hat{y}_i) \\ \hat{y}_i = C_i\widehat{\xi}_i + D_{p_i}p_{ref_i} + D_{u_i}u_i \end{cases} \tag{15}$$

where $\widehat{\xi}_i$ corresponds to the ξ_i estimation being $\widehat{\xi}_i = (\widehat{\xi}_{1_i}\widehat{\xi}_{2_i}\widehat{\xi}_{3_i})^T$ and with the gain matrices

$$K_i = \begin{pmatrix} k_{1_i} \\ k_{2_i} \\ k_{3_i} \end{pmatrix} = \begin{pmatrix} k_{11_i} & k_{12_i} & k_{13_i} & k_{14_i} \\ k_{21_i} & k_{22_i} & k_{23_i} & k_{24_i} \\ k_{31_i} & k_{32_i} & k_{33_i} & k_{34_i} \end{pmatrix} \tag{16}$$

The dynamics of the estimation error $\widetilde{\xi}_i = \xi_i - \widehat{\xi}_i$ for axis i are obtained as

$$\dot{\widetilde{\xi}}_i = (A_i - K_iC_i)\widetilde{\xi}_i - (B_F + K_iD_{F_i})F_i \tag{17}$$
$$\widetilde{y}_i = y_i - \hat{y}_i = C_i\widetilde{\xi}_i + D_{F_i}F_i \tag{18}$$

Then, if matrix $(A_i - K_iC_i)$ is designed to have eigenvalues with negative real part so that the observers be stable, observer-based dynamic force observers may be suggested as

$$\widehat{F}_i = D_{F_i}^{\dagger}(\widetilde{y}_i - C_i\widetilde{\xi}_i) \tag{19}$$

with the property

$$\widehat{F}_i = D_{F_i}^{\dagger}(-C_i\widetilde{\xi}_i + \widetilde{y}_i) = D_{F_i}^{\dagger}D_{F_i}F_i = F_i \tag{20}$$

In the case studied here where $D_F^{\dagger}C = 0$, a particularly simple form of an unbiased force observer is obtained as

$$\widehat{F}_i = D_{F_i}^{\dagger}\widetilde{y}_i \tag{21}$$

Stochastic Force Estimation Error Dynamics

In the case where stochastic disturbances are present, we consider the system dynamics for each axis i

$$\begin{cases} \dot{\xi}_i = A_i\xi_i + B_ip_{ref_i} + B_uu_i + B_FF_i + v_{\xi_i} \\ y_i = C_i\xi_i + D_{p_i}p_{ref_i} + D_{u_i}u_i + D_{F_i}F_i + v_{y_i} \end{cases} \tag{22}$$

with uncorrelated stochastic disturbance processes v_{ξ_i} and v_{y_i} such that

$$\mathscr{E}\left\{\begin{pmatrix} v_{\xi_i} \\ v_{y_i} \end{pmatrix}\right\} = 0, \quad \mathscr{E}\left\{\begin{pmatrix} v_{\xi_i} \\ v_{y_i} \end{pmatrix}\begin{pmatrix} v_{\xi_i} \\ v_{y_i} \end{pmatrix}^T\right\} = Q_i = \begin{pmatrix} Q_{i_{\xi_i\xi_i}} & Q_{i_{\xi_i y_i}} \\ Q_{i_{y_i\xi_i}} & Q_{i_{y_i y_i}} \end{pmatrix}$$

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

$$\widetilde{F}_i = F_i - \widehat{F}_i = F_i - D_i^\dagger y_i = -D_i^\dagger v_{y_i} \quad (23)$$
$$\mathscr{E}\{\widetilde{F}_i\} = 0, \quad \mathscr{E}\{\widetilde{F}_i\widetilde{F}_i^T\} = D_i^\dagger Q_i (D^\dagger)^T \quad (24)$$

and

$$\widetilde{F}_i = F_i - \widehat{F}_i = F_i - D_{F_i}^\dagger(\widetilde{y}_i - C_i\widetilde{\xi}_i) = -D_{F_i}^\dagger v_{y_i} \quad (25)$$
$$\mathscr{E}\{\widetilde{F}_i\} = 0, \quad \mathscr{E}\{\widetilde{F}_i\widetilde{F}_i^T\} = D_{F_i}^\dagger Q_i (D_{F_i}^\dagger)^T \quad (26)$$

Using transfer function notation, we have

$$\begin{aligned}
\widehat{F}_i(s) &= D_{F_i}^\dagger[-C_i(sI - A_i + K_iC_i)^{-1}(B_F + K_iD_{F_i})]F_i(s) \\
&+ D_{F_i}^\dagger D_{F_i}F_i(s) + D_F^\dagger v_{y_i}(s) \\
&= F_i(s) + D_{F_i}^\dagger v_{y_i}(s) \quad (27)
\end{aligned}$$

