A STUDY OF MINIMAL SENSOR TOPOLOGIES FOR SPACE ROBOTS

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Abstract Sensing in space robotic systems is expensive but necessary to compensate for imprecise actuation, disturbances, and modeling errors. It has been shown that force/torque sensors can identify actuation efforts including joint torques and reaction jet forces for multi-manipulator free-flying space robots and greatly improves system precision. This paper studies the minimum number of sensors which can identify these actuation efforts. The method uses force/torque sensors to isolate sections of the system, which are reduced to canonical elements. This allows the analysis of a small number of elements. The results of the analysis of the canonical elements are combined to determine the number of sensors needed for the original system. Configurations of one- and two-manipulator space robots are examined here and the minimal number of sensors shown.

1. Introduction

Autonomous robots will be needed for future space missions such as satellite capture and on orbit construction of large space structures including space telescopes and solar power stations (see Fig. 1) [Ueno 2003, Staritz 2001]. For these missions a space robot needs to perform precise motion and force control using its manipulators and reaction jets [Matsumoto 20002]. However, in space actuation can be imprecise and constrained by inherent nonlinearities. Sensing is necessary to compensate for torque disturbances due to joint friction, reaction jet variability and bias, thermal warping effects, and modeling errors [Breedveld 1997]. Sensing in space is limited and expensive because of hardware cost and system complexity. The objective of this work is to study the system topologies that minimize the number of sensors needed to measure joint torques and reaction jet forces for space robots.

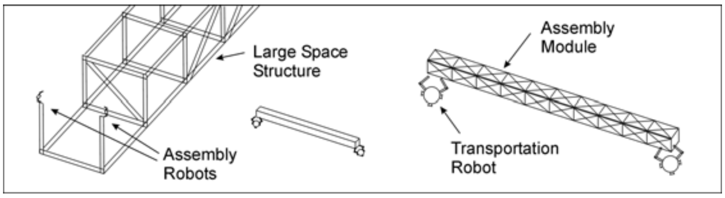


Figure 1. Construction of a large space structure by teams of robots

Sensor-based methods to compensate for actuation nonlinearities and errors have been shown to provide precise control. Friction has proven difficult to model but control methods have been developed that use joint torque sensors to compensate successfully for friction [Vischer 1995]. However, placing a sensor at every actuator increases weight, cost, and complexity, and reduces system reliability, motivating study of minimal sensing methods to measure actuation, such as a gyro-based method for detecting faults for thruster-controlled spacecraft [Wilson 2002].

To avoid internal joint-torque sensors a method called Base Sensor Control (BSC) was developed for fixed-based terrestrial manipulators [Morel 2000]. BSC uses measurements from a six-axis force/torque sensor to estimate joint torques for closed-loop control. This method has recently been extended for space robots and it has been shown that force/torque sensors mounted between the manipulators and spacecraft can determine both the joint torques and the reaction jet forces and moments [Boning 2006]. This paper uses the method to examine the best placement and the minimum number of force/torque sensors for a given space robot to simultaneously measure joint and spacecraft actuation.

This problem could be solved by exhaustive analysis. However, varying the number of manipulators p, the number of links n, reaction jets or not, payload or not, and considering force/torque sensors at the base of the manipulator or at the end-effector, the number of cases c that need to be considered grows rapidly ($c = 16\,\mathrm{p} \times \mathrm{n}$). Here, it is shown that most cases are topologically similar and the space of possible solutions can be reduced to a small number of similar cases called canonical elements. The dynamic analysis is needed only for these elements and the results can be applied to more general systems.

2. Analytical Development

The systems studied are free-flying space robots with multiple manipulators (see Fig. 2). It is assumed that the spacecraft and links are three-dimensional rigid bodies (for example, fuel slosh is not considered). It is also assumed that the actuator forces and moments and friction at each joint and reaction jet forces are unknown. Further, it is assumed that there are no additional external loads acting on the system such as gravity gradient effects. For this study, quantities measured are assumed to be known exactly and include accelerations. If the manipulator is holding a payload it is assumed that the end-effector makes a firm grasp.

