Identification of Actuation Efforts using Limited Sensory Information for Space Robots

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***Abstract* - Autonomous space robots are needed for future missions such as satellite capture and large space structure construction. Precise control of these space robots is important for space missions but real world factors such as unpredictable actuator behavior can degrade performance. Sensing capabilities in space robots to measure and compensate for this uncertainty are limited by the practical issues of issues of weight, complexity and reliability. This paper presents a method that does multi-actuator sensing with a reduced number of actuators. A force/torque sensor is mounted between a space robot's spacecraft and its manipulators and is used to identify manipulator joint actuator outputs while simultaneously estimating spacecraft thruster forces and moments. Theoretical development and simulation results are presented.**

I. INTRODUCTION

A. Motivation

Future space missions are expected to require autonomous space robots (see Figure 1). These space missions include satellite capture and servicing, debris mitigation, large space structure construction and maintenance, and assembly and manipulation of solar power stations [1][2][3][4]. The robots used for space missions will need to perform precise motion and force control using its manipulators and reaction jets. See Figure 2. However actuation errors can degrade this performance if not compensated using inner closed-loop force/torque control. For space applications, the need to limit system weight results in high gear ratio drives, while conditions in space require the use of dry lubrication in robot joints and transmissions. The result is that these joints have high non-linear Coulomb friction [5]. Reaction jets or thrusters are used to control the large motions of free-flying space robots. These thrusters are used in pulse width modulated (PWM) or pulse width-pulse-frequency modulated (PWPFM) mode that is highly nonlinear [6]. Thruster performance is sensitive to such effects as due to thermal changes, and variation to fuel supply level. These joint and thruster actuation characteristics can degrade system performance.

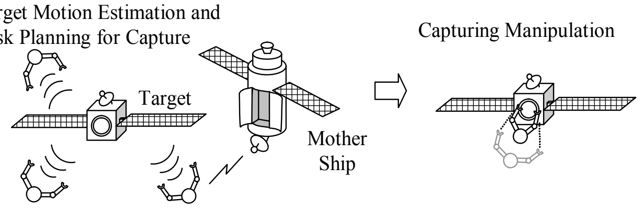

Figure 1. Mission scenario for robotic satellite capture

For the satellite capture task, multiple manipulators will be used to reduce the required forces and moments during satellite capture yet the system will need large gear ratio transmissions and large joint motors to provide enough torque and force to stabilize relative motion between the satellite and the space robot. For large scale space structure construction, the space robot needs to move the assembly components over large distances, and then perform fine maneuvers to attach them to the other components, also requiring substantial thrusters and strong manipulators capable of precise control. A concept of a space robot with two manipulators and spacecraft thrusters is shown in Figure 2.

Robot actuator efforts (manipulator joint motors and vehicle attitude control jets) must be measured for good control system performance. Many sensors would be needed to measure every effort and such direct a measurement of all actuation is impractical. For example, to directly measure the force or torque of all the actuators on the simple system shown in Figure 2 would require a minimum of 26 sensors, with the associated cabling, electronics, power supplies, etc. More redundant thruster configuration could require substantially more sensors. The failure of any one of these sensors could result in a total system failure and hence poor system reliability. This paper addresses the problem of estimating actuator efforts using a reduced number of sensors.

B. Background and Literature

A number of effective methods for dealing with imprecise actuation approaches in conventional ground based manipulators have been developed, including sensor-based and adaptive compensation, and model-based. These methods have principally focused on friction compensation. When sensors are available, measurement-based control provides direct feedback of actuation effort for closed-loop force or torque control [10][11]. These methods are desirable because they do not require a model and hence are robust to system changes with time. However, for a complex space robot they would require multiple sensors that increase cost, weight and complexity, and reduce system reliability. Therefore it is desirable to develop a method that uses limited sensing to measure actuation efforts.

Adaptive control methods have been developed to estimate unknown joint actuator friction parameters [7]. However, adaptive control formulations can be complex especially for high degree-of-freedom space systems, making their implementation difficult [8]. In addition, they have not yet been extended to the identification of attitude control jets forces and moments. Also for space systems, there is a preference to rely on measurement of uncertainty and errors rather than indirect computation due to the very wide range of environmental conditions that can affect system parameters and the need to avoid dangerous transient behaviour during adaptation.

