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Automatic Calibration Procedure for a Robotic Manipulator Force Observer*

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Abstract—In this paper, we propose a method for self-calibration of a robotic manipulator force observer, which fuses information from force sensors and accelerometers in order to estimate the contact force exerted by a manipulator to its environment, by means of active motion. In robotic operation, during contact transition accelerometers and force sensors play a very important role and serve to overcome many of the difficulties of uncertain world models and unknown environments, limiting the domain of application of current robots used without external sensory provided. The calibration procedure helps to improve the performance as well as enhanced stability and robustness for the transition phase. A variety of accelerometers were used to validate the procedure. A dynamic model of the robot-grinding tool using the new sensors was obtained by system identification. 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.

Index Terms—Self-calibrating Robots, Sensor Fusion, Observers, Force Control, Robot Control.

I. INTRODUCTION

Robot manipulation often involves mechanical interaction of the robot with its environments. Therefore, the manipulation can be controlled only after the interaction forces and moments are controlled directly. This is why force control is required in robotics manipulation. For force control to be implemented, information regarding forces and moments at the point of contact has to be fed back to the controller. This fact imposes as prerequisite an accurate contact force measurement.

The force sensor is usually a wrist force sensor installed between the end-effector and the last joint of the manipulator. The signals detected by the wrist force sensor, however, consist not only of the contact forces but also of the inertial forces of the end-effector and payload [1]. If the manipulator starts in contact and stays in contact throughout the task, it may be reasonable to assume that the contact force can be measured directly by the force sensor, because in such case the inertial force is far smaller than the contact force. In free motion, however, the force sensor signals consist only of the inertial force of the end-effector and payload. Inertial force interference may be significant enough to degrade feedback signal quality and performance

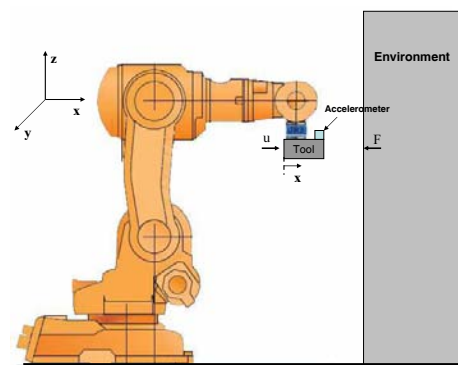


Fig. 1. Interaction between the robot tool and its environment.

of the position controller if the manipulator travels at high speed.

In order to overcome this problem, a new fusion of force and acceleration sensors was proposed in [2], which combines force sensors and accelerometers using an observer based on a Kalman Filter in order to obtain a suitable environmental force estimator.

The goal of this work was to develop, using the force observer proposed on [2], an automatic calibration procedure for a robotic manipulator force observer. This method offers an easy way to properly fuse information from accelerometers attached to the robot tool with that of force sensors.

The calibration of a manipulator and its sensors parameters is normally done in a well-controlled laboratory environment. This, together with internal sensing data, is used to identify the kinematic model or parameters of the system [3]. However, accurate calibration data through external sensing¹ is expensive and difficult to obtain. For a system that functions outside of a controlled laboratory environment, it would be desirable not to use special-purpose calibration equipment to calibrate new parameters of the system like could be the offset of a new sensor.

The main advantages this procedure offers are: its independence of the type of accelerometer, an inexpensive

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¹External sensing is referred to as sensing done by using a device that is not part of the system. On the other hand, internal sensing means that measurements are exclusively taken by sensors resident in the system.

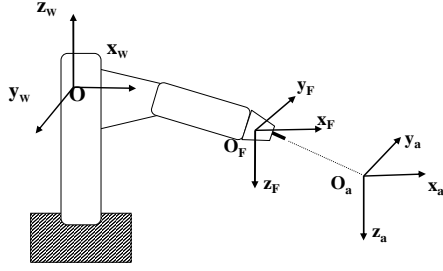


Fig. 2. Coordinate frames of the system.

calibration due to the non-existent cost for extra calibration devices, and a fast execution for the simplicity of the algorithm developed.

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 automatic calibration procedure approach. The setup of the system is described in Sec. IV. In Sec. V, the Modeling and Control is described. Section VI shows some results obtained with different accelerometers. Finally, the conclusions are presented in Section VII.