The approach taken here is to divide the system at each six-axis force/torque sensor into subsystems. The subsystems are categorized by a small set of canonical elements. The dynamics of the canonical elements are analyzed using Newton's method to find intermediate forces and torques. Finally, the results are applied to the original system to find the minimum number of sensors required to calculate the actual net joint efforts (eliminating the effects of friction) and the actual thruster forces and reaction wheel moments.

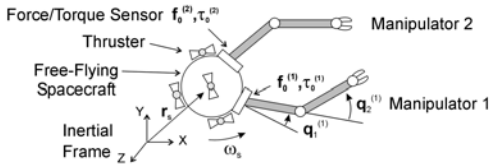


Figure 2. Space robot with sensors between spacecraft and manipulators

2.1 Categorizing by Canonical Element

All the subsystems created by isolating sections for the space robots at force/torque sensors can be reduced to the canonical elements in Fig. 3. The force/torque sensors provide the known interface forces and moments. The canonical element for a given subsystem is determined by reducing the subsystem following rules which are shown in Fig. 4. First the system is divided at the force/torque sensors and the sensors are replaced with equal and opposite known force/torques. Next, zero end loads at the end-effectors are replaced with known force/torques, since zero loads are known loads. Adding these zero loads allows more cases to be considered as one type. Then, reaction jets are replaced with unknown force/torques. Finally, branches are replaced with chains. If a known load is applied at the end of a chain, it is equivalent to applying a known load at the branching point. The same is true for an unknown load.

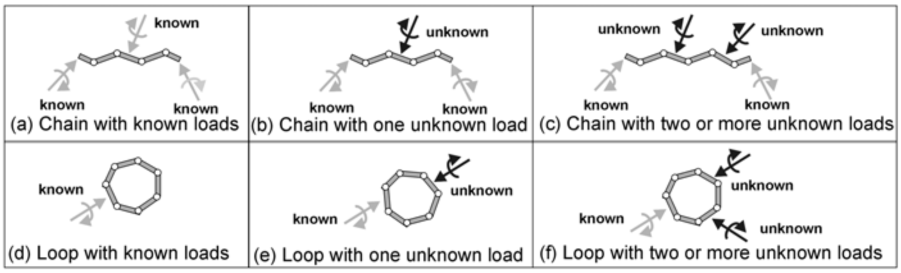


Figure 3. Canonical system elements

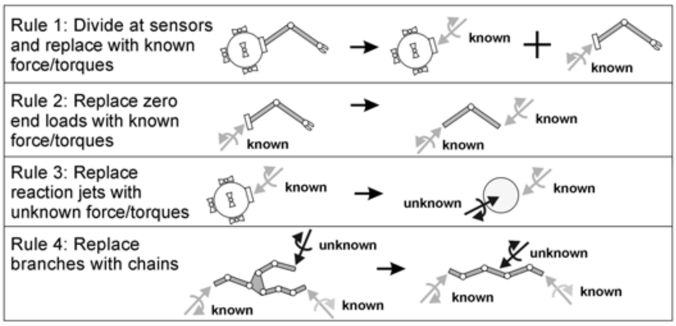


Figure 4. Reduction to canonical elements

An example of the application of these rules is given in Fig. 5 which shows how the unknown reaction jets on a spacecraft become the canonical element chain with one unknown. More examples are shown in Fig. 6. Fig. 6(a) (Case 1) is a free-floating (no thrusters) space robot with two manipulators and a single force/torque sensor. The sensor separates the system into two canonical elements, both chains with known loads. Fig. 6(b) (Case 2) shows a free-floating robot with a single sensor at the wrist, equivalent to a chain with known loads. The sensor measures very little, since there is no payload in this case. Fig. 6(c) (Case 3) shows a free-flying space robot with a single sensor between the spacecraft and both manipulators. Fig. 6(d) (Case 4) shows a system that contains a closed kinematic chain or loop.