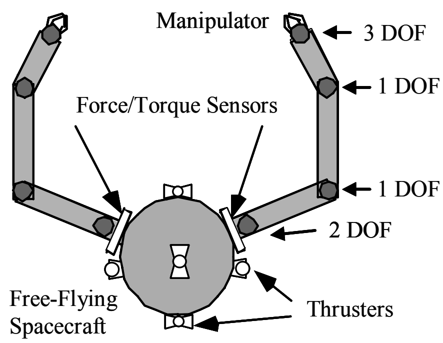

Figure 2. Space robot with force/torque sensors mounted between spacecraft and manipulator.

Model-based actuator effort compensation methods use mathematical models to predict actuator behavior [7]. However, these methods would not be robust in the hostile environment of space because model parameters change radically with conditions, load, position, temperature, and wear. Therefore model based compensation is not well suited to space applications. Other methods based on special command profiles to deal with imprecise actuation have been developed such as high frequency dither [9]. However, these methods have yet to be developed for space applications, in particular for reaction jet uncertainty.

C. *System Considered*

The approach proposed here to identify actuator efforts from limited sensor data using appropriate kinematic and dynamic models is an extension of the Base Sensor Control (BSC) method that has been developed for fixed-based terrestrial robots [12]. BSC is used in control algorithms to close an inner torque control loop. It identifies joint torques by placing a single six-axis force/torque sensor between its manipulator and its fixed base. Here one six-axis force/torque sensor is placed between each manipulator and its spacecraft (see Figure 2). In this paper it is shown that these sensors can simultaneously measure all of the system's the actuator efforts including the effectives of friction in the manipulator joints and jet reaction forces and torques. The measurements can be used in inner force or torque control loops to eliminate torque and thruster actuation error, improving the precision control system (see Figure 3). These sensors could also be used for continuous monitoring to detect degradation in actuator performance. The effectiveness of the method is demonstrated in simulation.

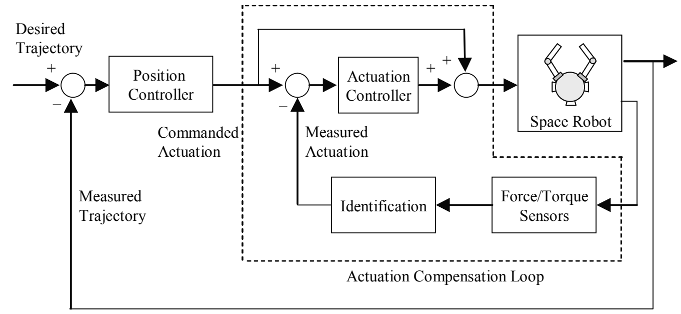

Figure 3. Inner loop identifies and compensates for actuator efforts while outer loop tracks desired trajectory.

II. ANALYTICAL DEVELOPMENT

A. *System Description and Assumptions*

The systems studied are free-flying space robots with multiple manipulators (see Figure 4). Each of the p manipulators has n links. It is assumed that there is a six-axis force/torque sensor between each manipulator and its spacecraft. Manipulators are assumed to have rotary joints, but the method developed here can be extended to translational joints. The spacecraft is assumed to be a rigid body.

