Proceedings *of the Ninth World Congress on the Theory of Machines and Mechanisms*, September 1-3, 1995, Milan, Italy.

End-point control of long reach manipulator systems

Mavroidis, C., Dubowsky, S. and Raju, V.
Department of Mechanical Engineering
Massachusetts Institute of Technology, Cambridge, MA 02139

Abstract: *Long reach manipulator systems (LRMS) are often used to perform tasks in difficult to reach locations. They consist of a dexterous manipulator carried by a deployable structure. Their supporting structure can exhibit substantial vibrations, making very difficult to control the system. Here, a control algorithm, called Inferred End-Point Control (IEC) is proposed. This algorithm is using the manipulator joint motion to compensate for the structure's vibration. Easily obtained strain measurements on the structure are used to estimate its motion. Experimental results obtained with two laboratory test beds are presented. They show that IEC yields stable and accurate manipulator end-effector positioning control in spite of vibrations of the system's supporting structure.*

Keywords: Long reach manipulators, End-point control, Vibrations, Manipulator Control, Elastic Manipulators

Introduction

In many field environments such as space, nuclear facilities or civil infrastructure sites, there is a need for remotely operated servicing tasks[1]. Examples of such operations are the repair of high voltage power transmission towers and lines, the inspection of underground storage tanks (Figure 1), the repair of bridges (Figure 2) and space systems maintenance [2-4]. Due to the problem of difficult accessibility and hazards, machines are needed to carry sensors, measurement systems, or small dexterous manipulators close to the task locations. While climbers, helicopters etc., are possible solutions to some of these problems, they can be very expensive and have low reliability. A promising class of systems for these applications are long reach manipulator systems (LRMS).

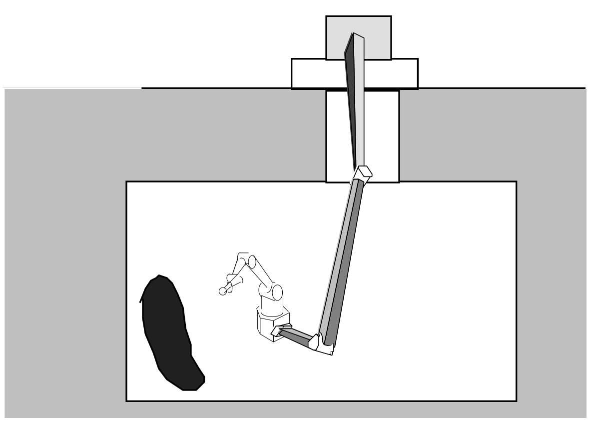


Figure 1: Inspection of underground tanks

A LRMS consists of a large, long reach deployable structure that carries a relatively small dexterous manipulator. The long reach structure would bring the small manipulator close to the task location and then lock its joints. While having significant potential, the development of LRMS require the solution of some fundamental control problems that can seriously limit their performance. A key problem is that external disturbances such as wind, and the motion of the manipulator itself can excite low frequency, lightly damped vibrations of the system's deployable structure. These vibrations would make the system difficult to control, corrupt the measurements and endanger the system with impacts on the site.

Relatively little work has been done to develop control and planning algorithms to deal with these problems. Some research has been done to reduce the effects of the supporting structure vibrations on the performance of long reach space manipulators [5]. A path-planning method has been developed, called the Coupling Map method, that finds paths for the small dexterous manipulator that minimize the vibrational energy transferred to its deployable structure during a space task[6]. Bracing methods have been suggested to increase system stiffness in some general applications of long reach systems [7]. Control methods have been proposed and are distinguished in two classes: damping control and end-point control. Methods of the first class aim to damp out the deployable structure's vibrations using the small manipulator controller [8-11]. While these methods can reduce the amplitude of supporting structure's vibrations, in many cases they require for some time, the manipulator to operate in non-optimal conditions, such as low-gain joint PID control [10], or follow strange manipulator joint trajectories, so that the vibrations damp out quickly.