II. PROBLEM FORMULATION

When contact manipulation with a surface using the end-effector of a robotic manipulator (Fig. 1), the force sensor measures two kinds of forces: the environmental or contact force (F) and the inertial force produced by acceleration (ma), that is:

$$u = F + ma \quad (1)$$

Usually, the task undertaken requires the control of the contact force F .

A. Description of coordinate frames and motion

As shown in Fig. 2, $O_F X_F Y_F Z_F$ and $O_A X_A Y_A Z_A$ correspond to the force sensor coordinate frame and the accelerometer frame respectively. 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 for $O_W X_W$ axis.

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

B. Input Variables and Definitions

- u_{X_F} Force sensor output for axis $O_F X_F$ (measured in N.)
- V_{X_A} Accelerometer output for axis $O_A X_A$ (measured in Volts.)
- a_{X_A} Acceleration for axis $O_A X_A$ (ms^{-2}).
- \hat{F}_{X_F} Force observer output for x-axis in frame $O_F X_F$

C. Elements to be Computed

Instead of seeking the exact values in terms of any a priori system knowledge, we let the algorithm itself to estimate them [5]. Thus, we are treating the system as being completely "black" to us. Our basic idea for self-calibration is to use designed motion sequences, e.g., pure translational motions, to estimate the following parameters used by the contact force observer.

Determination of the tool mass: To determine the mass of the tool, the procedure orients the robot in order to use the gravity acceleration as input.

Accelerometer calibration: In general, the desired calibration procedure for accelerometers should require no extra hardware and should be carried out automatically.

Basically, the existing calibration methods for accelerometers can roughly be divided into two groups. The first one is a static calibration which is based on placing an accelerometer in different orientations in the gravitational field and solving equation (2) for the unknown parameters.

$$V_{X_A} = K_{gain} a_{X_A} + V_o \quad (2)$$

where V_{X_A} is the sensor output voltage for $O_A X_A$ axis, K_{gain} is the sensitivity that relates the output voltage with the acceleration a_{X_A} (ms^{-2}) and V_o is the zero offset.

The second method, which is often used in the field of robotics and aviation, makes use of additional sensors like gyroscopes and sometimes, even the global positional system [6]. This kind of calibration, known as dynamic calibration, has the drawback that precise sensors are needed in order to obtain good calibration.

Design of the observer gains: In an industrial process, it is common to get signals corrupted by additive noise or interference. In some cases, the noise filtering procedure has the disadvantage of requiring excessively elaborate and costly hardware, because some signals and their respective noise might share a similar frequency spectrum or the frequency bands of the signal of interest and the noise are very close [6].

With simple addition of accelerometer sensors we would have a final signal with too much noise. The solution presented with the force observer reduced this problem but the selection of the observer gains requires a trade off between the noise and a fast response of our observer.

From [2], the contact force observer (\hat{F}_{X_F}) with low pass properties has the following structure

$$\hat{F}_{X_F} = k_{23}u_{X_F} - k_{23}m\ddot{\xi}_1 - k_{21}m\tilde{\xi}_1 \quad (3)$$

where k_{ij} are the observer gains, u_{X_F} is the force sensor measurement, m is the tool mass, ξ is the x position and $\tilde{\xi}$ is the position estimation error. The observer dynamics are summarized as the state space system:

$$\begin{cases} \dot{\tilde{\xi}} = (A - KC)\tilde{\xi} - BF_{X_F} + KD_u u_{X_F} - Ky \\ \dot{\hat{F}}_{X_F} = F_{X_F} - m(\beta - \Lambda_0 \tilde{\xi}_1) \end{cases} \quad (4)$$

where K is the observer gain.

III. THE NEW APPROACH

For this work, a static calibration is proposed to determine the offset (V_o) of the accelerometer and a dynamic calibration to calculate its sensitivity (K_{gain}). To estimate the former gain, a dynamic procedure has been chosen because, depending on the technology of the accelerometer, some of them can not measure the gravity acceleration, restricting this algorithm to those sensors capable of measuring accelerations from 0 Hz, which is the case for capacitive accelerometers. Finally, a least squares method was used to estimate K_{gain} .

