

Gravity and Drift in Force/Torque Measurements

Can Erdogan, Munzir Zafar, Mike Stilman

1 Introduction

Force control of robotic manipulators is increasingly becoming a popular technique to enable robots to interact with their environments in a safe manner. This is primarily achieved by using a force-torque sensor to sense the external forces interacting with the end-effector. This sensor is most commonly placed at the end of the wrist right before the end-effector as shown on left in Figure 1.

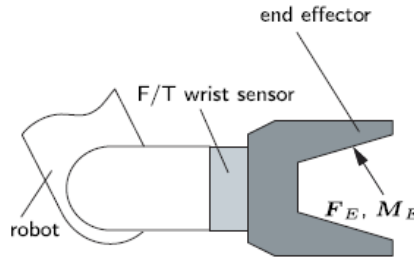


Figure 1: A generic placement of a f/t sensor where the end-effector weight affects readings.

When the sensor is placed before the end-effector, the sensor measures not only the external forces and torques acting on the end-effector but also those due to the **weight** and **motion** of the end-effector itself. We need to compensate for this effect of the end-effector to attain accurate estimation of the external force on the end-effector.

A secondary problem is the **drift** in the sensor values, that is the sensor values, in time, slowly change to a wrong value due to fabrication imperfections, heat and etc. A common approach is to compute an offset between the measurements and the true state of the sensor. For instance, if the gripper is isolated and stationary, then the readings should reflect only its weight. In such a situation, we can compute a new offset that we will keep decreasing from the future readings to estimate the true value. After a while, as the drift changes the readings again, we will recompute this offset in an appropriate scenario.

2 Background

A force/torque sensor with a frame S at origin o_S returns a 6×1 raw wrench reading ${}_S W_r^t(o_S)$ at time t which has the force and the moment values:

$${}_S W_r^t(o_S) = [f_x^t, f_y^t, f_z^t, m_x^t, m_y^t, m_z^t] \quad (1)$$

where the force and moment values are measured with respect to the $\{x, y, z\}$ axes of the S frame. Note that we interchangeably use the words torque and moment. To inspect these values and relate them to the weight of the end-effector and outside forces, we need to be able to discuss what these readings would be when considered in a different frames of reference S' and at different measurement points $o_{S'}$.

Changing the reference frame

Let ${}_{S_1} W(p)$ be the wrench reading for some force and torques applied to point p and measured with respect to the frame S_1 . Now, if we would like to know what the measurement would be with respect to another frame S_2 , we would only have to determine the rotation between the two frames S_1 and S_2 . Note that the location of the origins of the frames is not of importance because force and torque vectors are

free vectors, that is we only care about their direction and magnitude. Figure 2 delineates two frames S_1 and S_2 in some transformation as well as a couple of force and torque measured at some point. You can imagine sitting at origin of S_2 looking at x_2 and trying to evaluate what the force and torques should be in S_2 's coordinate frame.

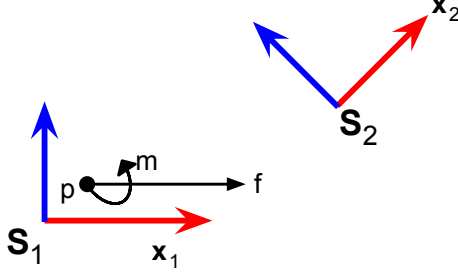


Figure 2: A force f and a moment m applied at point p and “observed” at reference frames S_1 and S_2

Let ${}_{s_2s_1}R$ be the rotation and ${}_{s_2s_1}t$ be the translation between the frames such that for a point q with coordinates q_1 in the coordinates q_2 is $q_2 = {}_{s_2s_1}R * q_1 + {}_{s_2s_1}t$. Then, the reading ${}_{s_1}W(p)$ in frame S_1 can be transformed to a reading in frame S_2 by simply rotating the forces and moments independently of each other with rotation ${}_{s_2s_1}R$:

$$\begin{aligned} {}_{s_2}W(p) &= \begin{bmatrix} {}_{s_2}F(p) \\ {}_{s_2}M(p) \end{bmatrix} = \begin{bmatrix} {}_{s_2s_1}R & 0 \\ 0 & {}_{s_2s_1}R \end{bmatrix} \begin{bmatrix} {}_{s_1}F(p) \\ {}_{s_1}M(p) \end{bmatrix} \\ &= \begin{bmatrix} {}_{s_2s_1}R & 0 \\ 0 & {}_{s_2s_1}R \end{bmatrix} {}_{s_1}W(p) = {}_{s_2s_1}{}^F T * {}_{s_1}W(p) \end{aligned} \quad (2)$$

where we used the F and M symbols to annotate the 3×1 force and moment vectors. We will be using the symbol ${}_{s_2s_1}{}^F T$ for the 2×2 matrix for a frame transformation between the two frames. Note that even though this notation might seem a bit more cumbersome, it is necessary because a wrench identifier ${}_{s_1}W_r^t(p)$ has four sources of information: (1) the frame S_1 , (2) the time of measurement t , (3) the point of measurement p , and (4) a qualifier such as r for raw measurement. Still, the notation in transformation still gives an intuition when inspect from right to left as in the rotation ${}_{s_2s_1}R$ changes the coordinates of a point p from p_1 to p_2 respectively from frames S_1 to S_2 .

