Contact Force Estimations Using Tactile Sensors and Force/Torque Sensors

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ABSTRACT

In this paper we present a method to estimate forces and moments applied to a robotic chain, which is based on the recursive Newton-Euler algorithm. The method uses a six axis force/torque (F/T) sensor, located at the base of the kinematic chain, together with a tactile sensor network, which covers most of the surface of the robot. The tactile sensors measure the contact locations, whereas the F/T sensor measures the magnitude and the direction of the contact forces. We show that the number of contacts that is possible to estimate reliably is strictly dependent on the amount of information retrieved from the sensors. When this critical number is exceeded, infinite solutions satisfy the estimation problem, though, in some cases we can choose one of the possible solutions and draw the probability distribution of its error.

Keywords

Force/Torque Sensor, Tactile Sensor, Force Estimation

1. INTRODUCTION

In most robotics applications, robots come into contact with the environment just with their end effectors. Nevertheless, robots could benefit from making contacts with other parts of their bodies, in the same way humans do when performing tasks such as writing, carrying heavy objects, or balancing.

This lack is mainly due to the fact that nowadays most robots do not have an artificial skin that allows them to detect and localize contacts. Either joint torque sensors or 6 axis F/T sensors are usually used to provide contact feedback to robots. However, with these sensors it is not possible to retrieve the exact contact location, unless we make strong assumptions about the contact (e.g. zero moment applied, known force direction). Moreover, the wrench (i.e. force and moment) that is applied at the contact point cannot be measured, unless the contact location is somehow known. Often these applications focus on controlling the joint torques rather than the contact wrenches, but this approach is not generally applicable because it does not control the interaction wrenches.

In the end, force control applications suffer from at least one of these limitations:

- the contact point has to be fixed and known a priori (usually the end effector)
- the geometry of the robot and the environment have to be known
- it is not possible to control the contact wrenches, but just the joint torques

In [6] a theoretical framework to model and control robots that are subject to multiple contacts is presented, but the authors do not discuss how to localize the contacts and estimate the contact forces/pressures. In [4], Park et al. present a compliant motion control framework for multiple contacts and test it with a PUMA560 manipulator. In the experiments the geometry and the stiffness of the environment are assumed to be known a priory in order to compute the contact points and the contact forces. A probabilistic approach has been proposed in [5], where the authors used an active sensing strategy to estimate at the same time robot the shape and the contact point. Nevertheless, the method only has been tested with extremely simple robot and environment geometries (the environment is a point and the robot link is a line) and the authors say that for more complex geometries more sophisticated active exploration strategies will likely be needed.

When both tactile sensors and F/T sensors are available we can estimate contact locations and contact wrenches, and so implement reliable contact force control. In this paper we present a method to estimate internal and external wrenches that is based on the well known *Recursive Newton-Euler Algorithm* (RNEA) [7]. The method has been implemented as an extension of the library *iDyn* [2], and it has been tested on the iCub humanoid robot [3]. We assume that the kinematics and dynamics parameters of the robotic chain are known and the position of each tactile sensor has been estimated (we used the method described in [1]). The first step of the proposed algorithm is unmodified with respect to the standard RNEA: it computes velocities and accelerations of all the links starting with the known velocity and acceleration of the chain base (either the base is fixed or an inertial sensor is necessary). In the second step we solve a system of linear equations to estimate the contact wrenches. Finally the classic recursive wrench propagation is computed in order to compute internal wrenches and joint torques.

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In Section 2 we explain how to build and solve the linear system for estimating the contact wrenches. Section 3 discusses the capabilities and the limitations of the presented method, looking at the future extensions.

2. METHOD

Let us consider a kinematic chain composed by N links, having a F/T sensor at the base (see Fig. 1), where $\mathbf{w}_i$ is the wrench (i.e. force and moment) exerted from link i to link i+1, $\ddot{\mathbf{p}}_{c_i}$ is the acceleration of the center of mass of link i and m_i is the mass of link i. We know $\mathbf{w}_0$ (i.e. the F/T sensor measure), the contact locations $\mathbf{r}_{0,ei}$, and we want to estimate the K contact wrenches $\mathbf{w}_{e1}, \ldots, \mathbf{w}_{eK}$.

