# Bias Estimation and Gravity Compensation For Force-Torque Sensors

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*Abstract:* - The accurate measurement of contact force and torque is very important in robotic applications where the manipulator comes in contact with the environment. In particular, these measurements can be used to protect the manipulator from excessive forces, control the applied force, and also guide the robot operation. In this work we describe a methodology for estimating the force/torque sensor bias, and the gravity component due to the sensor's own mass distribution. These estimates can be subtracted from the sensor readings during real-time operation, in order to improve the accuracy of the force/torque measurements.

*Key-Words:* - Force /torque sensor, bias estimation, gravity compensation

## 1 Introduction

In robotic applications where the manipulator comes in contact with the environment (e.g. assembly, material handling) it is necessary to monitor the contact forces and torques, in order to ensure that they do not exceed some desired safety limits, and also to incorporate them in some force feedback control law [1]. Almost always, the manipulator comes in contact with the environment only through its end-effector. The resulting contact forces can be monitored by using a special sensor, called *force/torque sensor* (FTS) located at the manipulator wrist. It has been shown [2] that these contact forces can be accurately predicted by simulating the operation of the wrist FTS, and that the readings provide information about the contact geometry and they can be used [3] to guide the robot operation.

Wrist force/torque sensors [4] typically use eight pairs of semiconductor strain gauges mounted on four deflection bars - one gauge on each side of a deflection bar. The gauges on the opposite open ends of the deflection bars are wired differentially to a potentiometer circuit whose output voltage is proportional to the force component normal to the plain of the strain gauge. Since the eight pairs of strain gauges are oriented normal to the *x, y, z* axes of the FTS coordinate frame, all the components of the force and torque can be determined by properly adding and subtracting the output voltages, respectively. In practice, the vector $\mathbf{W}$ that contains the eight raw readings is pre-multiplied by a *sensor calibration matrix* $\mathbf{R}$, which provides for scaling of the data, and also accounts for coupling effects between the gauges, at some given temperature.

Thus, if $\mathbf{F}_s = [F_x\ F_y\ F_z\ \tau_x\ \tau_y\ \tau_z]^T$ is the six-dimensional force and torque output of the FTS, then $\mathbf{F}_s = \mathbf{RW}$.

## 2 Problem Statement

Due to variations over time, inherent in most electronic components, and due to changes in the operating temperature, drift currents can occur, which result in biased readings. The bias in each force/torque component may be positive or negative, and is not accounted for in the calibration matrix. Furthermore, the unknown FTS mass distribution produces a force $\mathbf{F}_g$ due to gravity, which is included in the FTS measurements, and which varies, depending on the FTS orientation. Thus, the force/torque output of the FTS does not give us directly the contact force $\mathbf{F}_c$. Instead, the following equation is true:

$$\mathbf{F}_s = \mathbf{F}_b + \mathbf{F}_g + \mathbf{F}_c + \mathbf{F}_n + \mathbf{F}_v$$

where $\mathbf{F}_b$ is the FTS bias, $\mathbf{F}_g$ is the force/torque due to gravity exerted on the FTS mass, $\mathbf{F}_c$ is the contact force, $\mathbf{F}_n$ is the FTS output due to noise and $\mathbf{F}_v$ is the FTS output due to vibration and inertial forces. Our goal is to compute the constant bias force, and the varying gravity force, for arbitrary FTS orientations and corresponding robot configurations, so that we can get a more accurate estimate of the contact forces during the robot operation.

## 3 Methodology

In this work we assume that, except for bias, the FTS is properly calibrated for its operating temperature. This means that there are no significant changes in the gains of the amplifiers and thus we do not need to recompute a calibration matrix.

The gravity component depends solely on the FTS orientation, the FTS mass and the distance of the center of mass from the FTS-frame orthogonal axes (the FTS orientation is known from forward kinematics). Hence, in order to compute the gravity forces on the FTS, due to the FTS 's own mass, we need to estimate the *total mass* of the FTS, as well as its *center of mass.* We should stress that the mass and center of mass of the FTS depend also on the mass distribution of any tool attached to it (e.g. gripper), and thus their estimation should be repeated every time the tool changes. Of course, if the tool mass distribution is known with great accuracy, it can be used directly.

Since the force bias is included in all measurements, it must be subtracted from the measurements taken to estimate the mass and center of mass of the FTS. Thus, we need to estimate the force bias first. Since the operating temperature does not vary significantly during daily robot operation, we need to estimate the bias only once, before the beginning of the robot operation. The bias estimate will be subtracted from the FTS readings during real time operation.