Regarding the observer, note that the gain (K) is extremely important and determines the performance of the force estimator. To achieve good force estimations the environmental force should be big enough to deflect over the noise level of the system. In order to get this property, there exist different approaches to set this gain, namely: 'Pole Placement' and 'Kalman Filter' design. The Kalman Filter solution will be used for the automatic procedure. Considering that stochastic disturbances are present in our system, we have the following state space equation which represents the robot tool dynamics [2],

$$\begin{cases} \dot{\xi} = A\xi + B(u_{X_F} - F_{X_F}) + v_\xi \\ y = C\xi + D_u u_{X_F} + D_F F_{X_F} + v_y \end{cases} \quad (5)$$

with

$$E[v_\xi(t) v_\xi^T(\tau)] = Q(t)\delta(t - \tau); \quad E[v_\xi(t)] = 0 \quad (6)$$

$$E[v_y(t) v_y^T(\tau)] = R(t)\delta(t - \tau); \quad E[v_y(t)] = 0$$

$$E[v_\xi(t) v_y^T(\tau)] = S(t)\delta(t - \tau) = 0; \quad \text{for all } t \text{ and } \tau$$

Supposing that the noise processes v_ξ and v_y are white, Gaussian, zero mean, and independent with constant covariance matrices Q and R respectively. There exist an observer gain (K) for the state space system (4) that minimizes the estimation error variance due to the system noises. This gain is calculated as

$$K = PC^T R^{-1} \quad (7)$$

where the constant matrix P is computed as the solution of the Riccati matrix equation

$$PA^T + AP - PC^T R^{-1} CP + Q = 0 \quad (8)$$

The observer gain is chosen to minimize the estimation error variance due to the system noises, but not the variance due to the environmental forces. Note that gain $k_{23} = 1$ in order to fulfill the constraint imposed by Newton's law in (3).

A. Automatic Procedure

In this section we present an automatic procedure to solve the fusion of accelerometer and force sensors attached to the manipulator robot by just doing a set of experiments. This algorithm aims to manage any kind of accelerometer —e.g., a capacitive one— and integrate its data with the force sensor's in order to obtain a contact force observer with a suitable properties in terms of response and filtering.

The complete procedure is shown as follows. Note that $t_0 < t_1 < t_2 < t_3 < t_4$.

- 1) Place the robot with the tool so that $R_F^W = R_{F_1}^W$ being

$$R_{F_1}^W = Rot(Y_W, \alpha) Rot(X_W, \delta) Rot(Z_W, \theta) \quad (9)$$

which yields

$$R_{F_1}^W = \begin{pmatrix} c_\alpha c_\theta + s_\alpha s_\delta s_\theta & -c_\alpha s_\theta + s_\alpha s_\delta c_\theta & s_\alpha c_\delta \\ c_\delta s_\theta & c_\delta c_\theta & -s_\delta \\ -s_\alpha c_\theta + c_\alpha s_\delta s_\theta & s_\alpha s_\theta + c_\alpha s_\delta c_\theta & c_\alpha c_\delta \end{pmatrix} \quad (10)$$

with $s = \sin$, $c = \cos$, $\alpha = \frac{\pi}{2}$ rad, $\delta = \pi$ rad and $\theta = [0, 2\pi]$ rad. Initialize the force sensor and set $t_0 = t$.

- 2) Maintain the tool in that position from time t_0 to time t_1 avoiding any movement. Calculate

$$u_{X_F}^h = \frac{1}{(n_{t_1} - n_{t_0})} \sum_{k=n_{t_0}}^{n_{t_1}} u_{X_F}(k) \quad (11)$$

where n is the number of samples per second, $n_{t_0} = t_0 n$, $n_{t_1} = t_1 n$ and $u_{X_F}(k)$ is the x-axis JR3 measurement for sample k .

- 3) Place the robot with the tool so that $R_F^W = R_{F_3}^W$ (R_F^W for step 3) being

$$R_{F_3}^W = Rot(X_W, \delta) Rot(Z_W, \theta) \quad (12)$$

which yields

$$R_{F_3}^W = \begin{pmatrix} c_\theta & -s_\theta & 0 \\ c_\delta s_\theta & c_\delta c_\theta & -s_\delta \\ s_\delta s_\theta & s_\delta c_\theta & c_\delta \end{pmatrix} \quad (13)$$

Set $t_2 = t$.