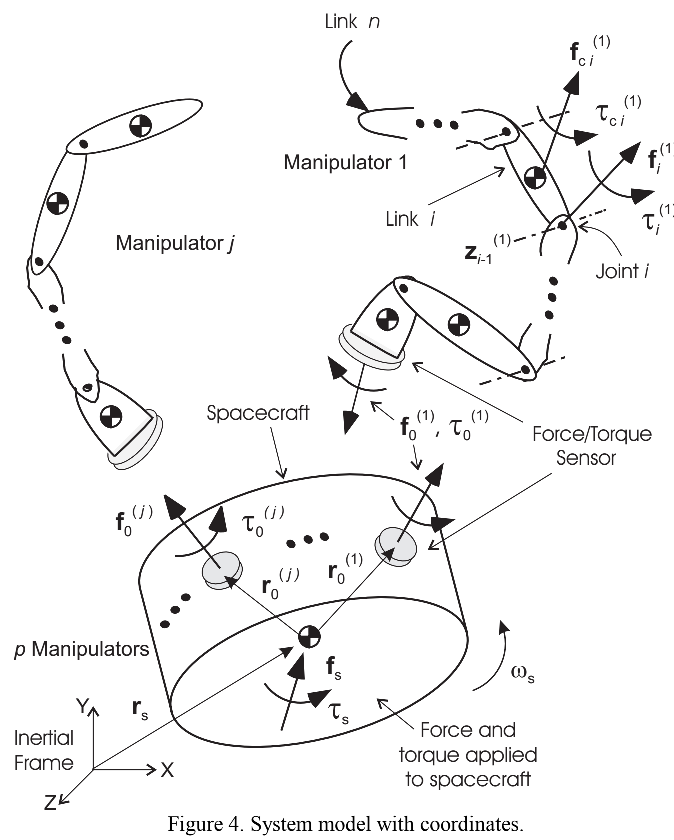

Figure 4. System model with coordinates.

The efforts of all the thrusters are represented by a single force and moment applied at the center of mass of the spacecraft. Fuel sloshing and flexible modes are not considered. Gravity gradient effects are neglected because they are small compared to the other forces.

The sensors force/torque measurements are used to identify the net torque output of the manipulator's actuators; the same measurements are used to identify in spacecraft thruster outputs. Other measured quantities are joint angles for each of the j manipulators ($\mathbf{q}^{(j)}$), linear acceleration of the spacecraft ($\dot{\mathbf{v}}_s = \ddot{\mathbf{r}}_s$), spacecraft orientation ($\boldsymbol{\theta}$), angular velocity of the spacecraft ($\boldsymbol{\omega}_s$) and angular acceleration of the spacecraft ($\dot{\boldsymbol{\omega}}_s$), see Figure 5. Quantities to be estimated are the applied thruster forces ($\mathbf{f}_\mathrm{s}$) and moments ($\boldsymbol{\tau}_\mathrm{s}$) and the torques ($\boldsymbol{\tau}_\mathrm{a}^{(j)}$) applied at the joints of the jth manipulator.

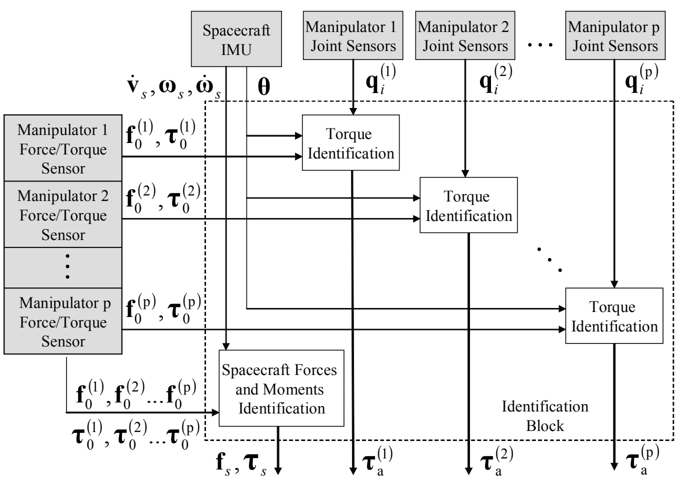

Figure 5. Actuation effort identification flowchart.

B. Method

The equations for linear momentum $\mathbf{p}_s$ and angular momentum $\mathbf{H}_s$ at the center of mass of the spacecraft are:

$$\begin{aligned} \mathbf{p}_s &= m_s \mathbf{v}_s \\ \mathbf{H}_s &= \mathbf{I}_s \boldsymbol{\omega}_s \end{aligned} \tag{1}$$

where $\mathbf{I}_s$ is the spacecraft inertia tensor and m_s is the spacecraft mass. From conservation of momentum, the time derivative of the momentum is equal to the forces and torques applied to the spacecraft:

$$\begin{aligned} \dot{\mathbf{p}}_s &= \sum \mathbf{f}^{ext} \\ \dot{\mathbf{H}}_s &= \sum \boldsymbol{\tau}^{ext} \end{aligned} \tag{2}$$