Figure 5. Reduction of unknown reaction jets to chain with one unknown

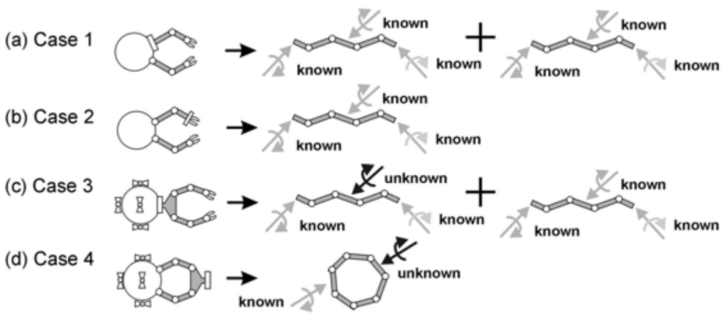


Figure 6. More reduction examples

2.2 Dynamic Analysis

The objective of this section is to determine if there is enough sensory information for a given subsystem topology to find the net actuator forces and moments on all joints and links in the subsystem. The friction at unactuated joints can also be measured. A representative space system is shown in Fig. 7(a). It is assumed that for this system the spacecraft linear acceleration $\ddot{\mathbf{r}}_s$, angular velocity $\boldsymbol{\omega}_s$ and acceleration $\dot{\boldsymbol{\omega}}_s$ can be measured or estimated. For each manipulator j, the forces $\mathbf{f}_0^{(j)}$ and torques $\boldsymbol{\tau}_0^{(j)}$ at each sensor are measured along with measurements or estimates of the joint angles $\mathbf{q}^{(j)}$, velocities $\dot{\mathbf{q}}^{(j)}$, and accelerations $\ddot{\mathbf{q}}^{(j)}$. Fig. 7(b) shows a typical link. Fig. 7(c) shows a link at a branch point.

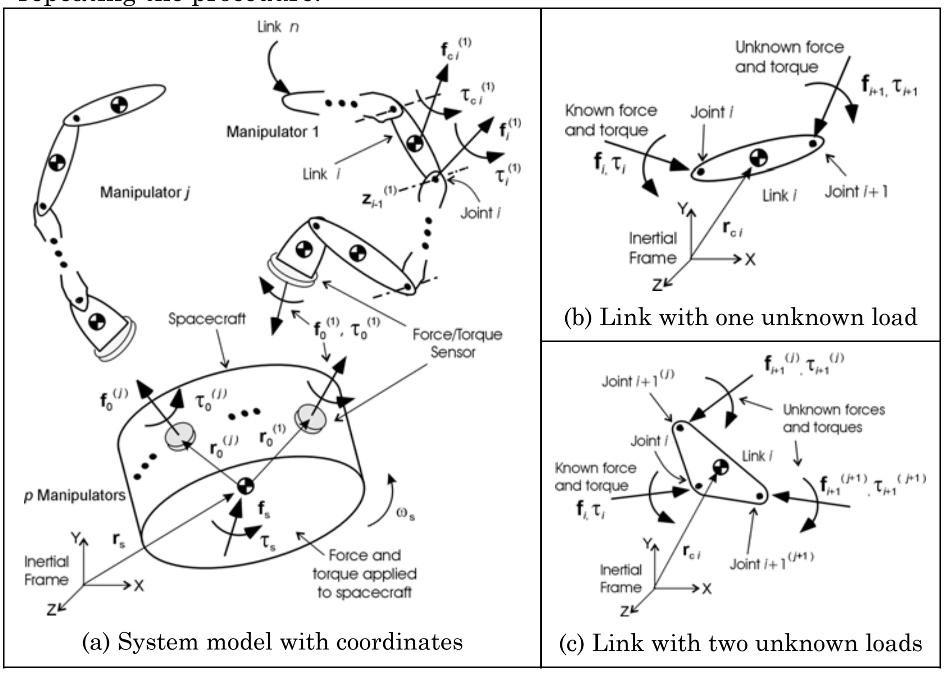
First it is noted that the positions, velocities, and acceleration of the links are known from system kinematics. To find the link's unknown actuator load, a link with only known forces and moments (given by a force/torque sensor) is located.Looking at the free body diagram in Fig. 7(b), from fundamental mechanics the unknown force $\mathbf{f}_{i+1}$ can be determined from the known force $\mathbf{f}_i$:

$$\mathbf{f}_{i+1} = \mathbf{f}_i - m_i \dot{\mathbf{v}}_{ci} \tag{1}$$

where m_i is the mass of the ith link and $\dot{\mathbf{v}}_{ci}$ is the acceleration at the ith center of mass. Similarly, the unknown torque $\boldsymbol{\tau}_{i+1}$ can be found from the known torque $\boldsymbol{\tau}_i$:

$$\boldsymbol{\tau}_{i+1} = -\mathbf{I}_i \dot{\boldsymbol{\omega}}_i - \boldsymbol{\omega}_i \times \left(\mathbf{I}_i \boldsymbol{\omega}_i\right) + \boldsymbol{\tau}_i + \mathbf{r}_{ci,i} \times \mathbf{f}_i - \mathbf{r}_{ci,i+1} \times \mathbf{f}_{i+1} \tag{2}$$

where $\mathbf{I}_i$ is the ith inertia tensor, $\boldsymbol{\omega}_i$ is the angular velocity ith link, and $\mathbf{r}_{ci,i}$ is a vector from the center of mass of the ith link to the ith joint. Force and torque calculations can be projected along the chain by repeating the procedure.



(a) System model with coordinates

(b) Link with one unknown load

(c) Link with two unknown loads

Figure 7. System models

When there are two unknown forces (such as in Fig. 7(c)) the forces and torques cannot be calculated directly. This situation can often be solved by starting at several points in the chain and propagating the known forces and moments to a common point. In other cases additional information (such as provided by an additional force/torque sensor) is needed to permit a solution. When all of the links in the system have been visited it is possible to determine if the given set of sensors is sufficient or if additional sensors are required.

2.3 Analysis of Canonical Elements

The above analysis can be applied case by case to the canonical elements in Fig. 3. First consider the chain with known loads (Fig. 3(a)). Starting with the link on the far left, it is possible to find the actuator torques on the first joint. Continuing with the links from left to right it is possible to find forces and torques on all joints in this system. Hence there are enough sensors to completely identify all actuation efforts for this case.

The canonical element chain with one unknown load also has enough sensors, but it is necessary to work inward from both ends of the chain simultaneously so that the single unknown load at the middle link can be determined. However, for any chain that has more than one unknown load (as in Fig. 3(c)) all actuator efforts cannot be determined without adding more sensors.

Loops can be resolved into two chains joined by two branching links. Loops are analysed by starting with a link that has only known applied loads and propagating the loads in both directions around the loop until the chain rejoins. It can be shown that there are not enough sensors to determine all actuation efforts for any of the three canonical elements with loops. However, inserting a sensor in a loop converts this problem into the case of the chain with known loads (Fig. 3(a)). To summarize, for all the canonical elements, only a chain with known loads (Fig. 3(a)) and a chain with one unknown load (Fig. 3(b)) have enough sensory information to determine all actuation efforts.

Using the analysis of the canonical elements, it is straightforward to apply the results to the original system to determine sensor placement. For any given robot configuration with multiple manipulators, links, branches, etc., it is possible to enumerate potential sensor placements, divide the system into subsystems at the sensors, classify each subsystem by its canonical element, eliminate the layouts where there is not enough sensory information, and find the minimal number and placement of sensors for the system.

3. System Topologies

Systems such as Fig. 2 were studied to determine the torques at each joint and the reaction jet forces. The parameters varied are number of manipulators (p=1, 2), number of links per manipulator (n=1, 2, many), reaction jets or not (free-flying or free-floating), and payload or not. The primary locations for sensor placement are the manipulator wrist and the manipulator base where it joins the spacecraft. For most cases it is not necessary to enumerate all the cases where the sensor is placed at any joint in between since they are often equivalent to the cases where there are sensors at the ends of manipulator.