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 $\widetilde{\xi}_i$ can be obtained as

$$\begin{aligned}
\dot{\widetilde{\xi}}_i &= (A_i - K_iC_i)\widetilde{\xi}_i + K_iC_i\xi_i + B_{F_i}F_i + k_{1_i}D_{p_i}p_{ref_i}(28) \\
&+ k_{2_i}D_{u_i}u_i - K_iy_i
\end{aligned}$$

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

$$\begin{aligned}
\dot{\widetilde{\xi}}_{1_i} &= (a_{11_i} - k_{11_i}c_{1_i})\widetilde{\xi}_{1_i} + a_{12_i}\widetilde{\xi}_{2_i} + a_{13_i}\widetilde{\xi}_{3_i} \quad (29) \\
&+ k_{11_i}c_{1_i}\xi_{1_i} - k_{1_i}y_i + k_{12_i}c_{2_i}p_{ref_i} + \alpha_{1_i}u_i
\end{aligned}$$

$$\begin{aligned}
\dot{\widetilde{\xi}}_{2_i} &= (a_{21_i} - k_{21_i}c_{1_i})\widetilde{\xi}_{1_i} + a_{22_i}\widetilde{\xi}_{2_i} + a_{23_i}\widetilde{\xi}_{3_i} \quad (30) \\
&+ k_{21_i}c_{1_i}\xi_{2_i} - \frac{1}{m}F_i - k_{2_i}y_i + k_{22_i}c_{2_i}p_{ref_i} + \alpha_{2_i}u_i
\end{aligned}$$

$$\begin{aligned}
\dot{\widetilde{\xi}}_{3_i} &= (a_{31_i} - k_{31_i}c_{1_i})\widetilde{\xi}_{1_i} + a_{32_i}\widetilde{\xi}_{2_i} + a_{33_i}\widetilde{\xi}_{3_i} \quad (31) \\
&+ k_{31_i}c_{1_i}\xi_{3_i} - k_{3_i}y_i + k_{32_i}c_{2_i}p_{ref_i} + \alpha_{3_i}u_i
\end{aligned}$$

where

$$\alpha_{1_i} = k_{13_i}\frac{c_{3_i}}{m} + k_{14_i}\frac{c_{5_i}}{m}$$
$$\alpha_{2_i} = k_{23_i}\frac{c_{3_i}}{m} + k_{24_i}\frac{c_{5_i}}{m}$$
$$\alpha_{3_i} = k_{33_i}\frac{c_{3_i}}{m} + k_{34_i}\frac{c_{5_i}}{m}$$

Deriving Eq. (29) and using Eqs. (30) and (31), an expression for the dynamics of $\widetilde{\xi}_{1_i}$ can be found as

$$\ddot{\widetilde{\xi}}_{1_i} - \Lambda_{1_i}\dot{\widetilde{\xi}}_{1_i} - (a_{12_i}\Lambda_{2_i} + a_{13_i}\Lambda_{3_i})\widetilde{\xi}_{1_i} = \beta_i - \frac{a_{12_i}}{m}F_i \quad (32)$$

with

$$\begin{aligned}
\Lambda_{1_i} &= a_{11_i} - k_{11_i}c_{1_i} \\
\Lambda_{2_i} &= a_{21_i} - k_{21_i}c_{1_i} \quad (33) \\
\Lambda_{3_i} &= a_{31_i} - k_{31_i}c_{1_i}
\end{aligned}$$

and

$$\begin{aligned}
\beta_i &= (a_{22_i} + a_{32_i})\dot{\widetilde{\xi}}_{2_i} + (a_{23_i} + a_{33_i})\dot{\widetilde{\xi}}_{3_i} + k_{21_i}c_1\xi_{2_i} \\
&+ k_{31_i}c_1\xi_{3_i} - k_{2_i}y_i - k_{3_i}y_i + (k_{22_i}c_2 + k_{32_i}c_{2_i})p_{ref_i} \\
&+ (\alpha_{2_i} + \alpha_{3_i})u + k_{11_i}c_{1_i}\dot{\xi}_{1_i}k_{1_i}\dot{y}_i + k_{12_i}c_{2_i}\dot{p}_{ref_i} + \alpha_{1_i}\dot{u}
\end{aligned}$$