Referring to Figure 4, where $\mathbf{f}_0^{(j)}$ are the forces and $\boldsymbol{\tau}_0^{(j)}$ are the torques measured by the sensors for the jth manipulator, the dynamics of the spacecraft can be written as a function of the forces and torques and the measured forces and torques applied by the manipulators:

$$\begin{aligned} m_\mathrm{s}\dot{\mathbf{v}}_\mathrm{s} &= \mathbf{f}_\mathrm{s} - \sum_{j=1}^{p} \mathbf{f}_0^{(j)} \\ \mathbf{I}_\mathrm{s}\dot{\boldsymbol{\omega}}_\mathrm{s} + \boldsymbol{\omega}_\mathrm{s} \times \left(\mathbf{I}_\mathrm{s}\boldsymbol{\omega}_\mathrm{s}\right) &= \boldsymbol{\tau}_\mathrm{s} - \sum_{j=1}^{p}\left(\boldsymbol{\tau}_0^{(j)} + \mathbf{r}_{s,0}^{(j)} \times \mathbf{f}_0^{(j)}\right) \end{aligned} \tag{3}$$

where $\mathbf{r}_{s,0}^{(j)}$ is a vector from the center of mass of the spacecraft to the jth sensor. To find the forces and torques applied to the spacecraft, the terms are rearranged to yield:

$$\begin{aligned} \mathbf{f}_\mathrm{s} &= \sum_{j=1}^{p} \mathbf{f}_0^{(j)} + m_\mathrm{s}\dot{\mathbf{v}}_\mathrm{s} \\ \boldsymbol{\tau}_\mathrm{s} &= \sum_{j=1}^{p}\left(\boldsymbol{\tau}_0^{(j)} + \mathbf{r}_{s,0}^{(j)} \times \mathbf{f}_0^{(j)}\right) + \mathbf{I}_\mathrm{s}\dot{\boldsymbol{\omega}}_\mathrm{s} + \boldsymbol{\omega}_\mathrm{s} \times \left(\mathbf{I}_\mathrm{s}\boldsymbol{\omega}_\mathrm{s}\right) \end{aligned} \tag{4}$$

This can be rewritten to yield vectors of spacecraft forces and torques:

$$\begin{aligned} \mathbf{f}_\mathrm{s} &= \sum_{j=1}^{p} \mathbf{A}_{fs}^{(j)}(\boldsymbol{\theta}) \begin{bmatrix} \mathbf{f}_0^{(j)} \\ \boldsymbol{\tau}_0^{(j)} \end{bmatrix} - f(\boldsymbol{\theta}, \boldsymbol{\omega}_\mathrm{s}, \dot{\boldsymbol{\omega}}_\mathrm{s}, \dot{\mathbf{v}}_\mathrm{s}) \\ \boldsymbol{\tau}_\mathrm{s} &= \sum_{j=1}^{p} \mathbf{A}_{\tau s}^{(j)}(\boldsymbol{\theta}) \begin{bmatrix} \mathbf{f}_0^{(j)} \\ \boldsymbol{\tau}_0^{(j)} \end{bmatrix} - f(\boldsymbol{\theta}, \boldsymbol{\omega}_\mathrm{s}, \dot{\boldsymbol{\omega}}_\mathrm{s}, \dot{\mathbf{v}}_\mathrm{s}) \end{aligned} \tag{5}$$

with the $\mathbf{A}$ matrices given by:

$$\begin{aligned} \mathbf{A}_{fs}^{(j)}(\boldsymbol{\theta}) &= \begin{bmatrix} \mathbf{1} & \mathbf{0} \end{bmatrix} \\ \mathbf{A}_{\tau s}^{(j)}(\boldsymbol{\theta}) &= \begin{bmatrix} \mathbf{S}_{s,0}^{(j)} & \mathbf{1} \end{bmatrix} \end{aligned} \tag{6}$$

where $\mathbf{1}$ is the identity matrix, $\mathbf{0}$ is the zero matrix. The skew symmetric matrix $\mathbf{S}_{a,b}$ denotes cross product, $\mathbf{S}_{a,b}\,\mathbf{f} \equiv \mathbf{r}_{a,b} \times \mathbf{f}$ where $\mathbf{r}_{a,b}$ is a vector from point a to point b and $\mathbf{S}_{s,0}^{(j)}$ is therefore the cross product matrix from the origin of the spacecraft to the origin of the force/torque sensor for the jth manipulator.

