Inferred End-Point Control of Long Reach Manipulators

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Abstract

The problem of the end-point control of long reach manipulator systems, consisting of a dexterous manipulator carried by deployable structures, is addressed. Such systems can be important where a manipulator must perform a task in a difficult to reach location. Power line maintenance systems and the Space Station Freedom’s external maintenance robot are examples. Their supporting deployable structures can exhibit substantial vibrations, making the system very difficult to control. Here, a sensor based control algorithm, called Inferred End-Point Control is proposed. Simulation and experimental results show that it yields stable and accurate manipulator end-effector positioning control despite of vibrations of the system’s supporting structure using easily obtained strain measurements.

1: Introduction

This paper addresses the important problem of controlling the motion of a long reach manipulator system (LRMS) that consists of a relatively small, relatively fast manipulator mounted on a larger, long-reach, deployable, flexible structure. Such systems are important for applications where a manipulator must perform a task in a difficult to reach location. Examples of such applications include the repair of high voltage power transmission towers and lines, the inspection of underground storage tanks, the repair of bridges and space systems maintenance [1-3]. The proposed Special Purpose Dexterous Manipulator (SPDM) mounted on the Space Station Remote Manipulator System (SSRMS) and the Japanese Experiment Module Remote Manipulator System (JEMRMS) proposed by the Japan’s NASDA (Figure 1,) are examples of long reach manipulator space systems now being developed [4, 5].

Even though the deployable structure is nominally stationary in its extended configuration during the execution of the system’s tasks, the motion of the small manipulator and external disturbances, such as wind, can excite vibrations of the supporting structure. These low frequency, undesired, and uncontrolled vibrations can degrade the accuracy of the system, increase task times, reduce system safety, and in general make the overall control of the system more difficult. It has been estimated that as much as 10 hours cumulative time would be spent, over 15 Space Station Freedom-assembly Shuttle flights, waiting for the RMS tip motion to damp down to within ±1 inch amplitudes [6]. Given the astronomical costs of space shuttle flight time, reducing this time would result in very significant cost saving.

Figure 1: Maintenance of space systems

Methods have been proposed to reduce the amplitude of vibrations of manipulator systems with flexible members by planning “graceful” system motions [7-9]. A path-planning method has been developed, called the Coupling Map method, that finds paths for the small dexterous manipulator of a long reach system that minimize the vibrational energy transferred to its deployable structure during a task [7]. It has also been shown that it is possible to plan the velocities of the manipulator path to further reduce these residual vibrations [9]. While substantial research has been done to develop methods to control the vibrations of flexible manipulators using their active joints [6,10,11], relatively little work has been
done to study the control of vibrations of long reach manipulator systems with passive supporting structures. A method for these latter systems that uses the small manipulator controller to increase the supporting structure damping coefficient so that its vibrations damp-out quickly has been recently proposed [9]. However this method requires very low gains which reduce the controller's bandwidth, limiting its use to times when the manipulator is not performing a task. While these methods can reduce the amplitude of supporting structure's vibrations in some cases, uncontrolled system vibrations remain an important problem in the applications of long reach manipulator systems.

It has been shown that if the end-point positions and orientations of the flexible based manipulator are measured in an inertial coordinate frame, or with respect to some target, then it is possible to control this end-point in spite of uncontrolled supporting structure vibrations [12-15]. In the laboratory, the manipulator end-effector positions and orientations can be measured accurately for simple planar systems or for small manipulator motions using vision, laser and ultrasonic sensor systems [16, 17]. However, making 6 degree of freedom end-point position and orientation direct measurements for large manipulator motions in an unstructured field environment can, in practice, be very difficult. It has been demonstrated that the controller of a fast mini-manipulator mounted on an actively driven simple planar flexible structure can reduce the end-effector's sensitivity to the supporting structure deflection if the manipulator base's motion is directly measured in an inertial space [18]. It has also been shown that when the manipulator base's motions are due to the uncontrolled vibrations of a supporting terrestrial vehicle on its suspension, the direct end-point position and orientation measurements can be replaced by combining measurements of the translations and rotations of the vehicle, which can be measured using ultra-sonic sensors and inclinometers [19]. Clearly, the direct measurement of the six motions of the base of a manipulator in many field applications such as in space would be either not feasible or very difficult.