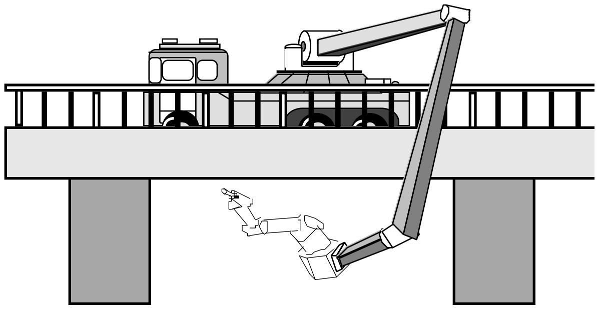


Figure 2: Inspection of bridges

In end-point control, the position and orientation in inertial space of the end-effector of the small manipulator, is controlled in spite of the supporting structure vibrations. The end-effector position feedback comes by either direct measurements of the position of the manipulator end-effector or by direct measurements of the position of the mounting point of the manipulator on its structure and then using the system kinematics to deduce the end-effector position. In both cases vision, laser or ultrasonic sensors have been used for the position measurements[12-17]. Clearly, the direct measurement of the six motions (three translations and three rotations) of the base of a manipulator or of its end-effector with these sensors, in many field applications such as in space, would be either not feasible or very difficult.

In this paper, the inertial position andµ 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.

Inferred End-point Control of LRMS

Consider a general long reach, flexible based manipulator such as shown in Figure 3. The position (three translations noted as x_b, y_b, z_b) and orientation (three rotations noted as three euler angles φ_x, φ_y, φ_z) of the reference system R_b defined at a point on the deployable structure corresponding at the manipulator mounting point, with respect to the inertial reference system R_i, is represented by a 6x1 vector called $\Psi=(x_b, y_b, z_b, \varphi_x, \varphi_y, \varphi_z)^T$. The inertial position and orientation of the manipulator end-effector reference system R_e with respect to R_i is defined by the nx1 vector X. For a general spatial manipulator n equals 6 and X is composed of the three components of the position vector of E with respect to R_i, (x_e, y_e, z_e), and three rotations (such as the euler angles θ_x, θ_y, θ_z) that describe the orientation of frame R_e with respect to R_i.

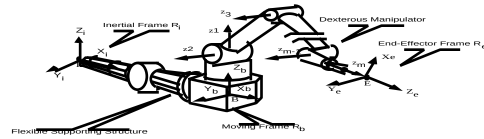


Figure 3: Schematic of a general LRMS

In Inferred End-point Control, as in classical fixed base impedance control, virtual forces, F, are exerted at the manipulator end-effector. Here these forces are function of the end-effector position and orientation:

$$F = K_p e + K_d \dot{e} = K_p(X_d - X) + K_d(\dot{X}_d - \dot{X}) \tag{1}$$

where X_d is the desired inertial end-effector position, e is the inertial end-effector position error and K_p and K_d are the position and velocity control gain matrices.

Using the transpose of the system Jacobian matrix, J, virtual forces, F, are transformed into manipulator joint torques, τ_m. The interaction forces, F_I, between the manipulator and its base appear in the formulation. However these can not be controlled and they act as disturbances to the system:

$$\begin{pmatrix} \tau_m \\ F_I \end{pmatrix} = J^T F = \left(J_m \ J_b\right)^T F \tag{2}$$

For long reach manipulators, the Jacobian matrix J has an augmented form composed of two submatrices: J_m which is the Jacobian matrix of the fixed base manipulator and J_b which is the matrix that transforms reference system's R_b linear and angular velocities into manipulator end-point velocities.

The manipulator torques, τ_m, will result in a manipulator motion that will tend to drive X to X_d. The manipulator's actual end-effector position vector X is calculated using estimates of the manipulator base position Ψ. The calculation of Ψ is done from strain measurements on the structure. Assuming an elastic linear supporting structure, a linear relationship exists between Ψ and the strains $\varepsilon=(\varepsilon_x \ \varepsilon_y \ \varepsilon_z \ \varepsilon_{xy} \ \varepsilon_{xz} \ \varepsilon_{yz})^T$ developed at any location on the structure:

$$\Psi(t) \quad \Psi_0 + A\varepsilon(t) \tag{3}$$

where: Ψ_0 is the value of Ψ due to the nominal geometry of the structure and A is a scaling matrix

A block diagram of the Inferred End-Point Control algorithm is shown in Figure 4.