In addition to estimating the forces and torques applied to the spacecraft, the joint torques can be estimated. To calculate the applied joint torques the dynamics of the links in the manipulator are included in the formulation. Since the links all belong to the same manipulator the superscript j has been dropped to simplify the notation. Writing the relationship to find the forces $\mathbf{f}_{\mathrm{c}i}$ and torques $\boldsymbol{\tau}_{\mathrm{c}i}$ at the center of mass of ith link in the system yields:

$$\begin{aligned} \mathbf{f}_{\mathrm{c}i} &= m_i \dot{\mathbf{v}}_{\mathrm{c}i} = \sum \mathbf{f}_{\mathrm{c}i}^{ext} \\ \boldsymbol{\tau}_{\mathrm{c}i} &= \mathbf{I}_i \dot{\boldsymbol{\omega}}_i + \boldsymbol{\omega}_i \times \left(\mathbf{I}_i \boldsymbol{\omega}_i\right) = \sum \boldsymbol{\tau}_{\mathrm{c}i}^{ext} \end{aligned} \tag{7}$$

The forces at the ith joint $\mathbf{f}_i$ can be calculated (recalling that $\mathbf{f}_0$ is measured by the manipulator force/torque sensor):

$$\mathbf{f}_i = \mathbf{f}_0 - \sum_{k=0}^{i-1} \mathbf{f}_{\mathrm{c}k} \tag{8}$$

Similarly, the torques at the ith joint $\boldsymbol{\tau}_i$ can be calculated:

$$\boldsymbol{\tau}_i = \boldsymbol{\tau}_0 - \mathbf{r}_{0,i} \times \mathbf{f}_0 - \sum_{k=0}^{i-1}\left(\boldsymbol{\tau}_{\mathrm{c}k} + \mathbf{r}_{\mathrm{c}k,i} \times \mathbf{f}_{\mathrm{c}k}\right) \tag{9}$$

where $\mathbf{r}_{0,i}$ is a vector from the origin of the force/torque sensor (the 0th joint) to the origin of the *i*th joint, and $\mathbf{r}_{ck,i}$ is a vector from the center of mass of the *k*th link to the origin of the *i*th joint. This torque is projected onto the axis of the joint to calculate the applied joint torque:

$$\tau_{ai} = \mathbf{z}_{i-1}^{\mathrm{T}} \boldsymbol{\tau}_i \tag{10}$$

where $\mathbf{z}_{i-1}$ is a unit vector aligned with the axis of the joint's rotation. Equations (7)-(10) are combined and the superscript notation indicating manipulator number is again shown to yield a vector of joint torques of the form:

$$\boldsymbol{\tau}_a^{(j)} = \mathbf{A}_{\tau a}^{(j)}(\mathbf{q}^{(j)}, \boldsymbol{\theta}) \begin{bmatrix} \mathbf{f}_0^{(j)} \\ \boldsymbol{\tau}_0^{(j)} \end{bmatrix} - f(\boldsymbol{\theta}, \mathbf{q}^{(j)}, \dot{\mathbf{q}}^{(j)}, \ddot{\mathbf{q}}^{(j)}, \boldsymbol{\omega}_s, \dot{\boldsymbol{\omega}}_s, \dot{\mathbf{v}}_s) \tag{11}$$

where each row *i* of $\mathbf{A}_{\tau a}^{(j)}$ is given by:

$$\mathbf{A}_{\tau a\ i}^{(j)} = \left(\mathbf{z}_{i-1}^{(j)}\right)^{\mathrm{T}} \mathbf{S}_{i-1,0}^{(j)} + \left(\mathbf{z}_{i-1}^{(j)}\right)^{\mathrm{T}} \tag{12}$$

and $\mathbf{S}_{i-1,0}^{(j)}$ is the cross product matrix from the origin of the *i*-1th joint to the origin of the force/torque sensor for the *j*th manipulator. The $\mathbf{A}$ matrices are relatively simple to derive and require minimal computation for generating the actuator estimates. The forces and torques can often be estimated by neglecting the higher order terms, when large external forces are absent and joint accelerations and velocities are relatively low such as a free-flying robot performing precision motions. Calculations have shown that these terms are small compared to the magnitude of the applied actuation effort in which case Equation (11) reduces to:

$$\hat{\boldsymbol{\tau}}_a^{(j)} = \mathbf{A}_{\tau a}^{(j)}(\mathbf{q}^{(j)}, \boldsymbol{\theta}) \begin{bmatrix} \mathbf{f}_0^{(j)} \\ \boldsymbol{\tau}_0^{(j)} \end{bmatrix} \tag{13}$$