In this work we estimate the mass, center of mass and bias of the FTS from a set of properly chosen FTS orientations. We use the robot manipulator to place the desired FTS orientations. All measurements are to be taken when the robot is in free space and not moving, so that contact forces and inertial forces are zero and vibrations are minimal. In order to minimize the effects of thermal and electrical noise ($\mathbf{F}_n$) in our measurements, the FTS readings can be fed to a low-pass running-average filter of adequate length.

## 4 Bias Estimation

Let the six-dimensional force-bias vector be $\mathbf{F}_b$ and our estimate of it be $\widehat{\mathbf{F}}_b$. The estimation of this vector is based on the following simple idea. Assume we want to compute the force bias $\mathbf{F}_{by}$ in the y-direction. We can position the FTS in a configuration such that $F_y$ is known to be zero. In this case the y-component of the measured force will be the bias. Alternatively, we can position the FTS in two configurations where the true forces are known to be $+F_y$ and $-F_y$. In this case the FTS readings will be $F_y+ F_{by}$ and $-F_y+ F_{by}$, respectively. Therefore the bias can be found from the average of the two measurements.

In a similar fashion, assume that the torque bias $\tau_{bx}$ needs to be computed. If we position the FTS in two configurations where the true forces are $(+F_y, + F_z)$ and $(-F_y, -F_z)$, then the FTS torque readings will be

$$\tau_x = (r_y F_z - r_z F_y) + \tau_{bx}, \; \tau_x = (-r_y F_z + r_z F_y) + \tau_{bx}$$

respectively, where $\mathbf{r}$ is the unknown center of mass of the FTS. Again, the bias can be found from the average of the two measurements.

In order to reduce the estimation error due to noise in the measurements, we can use more than one pair of force readings to estimate the torque and force biases. For this work we have used a total of $K$ = 24 suitable configurations, resulting in $K$ independent readings from the FTS. The corresponding rotation matrices $R_i$ for the K frames are given in the Appendix. The world (fixed) frame orientation coincides with $R_7$ and the z-axis of frame $R_7$ is the direction of gravity (actually the base of the PUMA may be slightly tilted).

The reasoning behind choosing these frames is the following. All the FTS frames are legal permutations of the world frame (they obey the right-hand rule). Therefore, two force components of the actual force are zero and the third is equal to $\pm mg$, where $g$ is the local gravity acceleration and $m$ is the mass of the FTS. Thus, the force biases $F_x$, $F_y$, $F_z$ can be measured by simply taking the average of all force measurements. Also, the frame pairs ($R_i$, $R_{i+1}$, $1 \le i \le 7$) are used to estimate the torque bias $\tau_{bx}$ based on the idea described earlier in this section. The torque bias is simply the average of all eight torque measurements about the $x$-axis. Similarly, the next four frame pairs are used to estimate the torque bias $\tau_{by}$ and the last four pairs are used for $\tau_{bz}$.

## 5 Estimation of Mass

Let the gravity vector expressed in world coordinates be $\mathbf{g}_I^T = [\ 0\ 0\ -g]$, where $g$ is the local gravity acceleration. If the FTS frame orientation for the $i$th measurement is $R_i$, then the gravity vector expressed in the FTS frame is $\mathbf{g}_{si} = R_i^T \mathbf{g}_I$.

The $i$th force measurement, after the bias has been subtracted, should be (in the absence of noise) $\mathbf{F}_i = m\mathbf{g}_{si}$. If we stack all force measurements $\mathbf{F}_i$, in a vector $\mathbf{F}$ and all known vectors $\mathbf{g}_{si}$ in a vector $\mathbf{G}$, we can estimate the mass of the force torque sensor by computing

$$m^* = \min_m (\mathbf{F} - m\mathbf{G})^T (\mathbf{F} - m\mathbf{G})$$

Its easy to show that the best estimate, in the least square sense, is

$$m^* = \frac{\mathbf{G}^T \mathbf{F}}{\mathbf{G}^T \mathbf{G}}$$

Note that mass information is also contained in the torque measurements. The torques due to the weight of the FTS are equal to the weight multiplied by the distances of the center of mass from the FTS frame *x, y, z* axes. This distance is small (fraction of a *mm)* and the torque measurements due to gravity are small in magnitude and thus more susceptible to noise. Thus, we estimate the mass based only on the measurement of the FTS weight.