- 4) Maintain the tool in this position from time t_2 to time t_3 avoiding any movement. Then calculate

$$u_{X_F}^v = \frac{1}{(n_{t_3} - n_{t_2})} \sum_{k=n_{t_2}}^{n_{t_3}} u_{X_F}(k) \quad (14)$$

where $n_{t_2} = t_2 n$ and $n_{t_3} = t_3 n$.

- 5) Calculate the offset voltage of the accelerometer V_o as

$$V_o = \frac{1}{(n_{t_3} - n_{t_2})} \sum_{k=n_{t_2}}^{n_{t_3}} V_{X_A}(k) \quad (15)$$

where $V_{X_A}(k)$ is the accelerometer output voltage for $O_A X_A$ axis.

- 6) Calculate the mass (m) as

$$m = \frac{|u_{X_F}^v - u_{X_F}^h|}{g} \quad (16)$$

where g is the gravity acceleration.

- 7) Apply to the robot a step change along axis $O_F X_F$ from t_3 to t_4 .

- 8) Calculate

$$K_{gain} = \frac{1}{(\theta(k)^T \theta(k))^{-1} \theta(k)^T Y(k)} \quad (17)$$

where θ and Y are vectors of dimension $(t_4 - t_3)n$ with n the number of samples per second and

$$\begin{aligned} \theta(k) &= V_{X_A}(k) - V_o \\ Y(k) &= \frac{u_{X_F}(k)}{m} \end{aligned}$$

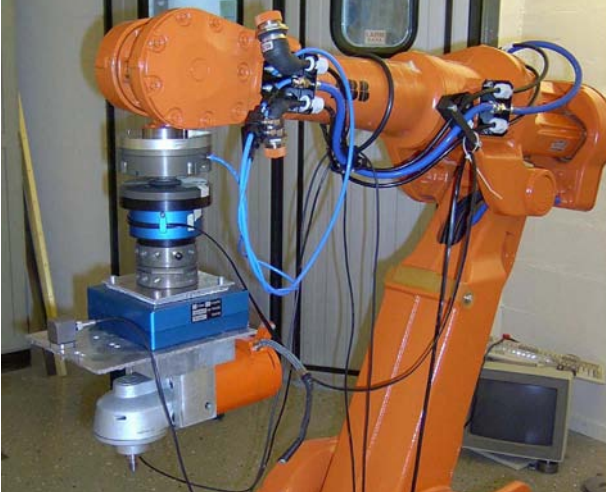


Fig. 3. The experimental setup. An ABB industrial robot IRB 2400 with an open control architecture system is used. The impedance control is performed perpendicular to the screen. Whereas the accelerometer is placed on the grinding tool, the Optidrive is placed between the tool and the JR3 sensor.

with $(k = t_{3n}..t_{4n})$.

- 9) Calculate the covariance matrices Q and R (Eq. 6).
- 10) Calculate the observer gain (K) as

$$K = PC^T R^{-1} \quad (18)$$

where the constant matrix P is computed as the solution of the Ricatti matrix equation

$$PA^T + AP - PC^T R^{-1} CP + Q = 0 \quad (19)$$

- 11) Set $k_{23} = 1$. Note that this new value does not affect the stability of the observer, only its static gain [2].

B. Speed Performance

Analyzing the algorithm for the automatic procedure, it is well appreciated that most time is consumed by the robot movements. Therefore, depending on the time the manipulator needs to carry out the movements and wait to stabilize in the goal positions, the execution of the procedure will last.

For the whole procedure applied to our ABB robot, the algorithm requires about 16s to calibrate the contact force observer. Once the movements are carried out, the number of arithmetic operations (N) calculated are approximately

$$N = ((t_1 - t_0) + 2(t_3 - t_2) + (t_4 - t_3))n \quad (20)$$

where n is the number of samples per second.

C. Error Analysis

The purposes of the error analysis are as follows [4]:

- It reveals what the critical factors influencing the accuracy are.
- It gives rise to various means for improving accuracy.
- It helps to determine whether one has properly implemented the algorithm. If the error is larger than a

threshold defined previously, something in the setup, programs or system are not in the right order.