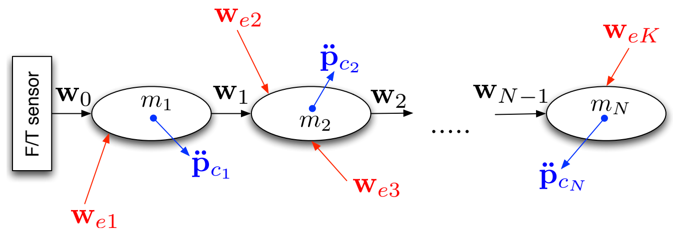

Figure 1: Generic kinematic chain with F/T sensor at the base.

Writing Newton's equation for each link and recursively substituting the internal forces we get:

$$\mathbf{f}_0 + \sum_{i=1}^{K} \mathbf{f}_{ei} = \sum_{i=1}^{N} m_i \ddot{\mathbf{p}}_{c_i} \tag{1}$$

We can do the same with Euler's equation:

$$\mu_0 + \sum_{i=1}^{K} (\mu_{ei} + \mathbf{r}_{0,ei} \times \mathbf{f}_{ei}) = \sum_{i=1}^{N} (\mathbf{r}_{0,c_i} \times m_i \ddot{\mathbf{p}}_{c_i} + I_i^i \dot{\omega}_i + \omega_i \times I_i^i \omega_i), \tag{2}$$

where I_i^i is the inertia of link i, ω_i and $\dot{\omega}_i$ are the angular velocity and acceleration of link i, and $\mathbf{r}_{0,c_i}$ is the vector connecting the chain base to the center of mass of link i. Noting that in (1) and (2) the only unknowns are the contact wrenches, the estimation problem may be solved rewriting these equations in matrix form $A\mathbf{x} = \mathbf{b}$, where $\mathbf{x} \in \mathbb{R}^u$ contains all the u contact unknowns, whereas $A \in \mathbb{R}^{6 \times u}$ and $\mathbf{b} \in \mathbb{R}^6$ are completely determined.

Building the system we consider three different types of contacts, depending on our priors:

1. **wrench**: 6 unknowns, $\mathbf{w}_e$, no priors
2. **pure force**: 3 unknowns, $\mathbf{f}_e$, the moment is known (usually it is supposed to be zero)
3. **force module**: 1 unknown, $||\mathbf{f}_e||$, both the force direction and the moment are known

The *pure force* contact can be used to reduce the number of unknowns when the contact area is considered so small that almost no moment can be applied. The *force module* contact can be used if the tactile sensors can measure the contact force direction.

2.1 Building A

The matrix A is built by adding columns for each contact. For every unknown wrench n we add 6 columns to A:

$$\begin{bmatrix} I & 0 \\ S(\mathbf{r}_{0,en}) & I \end{bmatrix}$$

where $S(\mathbf{v}) \in R^{3\times3}$ is the operator performing the cross product $\mathbf{v}\times$. For every unknown pure force n we add 3 columns to A:

$$\begin{bmatrix} I \\ S(\mathbf{r}_{0,en}) \end{bmatrix}$$

For every unknown force module n we add 1 column to A:

$$\begin{bmatrix} \hat{\mathbf{u}}_n \\ \mathbf{r}_{0,en} \times \hat{\mathbf{u}}_n \end{bmatrix}$$

where $\hat{\mathbf{u}}_n$ is the versor of the contact force $\mathbf{f}_{en}$.

2.2 Building b

The 6 dimensional vector $\mathbf{b}$ is defined as:

$$\mathbf{b} = \begin{bmatrix} \mathbf{f}_b \\ \mu_b \end{bmatrix} = \begin{bmatrix} \mathbf{f}_{eTot} \\ \mu_{eTot} - \mu_{eKnown} \end{bmatrix}$$

where μ_{eKnown} is the sum of the known external moments applied to the robotic chain (usually zero), whereas $\mathbf{f}_{eTot}$ and μ_{eTot} are defined as:

$$\mathbf{f}_{eTot} = -\mathbf{f}_0 + \sum_{i=1}^{N} m_i \ddot{\mathbf{p}}_{c_i}$$

$$\mu_{eTot} = -\mu_0 + \sum_{i=1}^{N} (\mathbf{r}_{0,c_i} \times m_i \ddot{\mathbf{p}}_{c_i} + I_i^i \dot{\omega}_i + \omega_i \times I_i^i \omega_i)$$