Changing the measurement point

Imagine a box on a desk and we push it from two opposite corners in opposite horizontal directions so that it moves. Let If the two forces, F_1 and F_2 , have the same magnitude, the box would simply rotate in place and not move. If F_1 is greater than F_2 , then it would start moving in the direction of the net total force, F_t as Figure 3B.

Let ${}_S W(p)$ be the wrench measurement on point p evaluated at frame S , due to the total force F_t . If we know the point of contact for the total force F_t , we can compute this wrench by taking the cross product of the vector from the point of contact c to p with the force vector:

$$F_p = F_t \quad (3)$$

$$M_p = (c_S - p_S) \times F_t \quad (4)$$

Note that the measured force at point p is preserved as the total force F_t on point c . Also, note that, we made the subtraction for the vector using the point coordinates in frame S and we assume that the force F_t is already measured in the frame coordinates. Now assume that we do not know the source or the magnitude of the total force but we can measure the effects of it, the wrench ${}_S W(p)$, on a point p in a rigid body. Moreover, we would like to compute the wrench on another point q due to the same force and moments on the rigid body. We can do this in two steps.

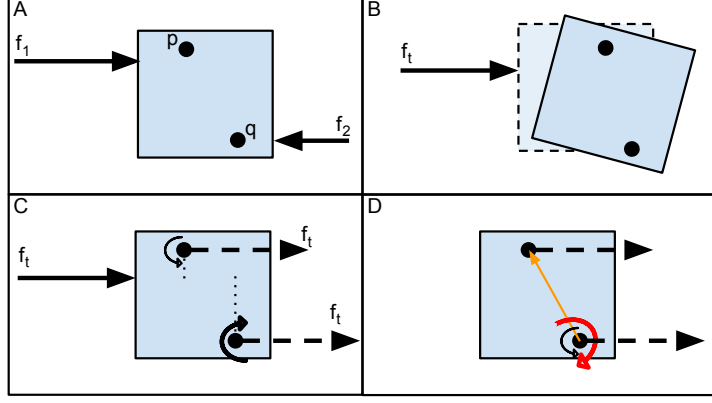


Figure 3: Computation of the effect of the source of a force/torque pair measured at point p on point q

First, note that the force is again going to be preserved, that is $F_q = F_p$. However, for the moment M_q , the force on p is going to induce a torque around q , M_q^p while the moment M_q itself is going to affect p as well (See Figure 3D). The total moment then is the sum of the moments from two different sources, one around p , and one induced by the force on p :

$$M_q = M_p + (p_s - q_s) \times F_t \quad (5)$$

Using Equation 5, we can rewrite the total wrench on q using the wrench notation simply as:

$$\begin{aligned} {}_sW(q) &= \begin{bmatrix} {}_sF(q) \\ {}_sM(q) \end{bmatrix} = \begin{bmatrix} I_{3 \times 3} & 0 \\ [p_s - q_s]_x & I_{3 \times 3} \end{bmatrix} \begin{bmatrix} {}_sF(p) \\ {}_sM(p) \end{bmatrix} \\ &= \begin{bmatrix} I_{3 \times 3} & 0 \\ [p_s - q_s]_x & I_{3 \times 3} \end{bmatrix} {}_sW(p) = {}_{S_1}^P T(q, p) * {}_sW(p) \end{aligned} \quad (6)$$

where $I_{3 \times 3}$ is a 3×3 identity matrix and the notation $[v]_x$ represent the skew symmetric matrix created using the vector v , often used for cross products. Note that this time, we use the symbol ${}_{S_1}^P T(q, p)$ with the left superscript P to indicate the transformation from point p to point q in the S_1 frame.

Chaining transformations on wrenches

In analyzing the force/torque values on the sensor, we have to consider the effect of force and moments at a point o_1 and evaluated within frame S_1 to another point o_2 within frame S_2 . Using the transformations we have discussed above as in the following:

$${}_{S_2}W(o_2) = {}_{S_2}^P T(o_2, o_1) * {}_{S_2S_1}^F T * {}_{S_1}W(o_1) \quad (7)$$

where we first change the frame from S_1 to S_2 and then, within the S_2 frame, move from point p to q .

3 Effect of gravity on sensor readings

Our goal in using the force/torque sensor is to estimate the forces and torques from the external world on the sensor point o_S in the base frame B at time t , that is, the external wrench ${}_B W_e^t(o_S)$. To reach this goal, we will have to consider a number of different frames for the external force, center of gravity of the gripper, the sensor and the room. Figure 4 demonstrates these frames for clarity. Note that even though the inertia of the gripper, J_c , is included in the figure, for now, we will assume that the gripper moves slowly and the wrench due to inertia is negligible.