To estimate the error introduced by the mass estimation, the following reasoning is made. Considering the real tool mass (m) as

$$m = \frac{R_{F_1}^W P_z - R_{F_3}^W P_x}{g} \quad (21)$$

where P_z and P_x are the tool weight in $O_W O_Z$ axis and in $O_W O_X$ respectively. Moreover, the estimated mass (m_e) is

$$m_e = \frac{R_{F_{e1}}^W P_z - R_{F_{e3}}^W P_x}{g} \quad (22)$$

where $(R_{F_{e1}}^W)$ and $(R_{F_{e2}}^W)$ are the rotation matrix (R_F^W) applied in steps 1 and 3 respectively. Then, the error introduced by the mass estimation (e_m) is

$$e_m = \frac{(R_{F_1}^W - R_{F_{e1}}^W)P_z - (R_{F_3}^W - R_{F_{e3}}^W)P_x}{g} \quad (23)$$

On the other hand, to calculate the error introduced by the accelerometer parameters estimation, the same reasoning follows. Then, the offset error (e_o) is estimated as

$$e_o = (R_{F_3}^W - R_{A_4}^W)V_o \quad (24)$$

where $R_{A_4}^W$ is R_A^W for step 4. Then, if the accelerometer frame and the force sensor frame are perfectly aligned, and besides $R_{F_4}^W = R_{F_3}^W$, the error (e_o) will be zero. On the other hand, the error introduced by the accelerometer gain estimation (e_g), is calculated as

$$e_g = \frac{R_{F_3}^W u_{X_F} - V_o m}{R_{F_3}^W a_{X_A} m} - \frac{R_{F_{e7}}^W u_{X_F} - (V_o + e_v)(m + e_m)}{R_{A_{e7}}^W a_{X_A} (m + e_m)} \quad (25)$$

where $R_{F_{e7}}^W$ and $R_{A_{e7}}^W$ are respectively R_A^W and R_A^W for step 7. It can be verified that if $R_{F_{e7}}^W = R_{A_{e7}}^W = R_{F_3}^W$ and $e_m = e_v = 0$, e_g is equal to zero.

Finally, the force observer error is estimated as

$$e_f = (m + e_m)R_A^W(a_{X_A} + e_a) - mR_F^W a_{X_A} \quad (26)$$

where

$$e_a = \frac{V - V_o}{K_{gain}} - \frac{V - (V_o + e_v)}{K_{gain} + e_g} \quad (27)$$

IV. EXPERIMENTAL SET-UP AND METHODS

The robot-tool system is composed of the following devices and sensors (Fig. 3): an ABB robot; a wrist force sensor; a compliant grinding tool—i.e., a device called Optidrive® that links the robot tip and the tool offering a compliant response for the x axis of the robot—and, finally, 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 [7]. 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 and Optidrive signals were read by the robot controller in real time via an analog input. Two kinds of different accelerometers have been attached to the tool of the robot in order to verify the algorithm proposed. These sensors have the following features:

| | Accelerometer 1 | Accelerometer 2 |
|-------------|-----------------|-----------------|
| Type | Capacitive | MEMS |
| Model | PCB | AD |
| Sensitivity | 100mV/g | 312mV/g |
| Range | 20g pk | 2g pk |
| Frequency | 0-500Hz | 0.01-5kHz |

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 [1]. Regarding to 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 and the Optidrive grinding tool subsystem, was considered using only one cartesian direction (x) of the robot which corresponds with the tool compliance (Fig. 4). As the system was composed by the robot and the tool with the Optidrive device, it was necessary to obtain the dynamics of both subsystems.