Then, for slowly time-varying environmental forces F_i, it is possible to obtain an estimate $\widehat{F}_i$ as

$$\widehat{F}_i = \frac{m}{a_{12_i}}(\beta_i - (a_{12_i}\Lambda_{2_i} + a_{13_i}\Lambda_{3_i})\widetilde{\xi}_{1_i}) \quad (34)$$

Defining the force estimation error as $\widetilde{F} = F - \widehat{F}$ and considering Eqs. (17) and (34), the observer dynamics may be summarized as the state space system:

$$\begin{cases}
\dot{\widetilde{\xi}}_i = (A_i - K_iC_i)\widetilde{\xi}_i + K_iC_i\xi_i + B_FF_i + k_{1_i}D_{p_i} \\
\quad\quad + k_{2_i}D_{u_i}u_i - K_iy_i \\
\widetilde{F}_i = F_i - \frac{m}{a_{12_i}}(\beta_i - (a_{12_i}\Lambda_{2_i} + a_{13_i}\Lambda_{3_i})\widetilde{\xi}_{1_i})
\end{cases} \quad (35)$$

where F_i is the input and $\widetilde{F}_i$ is the output. The transfer function from F_i to $\widetilde{F}_i$ is:

$$\begin{aligned}
\widetilde{F}_i(s) &= \frac{s(s + \Lambda_{1_i})}{s^2 + \Lambda_{1_i}s + (a_{12_i}\Lambda_{2_i} + a_{13_i}\Lambda_{3_i})}(\beta_i - \frac{1}{m}F_i) \\
&= H_i(s)(\beta_i - \frac{a_{12_i}}{m}F_i) \quad (36)
\end{aligned}$$

where $H_i(s)$ is a strictly stable transfer function for all $\Lambda_{1_i} > 0$ and $(a_{12_i}\Lambda_{2_i} + a_{13_i}\Lambda_{3_i}) > 0$. It has one zero at $s = 0$ which shows that the force estimation error converges to zero for constant environmental forces. Moreover, the parameters Λ_{j_i} and β_i contain all the information about the behavior of $\widehat{F}_i$; and, according to (32), by choosing appropriate observer gains K_i, it is possible to shape these dynamics. Using Eqs. (32) and (34), we calculate the estimated force as

$$\begin{aligned}
\widehat{F}_i &= \frac{m}{a_{12_i}}((a_{12_i}\Lambda_{2_i} + a_{13_i}\Lambda_{3_i})\widetilde{\xi}_{1_i} - (a_{12_i}k_{24_i} \\
&+ a_{13_i}k_{34_i})\ddot{\widetilde{\xi}}_{1_i} + (a_{12_i}\frac{k_{24_i}}{m} + a_{13_i}\frac{k_{34_i}}{m})u_i) \quad (37)
\end{aligned}$$

In order to provide suitable observer gains, we note that when $\widetilde{\xi}_1$ converges to zero according to specified dynamics, then it is suitable that Eq. (37) fulfills Newton's second law expressed in Eq. (4) thus imposing the following condition

$$k_{34_i} = \frac{1 - a_{12_i}^2 k_{24_i}}{a_{13_i}a_{12_i}} \quad (38)$$

Fig. 2. The experimental setup. An ABB industrial robot IRB 2400 with an open control architecture system is used. The wrist sensor is placed between the robot tip and an compliance tool where the grinding tool is attached. The accelerometer is placed on the tip of the grinding tool.

IV. EXPERIMENTAL SET-UP

The robot-tool system is composed of the following devices and sensors (Fig. 2): an ABB robot; a wrist force sensor; and an accelerometer.

The robotic system used in this experiment was based on an ABB robot (Irb 2400) situated in the Robotics Lab at the Department of Automatic Control, Lund University. A totally open architecture is its main characteristic, permitting the implementation and evaluation of advanced control strategies.

The controller was implemented in Matlab/Simulink using the Real Time Workshop of Matlab, and later compiled and linked to the Open Robot Control System [8]. The wrist sensor used was a DSP-based force/torque sensor of six degrees of freedom from JR3. The tool used for our 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 accelerometer 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 (ξ_i) was identified. An output-error model was calculated using the System Identification Toolbox of Matlab, the resulting model being as follows:

$$G_1(q) = \frac{1.2348q^{-1} - 1.5084q^{-2} + 0.3011q^{-3}}{1 - 1.0494q^{-1} + 0.0775q^{-2} - 0.0006q^{-3}} \quad (39)$$

The state space equations of the system were:

$$\begin{cases} \dot{X}_i = A_{d_i}X_i + B_{d_i}x_{p_{ref_i}} \\ y_i = C_{d_i}X_i \end{cases} \quad (40)$$