In this study, the problem of large end-point control of a fast manipulator mounted on a flexible, very lightly damped deployable structure with locked joints, without the need for direct end-point or manipulator base position and orientation measurements is addressed. The proposed control approach consists of an operational space control algorithm, called Inferred End-Point Control (IEC), that is shown to control the manipulator end-effector position and orientation in spite of the presence of supporting structure's vibrations and without the need for direct measurement of either the manipulator base motions or end-effector inertial position and orientation.

In this method, the inertial position and orientation of the base of the manipulator at its mounting point on the structure, are estimated using strain measurements made on the structure and a relatively simple static model of the structure. This base position information is used by the manipulator’s controller to infer the inertial end-point position and orientation and compensate for the vibrations of the structure. Simulation and experimental results obtained in this study suggest that the method is effective and can be practically implemented. Furthermore, the approach can be used in conjunction with supporting structure vibration reduction methods, such as the Coupling Map and velocity shaping to control the effects of any residual manipulator base vibrations.

2: Inferred end-point control

Inferred End-Point Control for long reach manipulator systems is based on Cartesian Based Controllers widely developed to control the end-effector positions of conventional fixed-base manipulators [20]. These controllers are designed so that virtual forces and moments are exerted at the manipulator’s end-effector [21]. Classically, the virtual forces and moments are simple functions of the cartesian space end-effector position and velocity errors, such as:

\[ F = K_p \dot{e} + K_d \ddot{e} = K_p (X_d - X) + K_d (\dot{X}_d - \dot{X}) \]  

where: \( F \) is the \( nx1 \) vector of virtual forces and moments at the manipulator end-effector, \( X \) and \( \dot{X} \) are the \( nx1 \) vectors of the inertial end-effector position and velocity \( X_d \) and \( \dot{X}_d \) are the \( nx1 \) vectors of the desired inertial end-effector position and velocity, \( e \) and \( \dot{e} \) are the \( nx1 \) vectors of the inertial end-effector position and velocity errors, \( K_p \) and \( K_d \) are \( nxn \) matrices of the position and velocity control gains and \( n \) is the number of degrees of freedom at the manipulator end-effector.

The end-effector virtual forces are transformed into manipulator joint torques:

\[ \tau_m = J_{rb}^T F \]  

where: \( \tau_m \) is the \( mx1 \) vector of the manipulator joint torques, \( J_{rb} \) is the \( mxm \) conventional Jacobian matrix of the fixed base manipulator.

The IEC algorithm for long reach manipulators uses forms of Equations (1) and (2). However, the effect of the 6 degree of freedom vibrational motion of the long reach manipulator supporting structure due to motions of the manipulator or to external disturbances, has to be taken into account.

Consider a general long reach, flexible based manipulator such as shown in Figure 2. A deployable, reconfigurable, lightly damped flexible structure is fixed at one end (point I in Figure 2) in inertial space and at the other end
nipulator in transforms reference system’s R, linear and angular velocities, manipulator base/structure interaction forces and moments, J is the nx(m+6) augmented Jacobian matrix of the long reach manipulator in ties into manipulator end-point velocities.

F is calculated using Equation (1). A modified form of

\[
\tau_m = J_T F = (J_m \, J_b) T F
\]

where: \( \tau \) is the \((6+m)\times1\) vector of the joint torques and manipulator base/structure interaction forces and moments, \( \tau_m \) is the \( m \times 1 \) vector of the manipulator joint torques, \( F \) is the \( 6 \times 1 \) vector of manipulator base/structure interaction forces and moments, \( J \) is the \( n \times (m+6) \) augmented Jacobian matrix of the long reach manipulator in \( R_p \), \( J_m \) is the \( n \times m \) Jacobian matrix of the long reach manipulator in \( R_b \), and \( J_b \) is the \( m \times 6 \) Jacobian matrix that transforms reference system’s \( R_b \) linear and angular velocities into manipulator end-point velocities.