Similarly the estimates for the net thruster forces and torques become:

$$\begin{aligned} \hat{\mathbf{f}}_s &= \sum_{j=1}^{p} \mathbf{A}_{fs}^{(j)}(\boldsymbol{\theta}) \begin{bmatrix} \mathbf{f}_0^{(j)} \\ \boldsymbol{\tau}_0^{(j)} \end{bmatrix} \\ \hat{\boldsymbol{\tau}}_s &= \sum_{j=1}^{p} \mathbf{A}_{\tau s}^{(j)}(\boldsymbol{\theta}) \begin{bmatrix} \mathbf{f}_0^{(j)} \\ \boldsymbol{\tau}_0^{(j)} \end{bmatrix} \end{aligned} \tag{14}$$

With the applied joint torques and the net thruster forces estimated it becomes possible to compensate for these errors in the actuation in a closed-loop controller for free-flying and free-floating space robots [13].

III. RESULTS

A. System Description

Figure 6 shows the system studied here. It is a space robot with two manipulators performing the pre-grasp portion of a satellite capture task. It is assumed that attitude control has been lost on the satellite due to improper orbital insertion, failure of components, or lack of fuel. When the robot gets close enough to the satellite, its manipulator tracks and reaches for a hardened grasping point on the satellite, such as the payload attachment ring. The objective of this part of the task is to track the grasp point (within a specified position and orientation error) on an uncontrolled spinning satellite long enough to allow a firm grasp to be made. It is assumed that the robot's end-point sensor can measure the relative position and orientation of the grasp point. It is assumed that inertial parameters of the robot are well known, but the characteristics of the joint friction are assumed to be unknown except that the friction is Coulomb in nature with magnitudes approaching twenty to fifty percent of the maximum torque. These values are typical for space robotic systems [16]. The thruster sizes needed for the satellite capture task are substantial compared to those used for satellite attitude control. The characteristics of the thruster errors are assumed to be unknown.

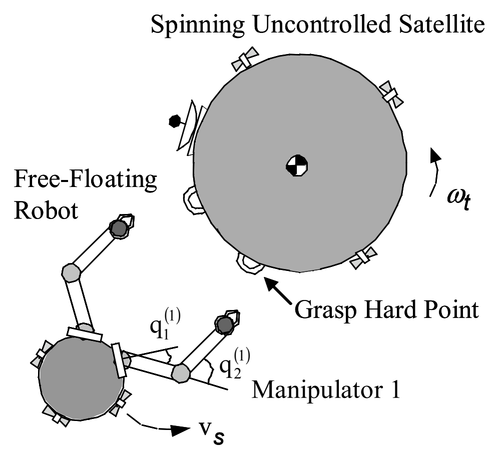

Figure 6. Flat spin satellite capture example

The parameters of the simulation are given in Table 1. The manipulators are symmetric, separated by a 90 degree angle and each has two links. The target satellite has a radius of 3 meters and is assumed to be spinning with an angular velocity $\boldsymbol{\omega}_t$ of three revolutions per minute.

TABLE I SPACE ROBOT PARAMETERS

	Length [m]	Mass [kg]	Inertia [kg m^2]
Spacecraft	4.2 (diameter)	2400	5808
Link 1	4	200	345
Link 2	3	100	106

B. Tracking Performance

The task was simulated in Matlab for a free-flying space robot, firing thrusters at the same time as the manipulator end-effectors are tracking the grasp points. The robot needs to avoid firing its thrusters in the direction of satellite [15]. The position of the end-effectors is controlled by a Jacobian transpose controller. The forces and torques are estimated but the actuation compensation loop is not closed in the simulation runs in order to permit the identification of the torques to be seen. In use it would be closed. Figure 7 shows the desired spacecraft trajectory and the desired end-effector trajectories for a representative case. Note that the two manipulator trajectories are different because they are reaching for different points on the rotating satellite.