We know that ideal sensor readings, ${}_sW_s^t(o_S)$, subscript s for sensor, are reaction wrenches due to external input wrenches, ${}_sW_e^t(o_S)$, and gripper wrenches, ${}_sW_g(o_S)$, due to its weight, all measured at the sensor origin and evaluated for the sensor frame. Moreover, we know that the wrench due to the

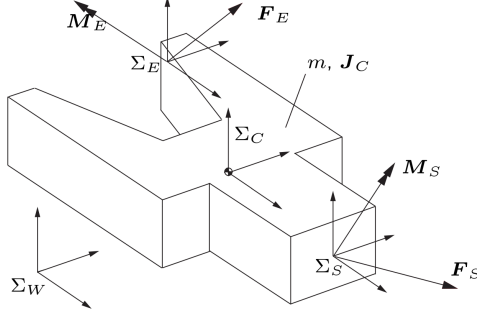


Figure 4: The frames we need to consider to compute the external wrenches (adapted from [1])

gripper weight is simply a force at the gripper origin o_G along the $-z$ axis of the room frame R with a magnitude of mg where m is the mass of the gripper. So, we can write the equation for the sensor readings ${}_S W_s^t(o_S)$ as follows:

$${}_S W_s^t(o_S) = {}_S W_e^t(o_S) + {}_S W_g^t(o_S) \quad (8)$$

$$\begin{aligned} &= {}_S W_e^t(o_S) + {}_S^P T(o_S, o_G) * {}_{SR}^F T^t * {}_R W_g(o_G) \\ &= {}_S W_e^t(o_S) + {}_S^P T(o_S, o_G) * {}_{SR}^F T^t * [0, 0, -mg, 0, 0, 0]^T \end{aligned} \quad (9)$$

where the gripper term in Equation 8 is time-varying because the gripper's pose with respect to the room frame might change in time. Note that for this pose, we only care about the rotation between the sensor and room frames, and not the location since forces and moments are free vectors.

Assuming that we have ideal sensor readings, ${}_S W_s^t(o_S)$, we can compute the external wrenches by reorganizing Equation 9 and transforming the external wrenches in the sensor frame ${}_S W_e^t(o_S)$ to the base frame ${}_B W_e^t(o_S)$ (which is the goal):

$$\begin{aligned} {}_B W_e^t(o_S) &= {}_S W_s^t(o_S) - {}_S^P T(o_S, o_G) * {}_{SR}^F T^t * [0, 0, -mg, 0, 0, 0]^T \\ &= {}_{BS}^F T^t * \left[{}_S W_s^t(o_S) - {}_S^P T(o_S, o_G) * {}_{SR}^F T^t * [0, 0, -mg, 0, 0, 0]^T \right] \end{aligned} \quad (10)$$

4 Handling drift

Force/torque sensors are rarely drift free because factors such as hardware imperfections can not be modeled accurately. Our observations have showed that readings start drifting from their average values a few times the standard deviation values within 20 minutes or so. Assuming this drift is not affected by the pose of the force/torque sensor or the wrenches that applied on it as it is used, we can compute a correction to the raw values every 10 minutes by estimating what the value should be from the state of the robot and comparing it with the measurements. Such a correction then would be applied to the following values before a new one is attained in a state where we know that there are no external forces and we can estimate the correct value.

In the following, we will show how to compute the idealized sensor readings from the raw readings by computing the correction offset. We start with the fact that an ideal sensor reading at time t , ${}_S W_t^t(o_S)$ is the summation of the raw reading ${}_S W_r^t(o_S)$ with the offset ${}_S W_o(o_S)$. Let $t = 0$ be the time where we can assume there are no external wrenches on the sensor readings: ${}_S W_e^0(o_S) = 0$. Then, following Equation 8, we know that the ideal wrench readings are only due to the weight of the gripper. Using these two concepts, we can compute the offset wrench ${}_S W_o(o_S)$ we want to add:

$$\begin{aligned} {}_S W_o(o_S) &= {}_S W_s^0(o_S) - {}_S W_r^0(o_S) = {}_S W_g^0(o_S) - {}_S W_r^0(o_S) \\ &= \left[{}_S^P T(o_S, o_G) * {}_{SR}^F T^0 * [0, 0, -mg, 0, 0, 0]^T \right] - {}_S W_r^0(o_S) \end{aligned} \quad (11)$$

where to compute the offset we simple estimate what the sensor reading should be from the mass of the gripper and subtract the raw reading from it. Now, having established the constant offset, we can first compute what the idealized sensor reading is at time t by adding to the raw reading the offset:

$${}_sW_s^t(o_S) = {}_sW_r^t(o_S) + \left[{}_S^P\mathbf{T}(o_S, o_G) * {}_{SR}^F\mathbf{T}^0 * [0, 0, -mg, 0, 0, 0]^T - {}_sW_r^0(o_S) \right] \quad (12)$$

and then get the correct external wrench estimate in the room frame using Equation 9.

Note that throughout this report, we do not discuss how to compute the transformation from the room frame to the sensor frame, ${}_{SR}^F\mathbf{T}^t$. Please refer to our kinematics report for that.

References

- [1] Georg Bätz, Michael Scheint, and Dirk Wollherr. Toward dynamic manipulation for humanoid robots: Experiments and design aspects. *International Journal of Humanoid Robotics*, 8(03):513–532, 2011.