This augmented form of Equation (2) is similar to the one developed for free-flying space robotic systems and manipulators mounted on mobile suspension vehicles [22, 23]. As with these systems, the augmented manipulator Jacobian has the form:

\[
J = (J_m \, J_b) = \begin{pmatrix} A(\psi) & 0 \\ 0 & A(\psi) \end{pmatrix} J_b \begin{pmatrix} 1 - A(\psi_B)B(\Theta)A(\psi)^T \\ 1 \end{pmatrix}
\]

where: \( J_b \) is the conventional \( n \times m \) Jacobian matrix of the fixed base manipulator in \( R_b \), \( \Theta \) is the \( m \times 1 \) vector of the manipulator joint angles, \( \psi \) is the \( 6 \times 1 \) vector of the manipulator base positions and orientation, \( A(\psi) \) is the \( 3 \times 3 \) rotation matrix of \( R_p \) with respect to \( R_b \) and \( B(\Theta) \) has the form

\[
\begin{pmatrix} 0 & -z_b^T & y_b^T \\ z_b^T & 0 & -x_b^T \\ -y_b^T & x_b^T & 0 \end{pmatrix}
\]

where \( (x_b, y_b, z_b) \) are the coordinates of \( E \) in \( R_p \).

The manipulator torques \( \tau_m \), given Equation (3), will result in a manipulator motion that will tend to drive \( X \) to \( X_d \). Since the interaction forces and moments \( F \) are not controllable, but determined by the characteristics of the deployment structure, they will act as disturbances to the system. They will, in general, result in some manipulator base motion and some end-effector errors that are compensated by the manipulator joint actions [23].

Since it is assumed that the direct measurement of the manipulator end-point position and velocity errors is not feasible for large end-effector motions in an unstructured field environment, the actual values of the manipulator’s end-effector position and velocity vectors, \( X \) and \( \dot{X} \), (see Figure 3) are calculated using estimates of the manipulator base position \( \psi \) and velocity \( \dot{\psi} \), which are obtained from strain measurements and a model of the structure and the measured manipulator joint angles \( \Theta \) and velocities \( \dot{\Theta} \). Comparing the values of \( X \) and \( \dot{X} \) to the desired \( X_d \) and \( \dot{X}_d \), provides the error signals for the operational space controller (Equation 1).

A block diagram of the Inferred End-Point Control algorithm is shown in Figure 3.

The calculation of \( \psi \) from strain measurements on the structure is key to the practical use of Inferred End-Point Control for long reach manipulator systems. Assuming an elastic linear supporting structure, a linear relationship exists between \( \psi \) and the strains developed at any location on the structure [24]:

\[
\psi(t) = \psi_0 + A \varepsilon(t)
\]

where: \( \psi_0 \) is the value of \( \psi \) due to the nominal geometry of the structure (the flexible structure is at rest - zero strain values), \( A \) is a \( 6 \times 6 \) scaling matrix and \( \varepsilon \) is the \( 6 \times 1 \) strain vector measured at any location on the structure. The vector \( \varepsilon \) is given by: \( \varepsilon = (\varepsilon_x, \varepsilon_y, \varepsilon_\theta, \varepsilon_{xy}, \varepsilon_z, \varepsilon_{yz})^T \).

![Figure 2: Schematic of a general LRMS](image-url)
For a very simple structure an analytical calculation of matrix $A$ is possible. For a more realistic engineering structure an experimental calibration procedure or a numerical method such as Finite Element analysis can be used [25, 26]. Research has been performed to find methods that identify the locations on the structure that will yield the best values of the strains to estimate $\Psi$ [26, 27]. The manipulator base velocity $\dot{\Psi}$ is numerically calculated in real-time from the values of $\Psi$.

![Figure 3: Inferred end-point control](image)

3: Algorithm evaluation

3.1: The MIT planar LRMS

A planar experimental flexible base manipulator system, called Shaky I, has been built to test path-planning and control methods for long reach flexible base manipulator systems [7]. Shaky I was used in this study to test Inferred End-Point Control. This system consists of a two link, two degree of freedom, planar manipulator mounted on a flexible structure (see Figure 4). Its simple planar design minimizes the effects of gravity to enable it to study algorithms for space applications.

The manipulator links are hollow aluminum bars 24 cm in length. Its joints are actuated by permanent magnet DC motors. Joint 1 has a transmission geared motor (Escap motor; torque constant equal to 0.020, gear ratio equal to 33:1), while Joint 2 has a direct drive motor (Mabuchi motor; torque constant equal to 0.023). Both motors have Hewlett-Packard optical encoders.