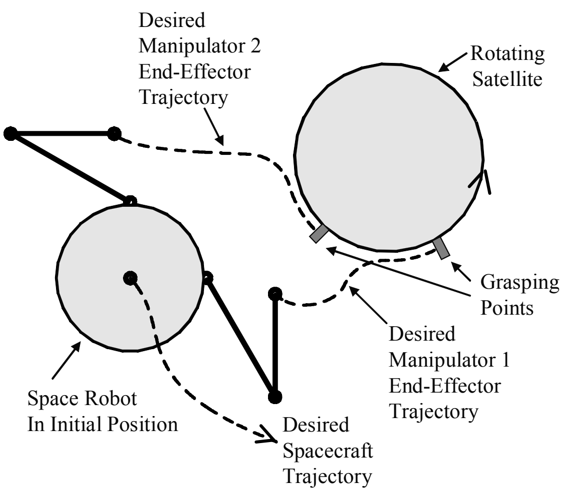

Figure 7. Desired spacecraft and manipulator end-effector trajectories

Figure 8 and Figure 9 show the end-effector position errors in the x and y directions for manipulators 1 and 2. The solid line shows the position error when there is no friction, and the dashed line shows the position error when there is Coulomb joint friction. Clearly the error is larger is the presence of uncompensated joint friction.

The effects of joint friction can also be seen in Figure 10 and Figure 11 which show the torques in both joints for manipulators 1 and 2. The thin solid line is the commanded torque, the solid line is the actual torque and the dashed line is the estimate of the torque. The commanded torque is generally larger than the actual torque due to the errors in the actuation. It can be seen that the method provides good agreement between the estimated value and the actual value especially for the first joint. Since the acceleration terms are neglected in the estimation algorithm for the results presented here, the method provides the best estimates for actuation closest to the sensor. In Figure 11 the method works well for the first joint, but the torques for the second joint show a limitation of the method. Since the joint virtually does not move the friction overwhelms the dynamic terms.

The spacecraft forces and moments are also estimated at the same time by the same sensor. The spacecraft forces in the x and y direction are shown in Figure 12. The thin line shows the commanded forces. The solid line shows the actual forces. The dashed line is the estimate value. It can be seen that the actual force values experienced by the spacecraft are substantially different than the commanded values. However, the method provides good agreement between the estimated actuation value and the actual value. The error between the estimate and the actual is less than five percent.