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

$$A_{d_i} = \begin{pmatrix} 49.6 & -55.8 & 0.4 \\ 658 & 641 & 4.8 \\ -8022 & 9077.2 & -1263 \end{pmatrix} \quad (41)$$

$$B_{d_i} = \begin{pmatrix} 214 \\ -444 \\ 7578 \end{pmatrix}, C_{d_i} = \begin{pmatrix} 1.2348 & -1.5084 & 0.3011 \end{pmatrix} \quad (42)$$

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

$$u_i = -LX_i + c_i\widehat{F}_i + l_r p_{ref_i} \quad (43)$$

with c_i as the force gain in the impedance control, $\widehat{F}_i$ 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_r 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
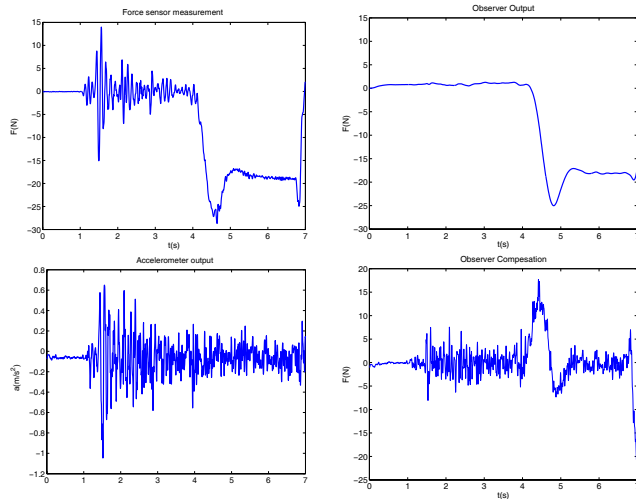
Fig. 3. Force measurement from the wrist sensor JR3 (upper-left), force observer output (upper-right), acceleration of the robot tip (lower-left) and observer compensation (lower-right). These results were obtained for x-axis.
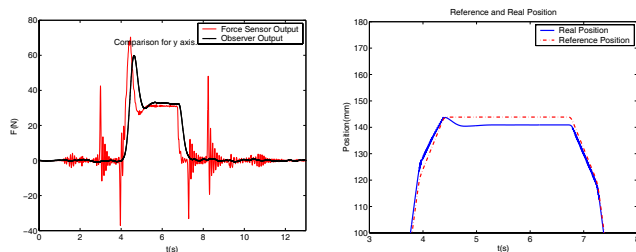

Fig. 4. Comparison between the observer output and the force sensor measurement for axis y (left).Real and reference position for *y* axis (right).

inertial forces. On the other hand, the reference and the real position of axis *y* of the robot during the experiment, where the force observer information was used to execute the impedance control, are shown in Fig. 4 (right).

The experiment for axis *z* is shown in Fig. 5 which depicts, at the top, the force measurement from the JR3 sensor (left) and the force observer output (right) while at the bottom, the power spectrum density for the composed signal $u - m\ddot{\xi}_z$ (left) and the observer output power spectrum density (right). Note how the observer cuts off the noise introduced by the sensors.

VII. CONCLUSIONS

A new contact force observer that fusions 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.
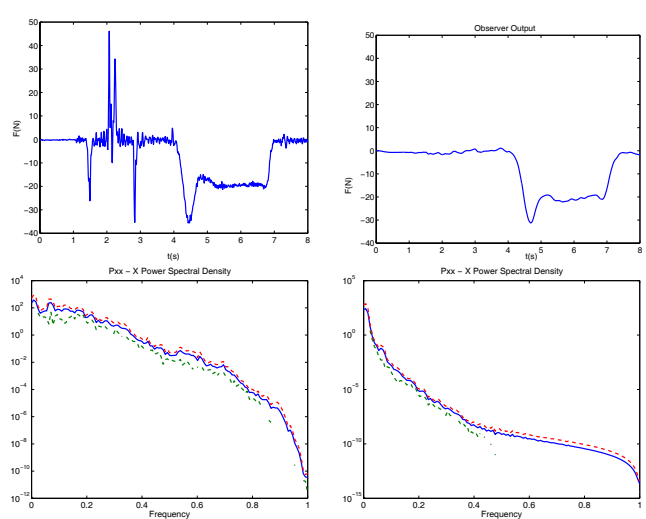

Fig. 5. Force measurement from the wrist sensor JR3 (upper-left), force observer output (upper-right), power spectrum density for the composed signal $u - m\ddot{x}$ (lower-right) and observer output power spectrum density (lower-left). These results were obtained for z-axis.

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.

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