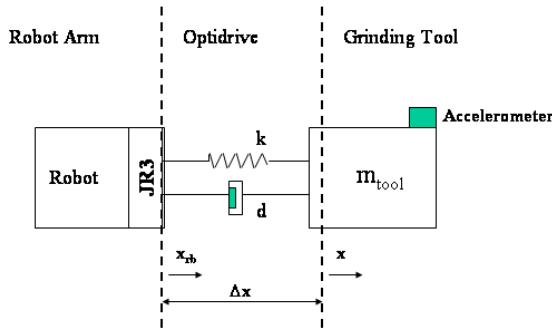


Fig. 4. Schematic robot-tool system with force sensor fusion where x_{rb} represents the position of the robot end-effector tip, x is the position of the tool and Δx is the distance between them

With respect to the robot, a linear dynamic model showing the relation between the position reference (x_r) and the current position of the robot tip (x_{rb}) (Fig. 4) was identified. An output-error model was calculated using the System Identification Toolbox of Matlab, the resulting model being as follows:

$$G_1(q) = \frac{1.2348q^{-1} - 1.5084q^{-2} + 0.3011q^{-3}}{1 - 1.0494q^{-1} + 0.0775q^{-2} - 0.0006q^{-3}} \quad (28)$$

On the other hand, the transfer function of the Optidrive-tool subsystem that relates x with x_{rb} can be written as:

$$G_2(s) = \frac{ds + k}{m_{tool}s^2 + ds + k} \quad (29)$$

where $m_{tool} = m$. In order to estimate the parameters of G_2 —that is, m_{tool} , the Optidrive stiffness k , and damping d —a least-squares approach was used. Then, considering the whole system model (*i.e.*, robot, tool, and sensors) and using Eqs. (28) and (29), the state space equations of the system were:

$$\begin{cases} \dot{x} = Ax + Bx_r \\ y = Cx \end{cases} \quad (30)$$

where $X = [\ddot{x}_{rb}, \dot{x}_{rb}, x_{rb}, x, \dot{x}]^T$ and

$$A = \begin{pmatrix} 49.6 & -55.8 & 0.4 & 0 & 0 \\ 658 & 641 & 4.8 & 0 & 0 \\ -8022 & 9077.2 & -1263 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & d/m_{tool} & k/m_{tool} & -k/m_{tool} & -d/m_{tool} \end{pmatrix}$$

$$B = \begin{pmatrix} 214 \\ -444 \\ 7578 \\ 0 \\ 0 \end{pmatrix}, C = \begin{pmatrix} 1.2348 & -1.5084 & 0.3011 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{pmatrix}$$

The impedance control approach was chosen as the control law to verify the properties of the new force observer designed using the automatic procedure. In this sense, a LQR controller was used to make the relation of impedance goes to zero [1]. The control law applied was

$$u = -LX + c\hat{F} + l_r x_r \quad (31)$$

with c as the force gain in the impedance control, \hat{F} the estimated environmental force, which in our case it was estimated using the force observer, x_r the position reference and l_r the position gain constant, L being calculated considering Eq. (30).

VI. RESULTS

Applying the automatic procedure to Accelerometer 1 and Accelerometer 2, the following results are obtained.

| | Acc1 | Acc2 |
|------------|----------|----------|
| mass | 12.55 kg | 12.76 kg |
| V_o | 5.0938 V | 5.9616 V |
| K_{gain} | -0.2937 | 0.2525 |

and the corresponding observer gains yield

$$K_1 = \begin{pmatrix} 0.0400 & 0.0006 & -0.0073 \\ 0.1000 & 0.0001 & 1.0000 \end{pmatrix} \quad (32)$$

and

$$K_2 = \begin{pmatrix} 0.0600 & 0.0002 & -0.0012 \\ 0.2250 & -0.0002 & 1.0000 \end{pmatrix} \quad (33)$$

The results obtained with Accelerometer 1 are presented in Fig. 5 and in Fig. 6. In the first one, it is appreciated how the observer helps to eliminate the inertial effects and

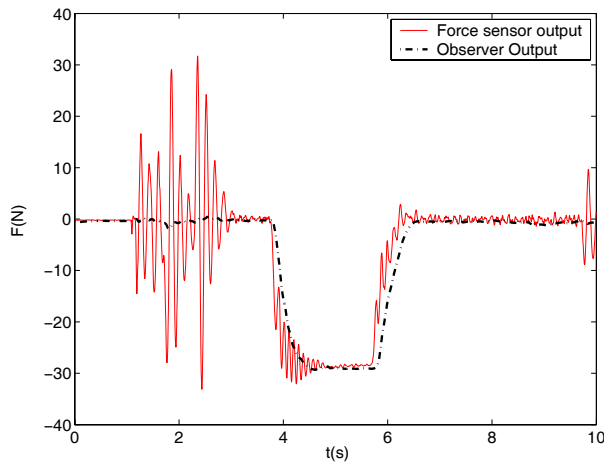


Fig. 5. Force measurement from the wrist sensor (solid-line) and observer output(dash-dot-line).