2.3 Solving the system

Once A and $\mathbf{b}$ have been computed, we can distinguish two cases. If the number of unknowns is less than or equal to the rank of A, then there is a unique $\mathbf{x}^*$ that minimizes the square error residual:

$$\mathbf{x}^* = argmin_x ||A\mathbf{x} - \mathbf{b}||^2$$

On the other hand, if the number of unknowns is bigger than the rank of A then the system admits infinite solutions. Unless we have some priors about the external wrench distribution, a reasonable choice is to select the solution that minimizes the norm of $\mathbf{x}$, which is the solution where the total external wrench is equally distributed between all the external contacts.

$$\begin{aligned} & \mathbf{x}^* = argmin_x ||\mathbf{x}|| \\ s.t. \quad & A\mathbf{x} = \mathbf{b} \end{aligned}$$

In both cases $\mathbf{x}^*$ may be computed as:

$$\mathbf{x}^* = A^+ \mathbf{b}$$

where A^+ is the pseudo-inverse of A.

The method has been implemented as an extension of the *iDyn* library and it has been integrated with other software modules to create an efficient software system able to estimate internal and external wrenches of the whole *iCub* robot. The estimated contact wrenches, together with a model of the robot, can be depicted in real time in a gui, as it can be seen if Fig. 2.

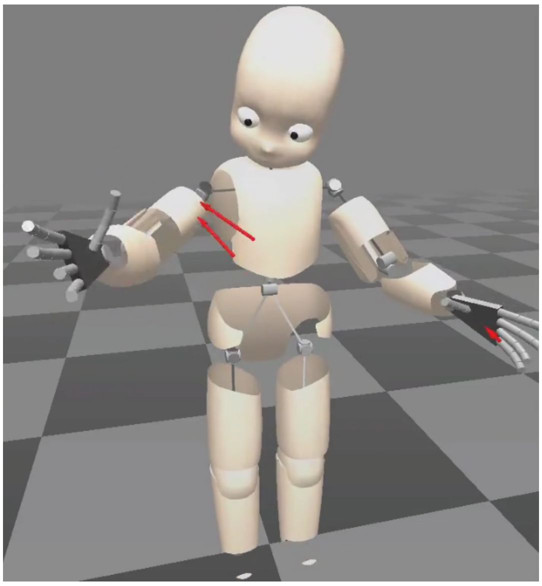

Figure 2: Gui depicting the iCub robot and the estimations of the contact forces as red arrows.

3. DISCUSSION AND CONCLUSIONS

When only one contact is detected, the presented method can easily estimate the contact wrench.

When two contacts are detected the number of unknowns in the linear system is twice the number of equations, so the contact wrenches are poorly estimated. To reduce uncertainties, if the contact areas are small, it is reasonable to assume that the applied moments are zero, so that the number of unknowns drops from 12 to 6. Unfortunately, when we do this, the rank of A drops from 6 to 5 (because the cross product matrix is rank deficient), so the system still admits infinite solutions. However, we carried out a numerical and analytical analysis simulating random forces with norm uniformly distributed in [0, K] Newton. In the end we found out that the norm of the error of the estimated forces is distributed as a *unilateral Gaussian*, with zero mean and standard deviation equal to about $K/4$. That is equivalent to say that the error of the estimate of the two forces, in norm, is less than $K/4$ with probability 0.68, and less than $K/2$ with probability 0.95.

Whenever more than two contacts are detected it is impossible to get a reliable estimate of the contact wrenches without imposing some constraints to the system. Noticing that contact forces are almost always directed towards the robot (i.e. pushing) and quasi-normal to the robot surface, we may constrain the force estimations to lie inside a cone built around the normal of the contact surface.

Additional information regarding the force direction and magnitude may be retrieved through the tactile sensors. For instance, with appropriate technology we may be able to estimate the directions of the contact forces with the tactile sensors. In this case the only unknown left would be the force intensity, so up to six contact forces could be estimated *reliably* (considering zero contact moments).

Another way to improve the estimation capabilities of the system is by adding joint torque sensors to the robot chain (the new version of the *iCub* is equipped with joint torque sensors). For each joint torque sensor we can add a linear equation to the system, increasing the number of unknowns that can be estimated reliably.

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