3.1 Minimum Sensor Configurations

The sensor placement method presented above was applied to space robots with one and two manipulators. A collection of single manipulator cases with and without thrusters is summarized in Fig. 8. In all cases with a single manipulator there was adequate sensing. Fig. 9-12 summarize the results for space robots with two manipulators. The cases in Fig. 9 do not have (or are not firing their) thrusters. The first row shows possible sensor placements when one sensor is available. It can be placed between the manipulator and the spacecraft, at the end effector, between both manipulators and the spacecraft, or at the end of both end-effectors. The second row shows placement of two sensors, the third three sensors, and the last row the only configuration with four sensors. All cases reduce to the canonical chain elements with at most one unknown load, except for the two loop cases which are crossed out. The crossed out cases do not have enough sensing to determine all actuation efforts. From the remaining cases which do have enough information it is easy to determine the minimal sensors (one) and their potential locations. These cases are outlined in bold. Fig. 10 shows the same cases as Fig. 9, except that the space robots now have thrusters. The addition of the unknown thruster loads does not change the results. There are still only two cases which do not have enough sensing, and a single force torque sensor is enough to determine actuation.

When the robots have no thrusters but carry a payload (see Fig. 11) there are more closed loops. Most of the loops are broken by a sensor so actuation can be determined but there are only two places to put a single sensor to determine actuation. Once again addition of unknown thruster forces does not significantly change the results (see Fig. 12).