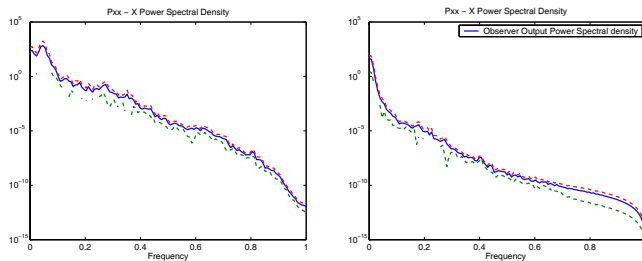


Fig. 6. Power spectrum density for composed signal $u - m\ddot{x}$ (left) and for the observer (right).

also improves the transition phase since the perturbations introduced by the inertial forces are compensated. In Fig. 6 (left), the power spectrum density for the composed signal $u - m\ddot{x}$ is shown. In Fig. 6 (right) the observer output power spectrum density is presented. Note that the observer cuts off the noise introduced by the sensors.

The results obtained applying the automatic procedure to Accelerometer 2 are shown in Fig 7. In these figures, we see how the observer eliminates the inertial effects. In Fig. 8, the force sensor measurement (left) and the observer output (right) are shown for an oscillation movement in free space where the perturbations inserted by the inertial forces were maximum.

VII. CONCLUSIONS

This paper introduced a high-speed, high-accuracy, versatile, simple, and fully autonomous technique for the calibration of a robotic manipulator force observer which fuses data from force sensors and accelerometers.

This procedure aims at offering a ‘plug-and-play’ solution for the integration of different kind of accelerometers with the final goal of obtaining an observer capable of estimating the contact force exerted by an industrial robotic manipulator. The final observer implies the improvement of the performance of the transition stage where the robot tasks lead to a contact between the robot tool and the environ-

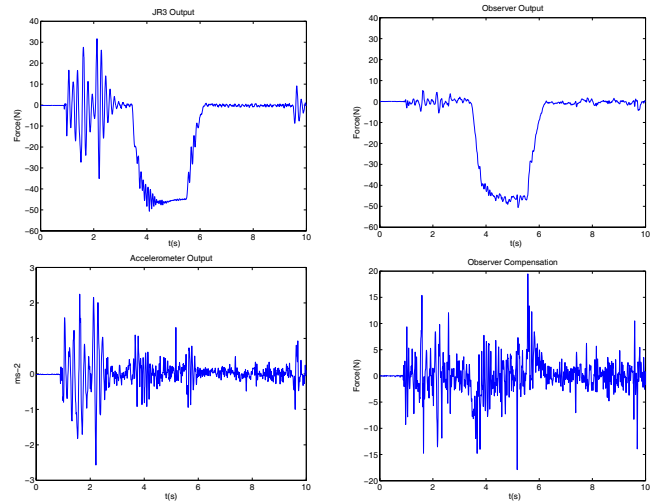


Fig. 7. Force measurement from the wrist sensor JR3 (upper-left), force observer output (upper-right). Acceleration of the robot tip (lower-left) and observer compensation (lower-right).

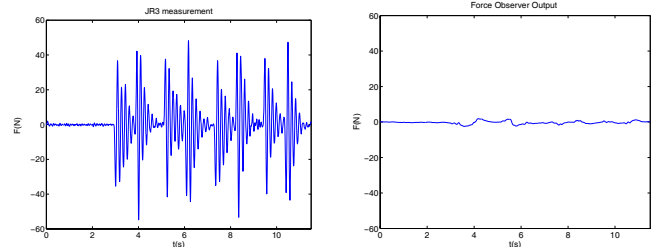


Fig. 8. Force sensor measurement (left) and observer output (right) measured during an oscillation movement in free space.

ment. The behavior of the observer and the performance of the proposed procedure were successfully verified attaching different types of accelerometers to an industrial robot.

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