The system’s flexible supporting structure consists of two 1/16” (0.159 cm) aluminum side plates that are 44.6 cm in length with hinged cross members. The cantilever nature of the beam-like structure is designed to provide low stiffness characteristics for bending in the horizontal plane and high stiffness characteristics for vertical bending and for all torsional directions. This results in essentially a one degree of freedom base motion with a range of $\pm 15$ cm, a natural frequency of approximately 0.8 Hz, and a stiffness of 16 N/m in the horizontal plane.

It can be shown from elementary mechanics that because the base structure is essentially a one degree of freedom system, only the bending strain $\varepsilon_y$ at the attachment point of the structure to the ground needs to be measured to predict the motions of the end of the beam [28]. At this point, the flexible structure’s bending strains are the largest, and the resolution of the measure of the deflection of the beam is greatest. This experimental set-up is controlled by a 32-bit Motorola 68030 microprocessor single board computer running at 20 MHz. VxWorks is used as a real-time operating system.

![Figure 4: The MIT planar LRMS](image)

A linearized model of system’s dynamics was used to select the system’s IEC gains $K_p$ and $K_d$ in Equation (1). Applying classical control design methods the following gain matrices $K_p$ and $K_d$ were selected:

\[
K_p = \begin{bmatrix} 20 & 0 \\ 0 & 20 \end{bmatrix}, \quad K_d = \begin{bmatrix} 4 \\ 0 \end{bmatrix}
\]

These gave linear closed loop poles at $-1$, $-10$, $-3+8i$, giving an approximate dominant response of a first order system. The system’s performance including the non-linear dynamic characteristics of the system, was studied, with these controller gains, using a computer software package called RiBS (Rigid Body Simulator) [29]. It was found that for any configuration and path permitted by the hardware, the system had a stable and accurate response [30]. The system kinematics and the detailed description of the inferred endpoint controller analysis and design for this system are presented in [30].

3.2: System experimental performance

The experimental results confirmed the effectiveness of the IEC approach shown in the simulation studies.

The basic character of the control can be seen in disturbance rejection tests such as shown in Figure 5. Here, the system’s end-effector is moved to a specified cartesian space position. The base is then manually moved back and forth in the $Y_b$ direction while the manipulator is...
commanded to keep its end-point at its fixed cartesian position. Figure 5b shows the end-point position about its commanded y cartesian position value.

The maximum deviation from its desired end-point position is 0.3 cm while the base motion (Figure 5a) is more than an order of magnitude larger. This is a good result considering the controller is only using a single strain measurement and a very simple model to estimate the base $Y_b$ displacement. With classical joint control the end-effector error is approximately equal to the base motion of $\pm 4$ cm.

Figure 5: Disturbance rejection test

Figure 6 shows the results for a tracking test that is more representative of a realistic application. Here, the manipulator is commanded to track a cartesian space spline trajectory to arrive at a fixed task position. In spite of substantial base motions (Figure 6c) caused by the dynamic interactions between the manipulator and its supporting structure, the manipulator follows its commanded trajectory very closely (Figure 6a and 6b).

Figure 6: Trajectory tracking test

4: Conclusions

This research addresses the important problem of the end-point control of long reach manipulator systems mounted on highly flexible supporting structures. A sensor based, Inferred End-Point Control algorithm has been proposed and studied. The method uses simple strain sensors mounted on the structure to infer the manipulator end-point location in inertial reference system. Simulations and experiments on a simple laboratory system suggest that this control approach can yield stable and accurate manipulator end-effector positioning control despite of vibrations of its supporting structure. This technique is applicable to the control of large motions in an unstructured passive environment. It does not require special targets, lights or knowledge of the environment. In our current research we are investigating the combination of the IEC algorithm with graceful motion planning such as the Coupling Map. In addition, under a NASA funded INSTEP (In-Space Technology Experimental Program) program we are working with Martin Marietta, University of Puerto Rico and NASA Langley Research Center, to design an experimental system that will test in space (in a future space shuttle mission) the IEC method along with other control and planning methods for long reach space manipulators.
5: Acknowledgments

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6: References