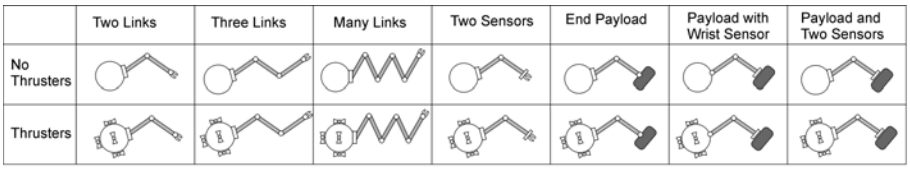


Figure 8. Space robot configurations for a single manipulator, no thrusters

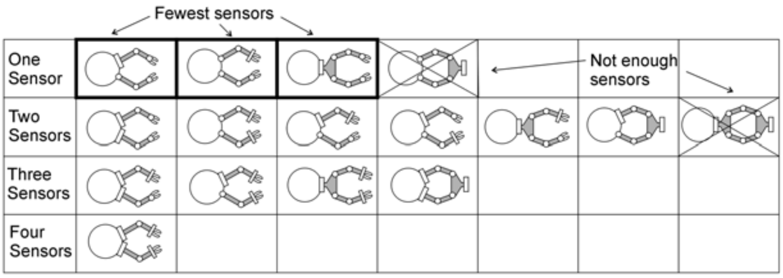


Figure 9. Space robot configurations for two manipulators and no thrusters

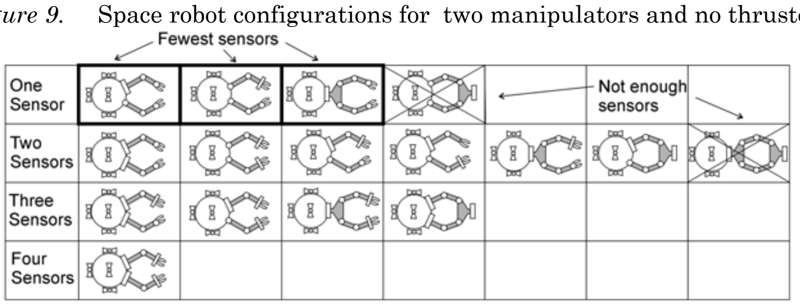


Figure 10. Space robot configurations for two manipulators and thrusters

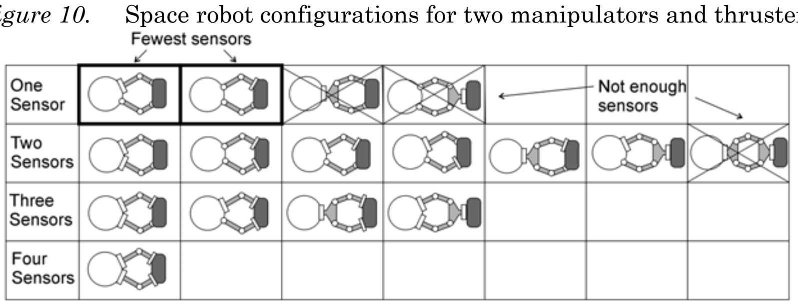


Figure 11. Space robot configurations for two manipulators and payload

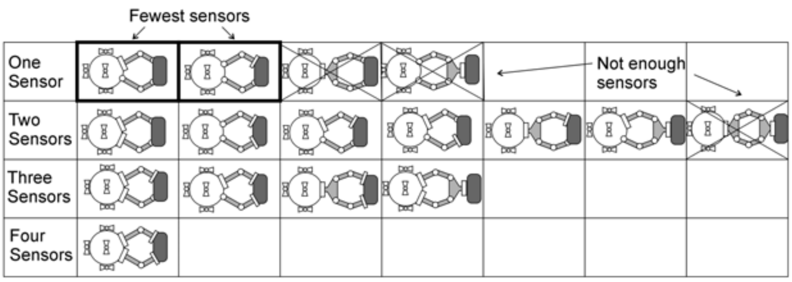


Figure 12. Space robot configurations for two manipulators, payload, thrusters

4. Illustrative Examples

To demonstrate the validity of the basic method it is applied to the system shown in Fig. 2. One sensor could be used; however two sensors are included here to provide sensor redundancy. With failure of one sensor this system could still maintain precise control. Simulations were run where a satellite capture task was simulated in Matlab for the free-flying space robot, firing its thrusters at the same time as the manipulator end-effectors were tracking the grasp points on the satellite [Boning 2006]. Fig. 13 shows joint torques for the first manipulator. The manipulators have very high friction, 50% of their maximum capable torque. The method's torque estimate and actual applied torque agree very well even though the manipulator is unable to follow the torque command due to very large friction. In this case, a torque loop is not closed to compensate for friction. With a valid torque estimate this could be accomplished but control algorithms are beyond the scope of this paper. Fig. 14 shows the results of the same sensor measurements used to estimate the applied spacecraft reaction jet forces. The actual reaction jet forces do not match the commanded due to nonlinear effects. However the method is still able to estimate these forces.

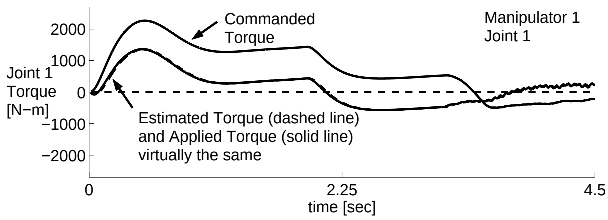


Figure 13. Manipulator 1 torques for the satellite capture task

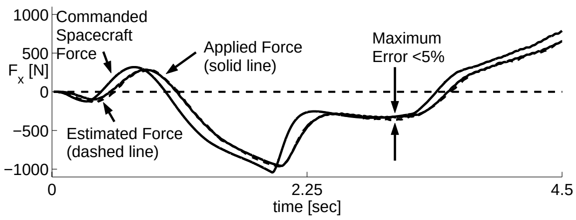


Figure 14. Continuous commanded net thruster forces, satellite capture task

5. Conclusions

In space robots, actuator effort sensing is required for precise control. However, such sensing adds complexity, weight and cost. Hence it is important to minimize the number of sensors used. Here it is shown that there are minimum sensor configurations that are able to determine system actuation precisely. It was found that a base force torque sensor for each manipulator can provide an estimate for friction in the joints and applied reaction jets. A wrist force torque sensor for each manipulator can also be used to estimate joint friction and applied reaction jet forces. However, additional sensors are needed for cases when there are closed kinematic loop configurations.

The methods shown here can be applied to other situations such as unknown contact forces at the end-effector, unknown payload mass, or payload gripped with pin joints (rather than rigidly grasped). Systems with reaction wheels can be considered with this methodology. The approach is useful to study redundant sensor configurations and accommodate sensor failure. Current studies are underway to consider the effects of higher order dynamics and sensor noise. An experimental validation of the method is expected to be completed shortly (in time for the ARK conference).

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