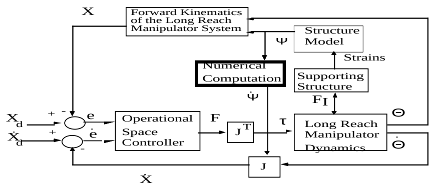


Figure 4: IEC for LRMS

Algorithm evaluation

The Inferred End-point Control has been demonstrated with simulations and experiments. In this paper we present experimental results obtained on a planar two degree of freedom manipulator mounted on a flexible base and on a three-dimensional long reach manipulator test-bed that has been designed and fabricated in our laboratory.

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 [6]. 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 5.) 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 ±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 ε_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. 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.

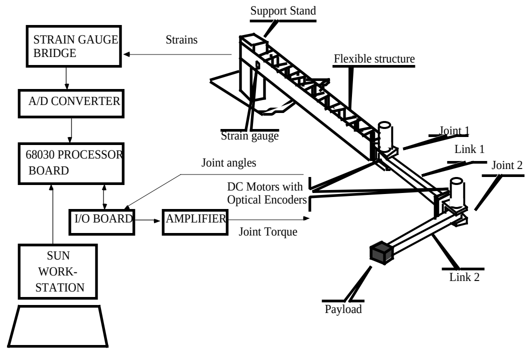


Figure 5: The MIT planar LRMS

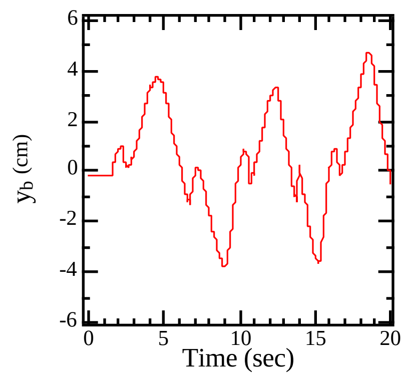


Figure 6: Base motion of Shaky I in a disturbance rejection test

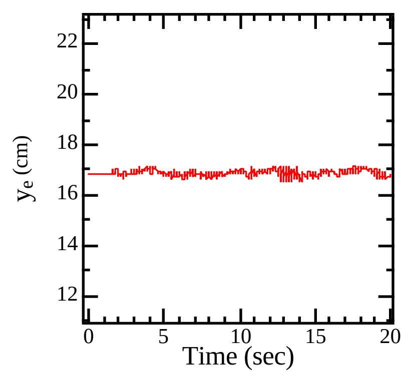


Figure 7: Shaky I end-point motion for disturbance rejection test

The basic character of the control can be seen in disturbance rejection tests such as shown in Figures 6 and 7. 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 7 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 6) 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 ±4cm.

A complete description of the results obtained with Shaky I can be found in [18].

The MIT spatial LRMS: To study the behavior of LRMS and test path-planning and control algorithms using more realistic systems, a three dimensional experiment called Shaky II, has recently been built. Shaky II consists of a 5 foot vertical flexible member that supports a PUMA 250 (see Figure 8.) The supporting structure is a sculptured 3" thin wall diameter non-metallic (PolyVinyl Chloride) tube.

The supporting tube has a series of diamond shaped holes at its lower end. The structure has been modeled using finite elements[19]. Like Shaky I, Shaky II vibrations are lightly damped. The flexible structure has a range of motion of ±8 cm with a stiffness of 660 N/m and a natural frequency of approximately 0.9 Hz in each direction of the horizontal plane.

Strain gauges are used to estimate the dominant motion of the flexible structure, see equation (3). The strain gauge locations are chosen using two criteria: (i) maximum strain location and (ii) minimum condition number for matrix A of equation (3) (i.e. matrix A should be well conditioned). Using these criteria, a search algorithm and the finite element model of the structure, the best strain gauge location was found to be between the third and fourth level of holes (see also Figure 8.)

Experimental results of the IEC with Shaky II have been obtained. These results have shown that for any configuration and path permitted by the hardware, the system under IEC had a stable and accurate response. Figures 9 and 10 show the results for a tracking test. 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 (Figures 9a and b) caused by the dynamic interactions between the manipulator and its supporting structure, the manipulator follows its commanded trajectory very closely (Figures 10a and 10b.)

