DEPLOYABLE SPACE MANIPULATOR CLOSED-LOOP CONTROL, IDEAS AND POSSIBILITIES OF USING GPS AS A SENSOR

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ABSTRACT

In the area of study of the dynamics and control of large flexible spacecraft one of the most challenging areas is that of large space-based robotic manipulators. The Deployable Space Manipulator is a large manipulator concept for Low Earth Orbit operation with one rotational joint and one prismatic joint. In this paper the dynamics of the manipulator undergoing large rotational motion while carrying a payload and extending its length are developed and the need for closed loop control is discussed. An output feedback closed loop control approach is presented and a concept for using GPS antennas mounted on the structure as feedback sensor for the control law is presented and discussed.

INTRODUCTION

Existing and proposed space-based manipulators such as the Shuttle Remote Manipulator System (SRMS), the Space Station RMS (SSRMS), the European Robotic Arm (ERA), etc. all contain two links with revolute joints at the attachment point and at the joints. Considerable research has been invested to study the dynamics and control of such multi-link manipulators (Juang et al., 1989), (Skaar and Ruoff, 1994), (Junkins and Kim, 1993). On the other hand, the related problem of a manipulator with a deployable (telescopic) link has not been addressed from a control perspective in as much detail. As pointed out by Kirk and Romero (1996) and more recently by Hokamoto et al. (1998) this manipulator design has advantages over the traditional two link manipulators, such as: simpler inverse kinematics, simpler equations of motion, and the absence of singular configurations which guarantees the nonsingularity of the Jacobian matrix for the inverse kinematics.

Deployable space manipulators (DSMs), such as the one proposed in this paper, have been studied by Marom and Modi (1993), Hokamoto et al. (1995), and Hokamoto et al. (1998). This work expands the available literature by studying a fully flexible dynamical model and active vibration control for the manipulator while performing a slew manoeuvre plus a length extension.

The rest of the paper is organised in major sections presenting first the system dynamics in condensed form, then the control strategy designed for the manipulator, followed by results of the vibration attenuation capabilities of the vibration control system. After which the issue of sensors is presented and GPS antennas are discussed as possible candidates, and finally some conclusions.

SYSTEM DYNAMICS

The DSM study is conducted via computer simulations of the dynamic equations of motion, which are derived in this section. The manipulator is idealised as two homogeneous coaxial beams, the manipulator's lower link (link 1) being connected at point $\mathbf{O_1}$ to an orbiting structure and the upper link (link 2) having an axial motion through link 1 (Figures 1 and 2). The coordinate system defined for the analysis is shown in Figure 2, with the X-axis along the length of the DSM, the Y-axis perpendicular defining the plane of vibration of the DSM, and the Z-axis out of the plane completing the right handed coordinate system. The system has a rotational motion about the Z-axis produced by a torque motor at the base of the manipulator. Thus, link 2 has both rotational and axial motion. The axial motion is idealised as a predetermined force acting at the base of link 2. Structural damping is neglected in the manipulator since it is traditionally very low for space structures (Skaar and Ruoff, 1994) and it is difficult to predict due to the composite nature of space robotic manipulator links. Coupling between rigid-body angular velocity and elastic displacement is included as well as the contribution of the axial load to the bending of link 2.

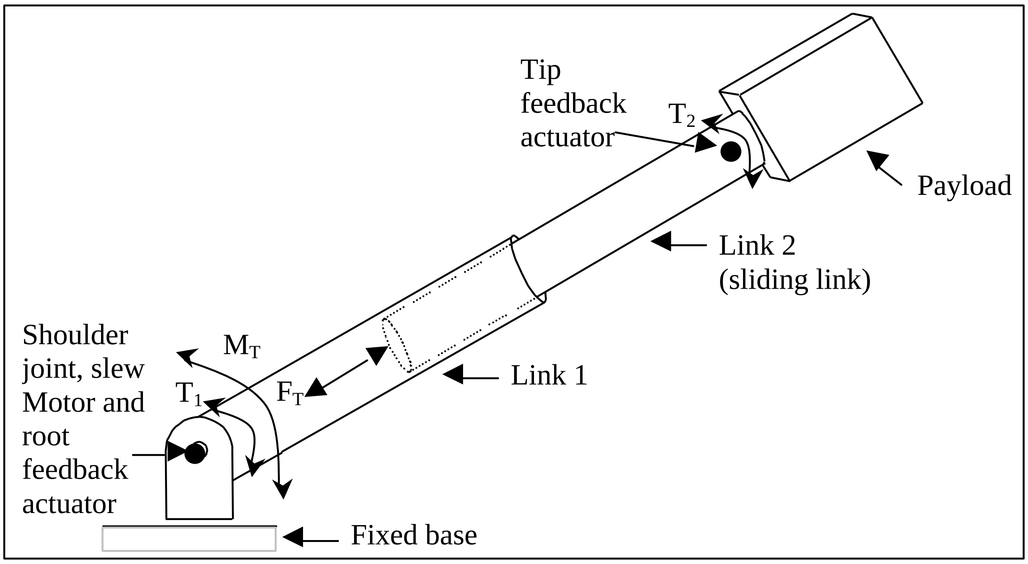

Fig. 1. Deployable Space Manipulator

The total energy of the system is given by the following equations:

$$\begin{aligned}\mathbf{T} = {} & \frac{1}{2}\int_0^{L_1} r_1\left[\left(-y_1(x)\dot{q}\right)^2 + \left(x\dot{q} + \dot{y}_1(x)\right)^2\right]dx + \frac{1}{2}\int_{L_1-b}^{L_1} r_2\left[\left(\dot{a} - y_1(x)\dot{q}\right)^2 + \left(x\dot{q} + \dot{y}_1(x)\right)^2\right]dx + \\ & + \frac{1}{2}\int_0^{a} r_2\left[\left(\dot{a} - y_2(x)\dot{q} - y_1(L_1)\dot{q}\right)^2 + \left((L_1 + x)\dot{q} + \dot{y}_1(L_1) + \dot{y}_2(x)\right)^2\right]dx + \\ & + \frac{1}{2}M_p\left[\begin{array}{l}\left(\dot{a} - y_2(a)\dot{q} - y_1(L_1)\dot{q}\right)^2 + \\ \left(\left(L_1 + a + \frac{1}{2}L_p\right)\dot{q} + \dot{y}_1(L_1) + \dot{y}_2(a) + \frac{1}{2}L_p\dot{y}_2'(a)\right)^2\end{array}\right] + \frac{1}{2}I_p\left(\dot{q} + \dot{y}_2'(a)\right)^2\end{aligned} \qquad (1)$$

$$\begin{aligned}\mathbf{V} = {} & \frac{1}{2}EI_1\int_0^{L_1}\left(\frac{\P^2 y_1}{\P x^2}\right)^2 dx + \frac{1}{2}EI_2\int_{L_1-b}^{L_1}\left[\left(\frac{\P^2 y_1}{\P x^2}\right)^2 + P_1(x)\left(\frac{\P y_1}{\P x}\right)^2\right]dx + \\ & \frac{1}{2}EI_2\int_0^{a}\left[\left(\frac{\P^2 y_2}{\P x^2}\right)^2 + P_2(x)\left(\frac{\P y_2}{\P x}\right)^2\right]dx\end{aligned} \qquad (2)$$

where **T** is the kinetic energy and **V** the potential energy of the system.

Eqs. 1 and 2 describes the DSM as a system with three distinct coordinates, the rigid body angle of rotation, ***q***, and the two distributed coordinates y_1 and y_2 which describe the deflections of the flexible links. The extended length of link 2, *a*, is also a coordinate of the system but it has been assumed to be always known in this development since the force of deployment is commanded following a predetermined deployment or contraction schedule.

To discretize the two distributed coordinates the assumed mode method is used to describe the bending displacements y_1 and y_2 (Figure 2) as finite series:

$$y_1(x,t) = \sum_{i=1}^{n} a_i(t) f_i(x, L_1) \tag{3}$$

$$y_2(x,t) = \sum_{v=1}^{m} b_v(t) j_v(x, a) \tag{4}$$

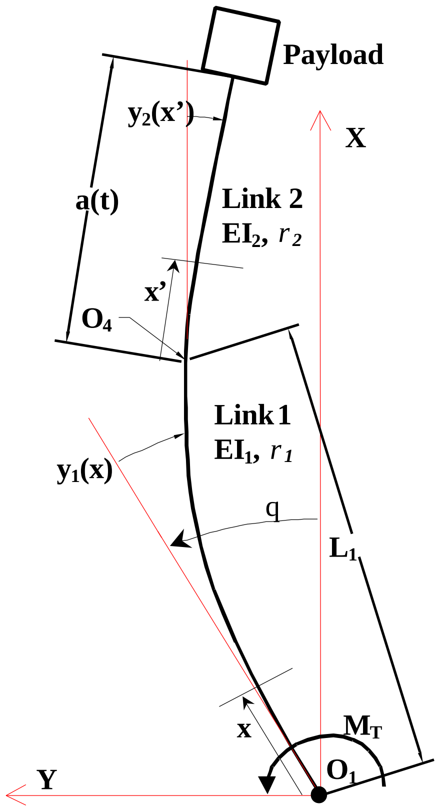

Fig. 2. DSM Elastic Deformation

In Eqs. 3 and 4 the variables a_i and b_v become generalised coordinates of the system, f_i and j_v are a series of assumed shape functions. As remarked by Yuh and Young (1991) and by Tabarrok et al. (1973) it is worth noting that the functions j_v depend on *a*, the length of link 2 outside link 1, and since *a* is changing in time in a prescribed manner, j_v is time varying. The assumed functions used, in Eqs. 3 and 4 for f_i and j_v, are the deflection shapes of a cantilever beam plus an end mass. Thus producing a model of order three for the DSM, which simulates its two lowest frequencies of vibration plus the rotation with respect to the base.