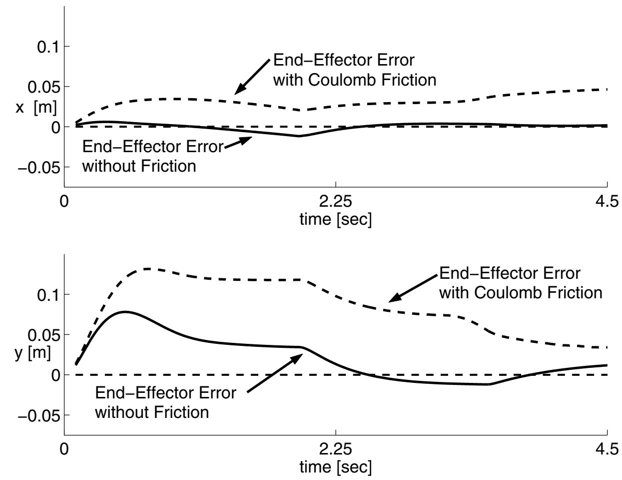

Figure 8. Manipulator 1 end-effector position error

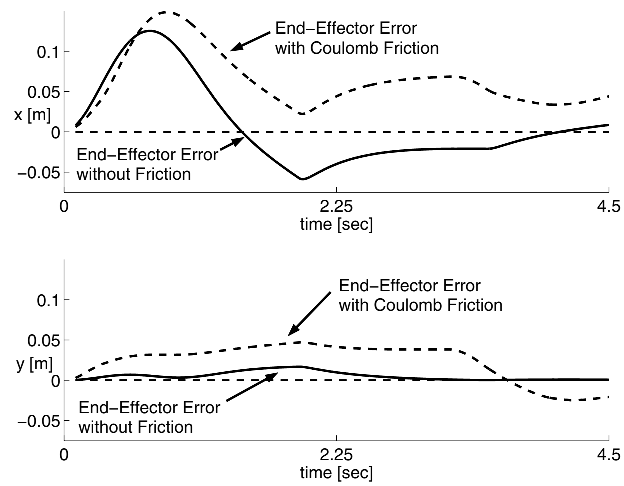

Figure 9. Manipulator 2 end-effector position error

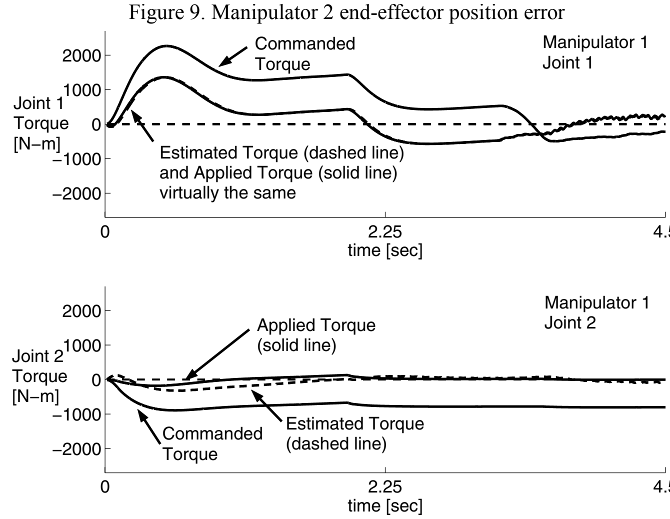

Figure 10. Manipulator 1 torques for the large satellite capture task

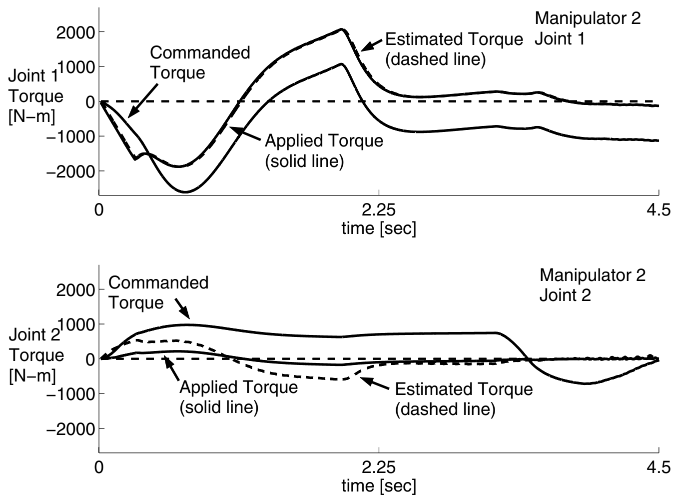

Figure 11. Manipulator 2 torques for the large satellite capture task

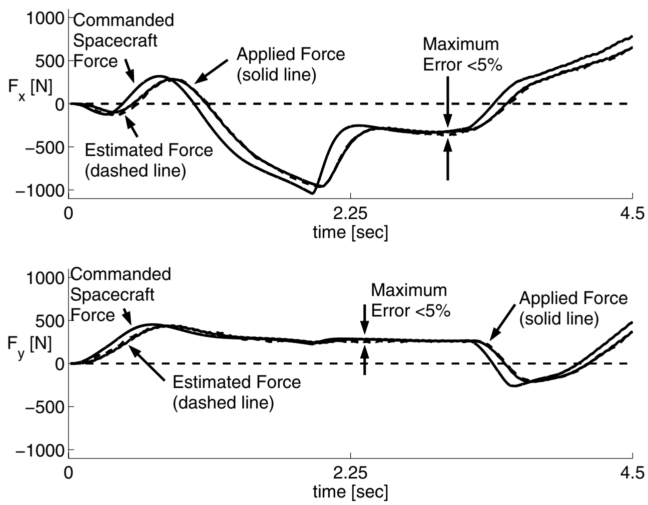

Figure 12. Continuous x and y commanded net thruster forces for the large satellite capture task

IV. CONCLUSIONS

In space robotic systems, due to practical considerations, the ability to predict actuator efforts can be degraded by such factors as friction, thermal, and other disturbances. Providing all the direct sensors to measure the actuator output so that the errors can be compensated can be impractical. However, dynamic models can be combined with limited sensing to provide estimates of these errors. This paper describes a method to use force/torque sensors with dynamic models of a space robot's manipulators to identify actuation forces and torques in robotic manipulators. These estimates can be used in an inner actuator control feedback loop. This controller can compensate for joint friction and spacecraft thruster inaccuracies and would take the form of a classical torque controller that requires individual joint torque sensors [11]. The cost, weight, and complexity of a single sensor is substantially less than that of multiple sensors required by direct measurements. Simulations demonstrate the effectiveness of this method.

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