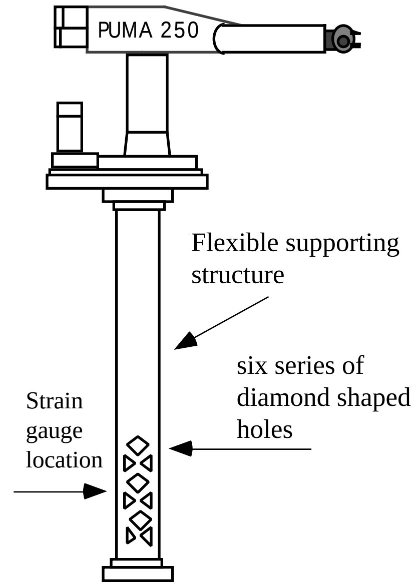
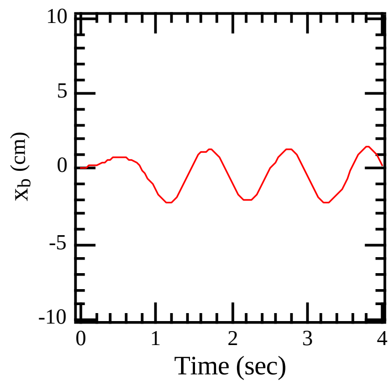
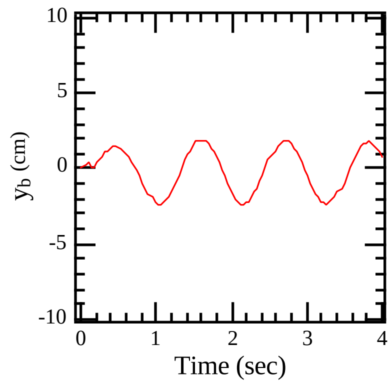


Figure 8: The MIT spatial LRMS



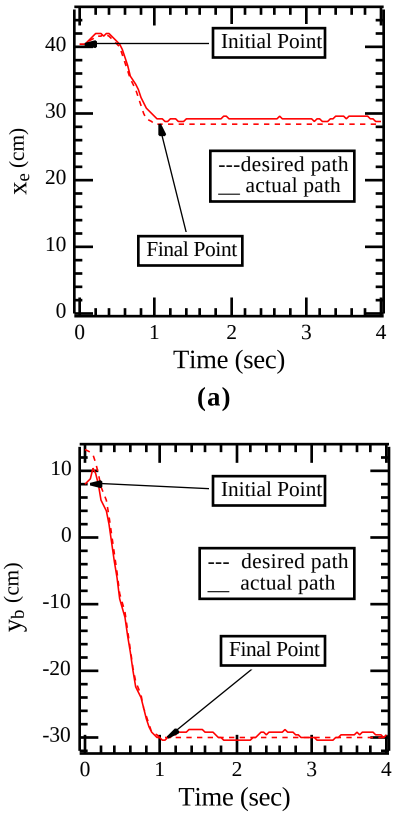
(a)



(b)

Figure 9: Base motion of Shaky II in a tracking test

It maintains this position with almost no oscillations. With a conventional PID joint controller the manipulator end-effector motion would be corrupted by the base motions, resulting in large end-effector errors (in the order of ±2cm.)



(b)

Figure 10: End-effector motion of Shaky II in a tracking test

Conclusions

In this paper, a method called Inferred End-point Control, that controls the end-effector of long reach manipulator systems in spite of the supporting structure vibrations has been presented. The method uses simple strain sensors mounted on the structure to infer the manipulator end-point location in inertial reference system. This technique is applicable to the control of large motions of LRMS in an unstructured environment. It does not require special targets, lights or knowledge of the environment. Experiments with two laboratory systems suggest that this control approach has a very good performance. In our current research 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.

Acknowledgment

The support of this work by NASA Langley Research Center Automation Branch, Grant NAG 1-801 is acknowledged.

References

1. NSF, Proceedings of the NSF Workshop on Sensors and Sensor Systems for Power Systems and Other Dispersed Civil Infrastructure Systems, April, 1994.

2. Soler R. and Guillet J., “Robotic Maintenance of the EDF Transmission (63 to 400 KV) Network: Feasability Study and Effects on Tower Design,” *Proceedings of the 6th International Conference on Transmission and Distribution Construction and Live Line Maintenance (ESMO ‘93)*, Las Vegas, NV, 1993, pp. 459-468.

3. Jansen J.F. et al, “Long Reach Manipulation For Waste Storage Tank Remediation,” *ASME, DSC-Vol. 31, Modelling and Control of Compliant and Rigid Motion Systems*, 1991, pp. 67-73.