# 6 Estimation of the Center of Mass

Information about the location of the center of mass of the FTS is contained only in the torque measurements. If the center of mass is located at **r,** then the torque due to gravity at the *i*th configuration, after the bias has been subtracted, is:

$$\tau_i = m\boldsymbol{r} \times \mathbf{g}_{\mathrm{si}}$$

All vectors are expressed in the FTS frame. The cross product in the previous equation can be written as $\tau_i = mA_i\,\boldsymbol{r}$, where

$$A_i = \begin{bmatrix} 0 & g_{iz} & -g_{iy} \\ -g_{iz} & 0 & g_{iz} \\ g_{iy} & -g_{iz} & 0 \end{bmatrix}$$

If we stack all the $K$ torque measurement vectors into a vector $\mathbf{T}$ and all the $A_i$ matrices in a matrix A ($3K \times 3$), then the center of mass $\mathbf{r}$ can be computed as the vector

$$\mathbf{r}^* = \min_{\mathbf{r}} (\mathbf{T} - m^* A\mathbf{r})^T (\mathbf{T} - m^* A\mathbf{r})$$

where $m^*$ is our best estimate of the mass. The solution is computed from the pseudo-inverse and is equal to:

$$\mathbf{r}^* = \frac{1}{m^*}(A^T A)^{-1} A^T \mathbf{T}$$

# 7 Gravity Compensation

If the estimates for the FTS mass are known, then our estimated force/torque due to gravity, for an arbitrary robot configuration, is equal to

$$\widehat{\mathbf{F}}_g = \begin{bmatrix} m^* R^T \mathbf{g}_I \\ m^* \mathbf{r}^* \times (R^T \mathbf{g}_I) \end{bmatrix}$$

where the gravity $\mathbf{g}_I$ is constant and known at a given location, and the rotation matrix $R$ defines the FTS frame orientation and is known from the robot manipulator forward kinematics.

# 8 Experimental Results

The FTS used in our experiment was the LORD 15/50 force/torque sensor [5]. This 6-axis sensor can read forces of up to 66.7 *N* and torque up to 5.65 *Nm*. The FTS is delivered fully calibrated at 22.2 degrees Celsius. The FTS was sampled every 5.4 *ms* (185 *Hz*) and a low-pass running-average filter of length 16 samples, was used to minimize the effects of thermal and electrical noise ($\mathbf{F}_n$) in our measurements. The measurements were taken after the robot had reached each desired position, in order to eliminate the vibration and inertial component $\mathbf{F}_v$.
The FTS was attached to the wrist of a PUMA 560 robot. The Unimation controller was used to move the PUMA 560 robot (and the FTS attached to its wrist) to the pre-specified configurations. Although the code was written for the particular robot, the estimation method is general and can be used on any manipulator. Furthermore, the same code will work when a rigid end-effector, possibly carrying some rigid load, is attached to the robot, after the FTS. We explicitly specify "rigid" because in our estimation method we assume that the center of mass is not changing.
The bias estimation procedure was implemented both in MATLAB and in the C language. The manipulator was commanded to move to the 24 pre-specified configurations shown in the Appendix. From the 24 force/torque measurements taken at those configurations, the estimates for the FTS mass and center of mass were found to be:

$m^* = 0.2489$ (*Kg*), $\mathbf{r}^* = [\,-0.9\ -0.1\ 7.1]^{\mathrm{T}}$ (*mm*)

and the bias vector was computed to be:

$\mathbf{F}_b = [.3128\ \ -1.0857\ \ 4.8458\ \ 0.0006\ \ .1732\ \ -.0431]^T$

where the first three numbers are expressed in Newtons (*N*) and the last three in Newton-meters (*Nm*). The mean square root estimation error for the forces was:

$$e=\sqrt{\frac{(\mathbf{F}-m^{*}\mathbf{G})^{T}(\mathbf{F}-m^{*}\mathbf{G})}{K}}=0.2111\quad(N)$$

and the maximum absolute force errors were:

$e_{max} = [0.146\ \ 0.3044\ \ 0.2696]^{T}$

For the torques, the mean square error was:

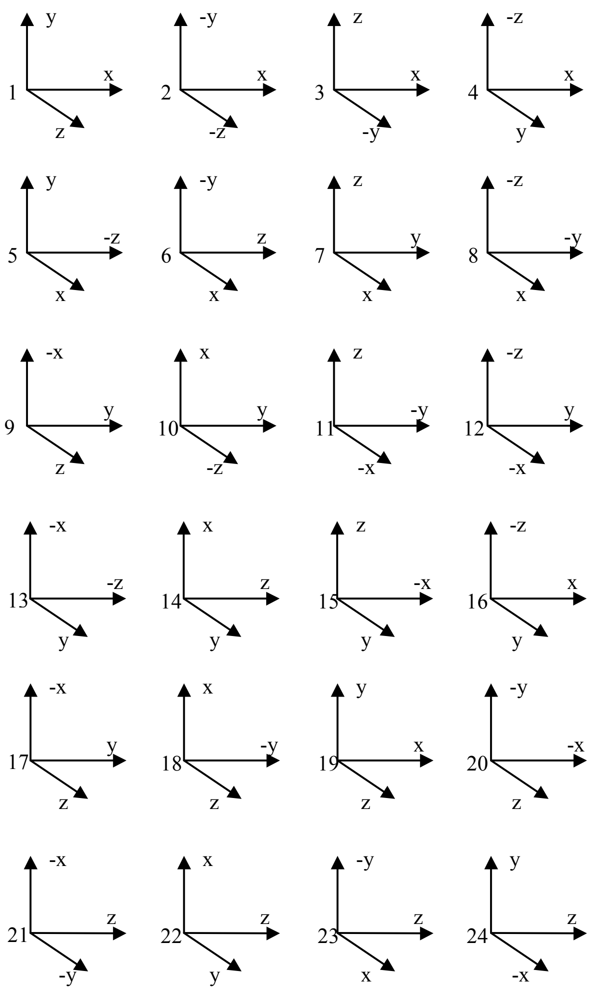
$$e=\sqrt{\frac{(\mathbf{T}-m^{*}A\mathbf{r})^{T}(\mathbf{T}-m^{*}A\mathbf{r})}{K}}=0.0031\quad(Nm)$$

and the maximum absolute torque errors were:

$e_{max} = [0.0037\ \ \ 0.0051\ \ 0.0025]^{T}\ \ (Nm)$

# 8 APPENDIX

The 24 FTS sensor frame orientations for the estimation of the force bias $\mathbf{F}_b$ are given below.




The corresponding rotation matrices $R_{2i+1}$, where $0 \le i \le 11$, for the FTS frame orientations are the following:

$$R_1=\begin{bmatrix}0&0&1\\1&0&0\\0&1&0\end{bmatrix},R_3=\begin{bmatrix}0&-1&0\\1&0&0\\0&0&1\end{bmatrix},R_5=\begin{bmatrix}1&0&0\\0&0&-1\\0&1&0\end{bmatrix}$$

$$R_7=\begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix},R_9=\begin{bmatrix}0&0&1\\0&1&0\\-1&0&0\end{bmatrix},R_{11}=\begin{bmatrix}-1&0&0\\0&-1&0\\0&0&1\end{bmatrix}$$

$$R_{13}=\begin{bmatrix}0&1&0\\0&0&-1\\-1&0&0\end{bmatrix},R_{15}=\begin{bmatrix}0&1&0\\-1&0&0\\0&0&1\end{bmatrix},R_{17}=\begin{bmatrix}0&0&1\\0&1&0\\-1&0&0\end{bmatrix}$$

$$R_{19}=\begin{bmatrix}0&0&1\\1&0&0\\0&1&0\end{bmatrix},R_{21}=\begin{bmatrix}0&-1&0\\0&0&1\\-1&0&0\end{bmatrix},R_{23}=\begin{bmatrix}1&0&0\\0&0&1\\0&-1&0\end{bmatrix}$$

The rotation matrices $R_{2i+2}$ are:

$$R_2=\begin{bmatrix}0&0&-1\\1&0&0\\0&-1&0\end{bmatrix},R_4=\begin{bmatrix}0&1&0\\1&0&0\\0&0&-1\end{bmatrix},R_6=\begin{bmatrix}1&0&0\\0&0&1\\0&-1&0\end{bmatrix}$$

$$R_8=\begin{bmatrix}1&0&0\\0&-1&0\\0&0&-1\end{bmatrix},R_{10}=\begin{bmatrix}0&0&-1\\0&1&0\\1&0&0\end{bmatrix},R_{12}=\begin{bmatrix}-1&0&0\\0&1&0\\0&0&-1\end{bmatrix}$$

$$R_{14}=\begin{bmatrix}0&1&0\\0&0&1\\1&0&0\end{bmatrix},R_{16}=\begin{bmatrix}0&1&0\\1&0&0\\0&0&-1\end{bmatrix},R_{18}=\begin{bmatrix}0&0&1\\0&-1&0\\1&0&0\end{bmatrix}$$

$$R_{20}=\begin{bmatrix}0&0&1\\-1&0&0\\0&-1&0\end{bmatrix},R_{22}=\begin{bmatrix}0&1&0\\0&0&1\\1&0&0\end{bmatrix},R_{24}=\begin{bmatrix}-1&0&0\\0&0&1\\0&1&0\end{bmatrix}$$

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