4. Knape B. and Berger A., “Development of a Remote Tank Inspection (RTI) Robotic System,” *Proceedings of the 4th ANS Topical Meeting, Robotics and Remote Systems*, M. Jamshidi and P. Eicker, editors, Albuquerque, NM, 1991, pp. 470-481.

5. Dubowsky S., “Dealing With Vibrations in the Deployment Structures of Space Robotic Systems,” *Proceedings of the 5th International Conference on Adaptive Structures*, Sendai, Japan, 1994.

6. Torres M.A., Dubowsky, S., and Pisoni, A., “Path-Planning for Elastically Mounted Space Manipulators: Experimental Evaluation of the Coupling Map,” *Proceedings of the 1994 IEEE International Conference on Robotics and Automation*, San Diego, CA, 1994, pp. 2227-2233.

7. Lew J. and Book W., “Bracing Micro/Macro Manipulators Control,” *Proceedings of the 1994 IEEE International Conference on Robotics and Automation*, San Diego, CA, pp. 2362-2368, 1994.

8. Book, W.J. and Lee, S.H., “Vibration Control of a Large Flexible Manipulator by a Small Robotic Arm,” *Proceedings of the American Control Conference*, Pittsburg, PA, Vol. 2, pp. 1377-1380, 1989.

9. Torres, M.A., *Modeling, Path-Planning and Control of Space Manipulators: The Coupling Map Concept*,

Ph.D. Thesis, Mechanical Engineering Department, MIT, Cambridge, MA, 1993.

10. Trudnowski D.J., Baker C.P. and Evans M.S., "Damping Control of a Large Flexible Manipulator Through Inertial Forces of a Small Manipulator," *Proceedings of the American Control Conference*, San Fransisco, CA, pp. 2878-2879, 1993.

11. Lew J., Trudnowski D., Evans M. amd Bennett D., "Micro-Manipulator Motion Control to Counteract Macro Manipulator Structural Vibrations," *Proceedings of the 6th ANS Topical Meeting, Robotics and Remote Systems,* Monterey CA, 1995, pp. 487-491.

12. Sharon A. and Hardt D., "Enhancement of Robot Accuracy Using End-Point Feedback and a Macro-Micro Manipulator System," *Proceedings of the 1984 American Control Conference,* San Diego, CA, 1984, pp. 1836-1842.

13. Chiang, W., Kraft R. and Cannon R. "Design and Experimental Demonstration of Rapid, Precise End-Point Control of a Wrist Carried by a Very Flexible Manipulator," *The International Journal of Robotics Research*, 10, 1, 30-40, 1991.

14. Hootsmans N. and Dubowsky S., "Large Motion Control of Mobile Manipulators Including Vehicle Suspension Characteristics," *Proceedings of the 1991 IEEE International Conference on Robotics and Automation*, Sacramento, Ca, April, 1991, pp. 2336-2341.

15. Ballhaus W.L. and Rock S.M., "End-Point Control of a Two-Link Flexible Robotic Manipulator with a Mini-Manipulator: Coupling Issues," *ASME, AMD-Vol. 141/DSC-Vol. 37, Dynamics of Flexible Multibody Systems: Theory and Experiments*, 1992, pp. 17-22.

16. Chalhoub N. and Zhang X., "Reduction of the End-Effector Sensitivity to the Structural Deflection of a Single Flexible Link: Theoretical and Experimental Results," *Transactions of the ASME, Journal of Dynamic Systems, Measurement and Control,* 115, 658-666, 1993.

17. Vaillancourt C. and Gosselin, G., "Compensating for the Structural Flexibility of the SSRMS with the SPDM," *Proceedings of the International Advanced Robotics Program, Second Workshop on Robotics in Space*, Canadian Space Agency, Montreal, Canada, July, 1994.

18. Rowe, P.S., *End-point Control of Elastically Mounted Robotic Systems: Simulation and Experimentation*, Bachelor Thesis, Mechanical Engineering Department, MIT, Cambridge, MA, 1994.

19. Thomas L. K., *Design of a Flexible Supporting Structure for a Long Reach Manipulator System*, Bachelor Thesis, Mechanical Engineering Department, MIT, Cambridge, MA, 1995.