Substituting Eqs. 3 and 4 into Eqs. 1 and 2 produce the discrete expressions for the energies of the system necessary for the application of the Lagrange equation:

$$\frac{d}{dt}\left(\frac{¶\,(T-V)}{¶\dot{\mathbf{q}}_\mathbf{i}}\right) - \frac{¶\,(T-V)}{¶\mathbf{q}_\mathbf{i}} = Q_i, \qquad i = 1,2,3,\ldots,n$$

which is applied for each of the discrete coordinates, $\mathbf{q_i}$, and equated to each of the control systems' inputs Q_i. Since the deployment time history is predetermined, the length *a* is not a discrete coordinate of the system so no equation of motion is needed.

The equations of motion relating any given input to the manipulator's degrees of freedom are thus produced, and the behaviour of the DSM can be studied.

CONTROL STRATEGY

The basic function of the DSM in orbit would be to grapple payloads from one position and manoeuvre to deliver them to a different position. As with the traditional two link revolute joint manipulators the main type of motion needed is that of rotation, or slew. To accomplish a slew the drive motor at the attachment point to the orbiting structure applies a torque at the base to rotate the entire manipulator. At the same time the DSM changes length according to a predetermined deployment action which extends its total length from 8 to 15 metres.

Since the inertia with respect to the rotation point is changing rapidly, due to the length change, the applied torque has to change to achieve the desired final slew angle. To achieve the slew a bang-bang angular acceleration profile is selected. This produces a smooth trajectory for the DSM, no net energy input to the manipulator as it is accelerated on the first half of the manoeuvre and decelerated on the second half. To achieve the bang-bang acceleration profile the inverse dynamics method based on a rigid DSM is used to calculate the needed torque, M_T. A sample torque profile is shown in Figure 3 for a DSM undergoing rotation plus extension carrying a 200 Kg payload.

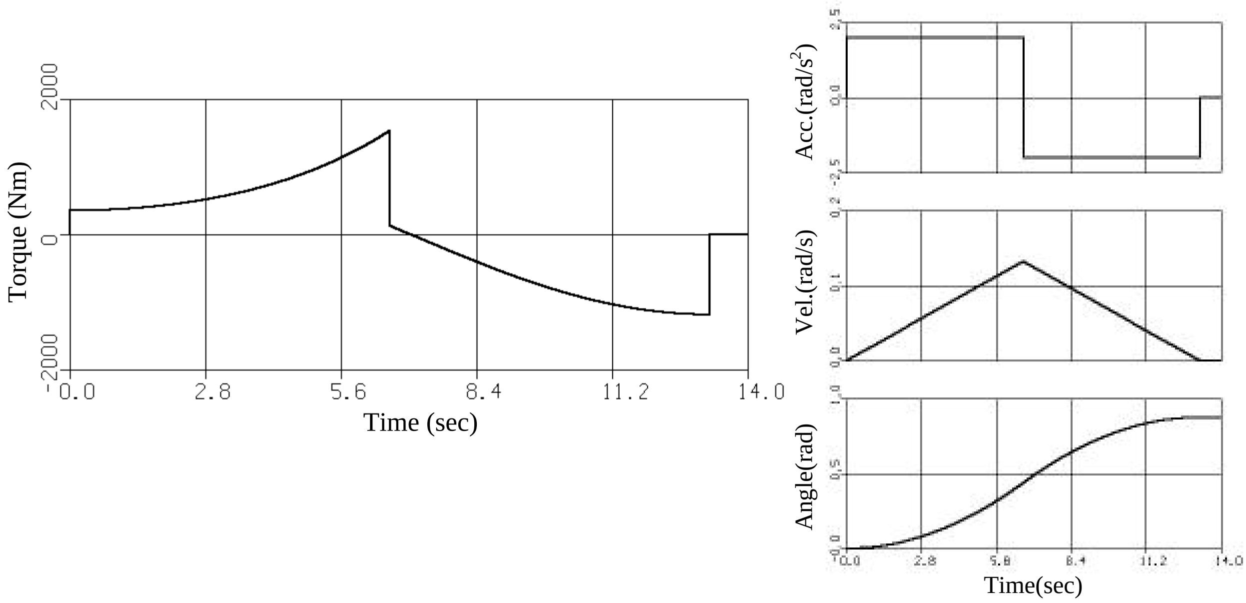

Fig. 3. Torque profile, slew acceleration, velocity and angle for a 50° slew of the DSM

The torque profile presented in Figure 3 shows the traditional three switches associated with a bang-bang optimal solution to the minimum-time problem, but with the difference that there are no flat sections in the torque applied to the manipulator. The torque changes throughout the slew manoeuvre based on the predetermined length change commanded to the manipulator.

VIBRATION ATTENUATION RESULTS

The application of the slew torque described in the previous section to the DSM will excite vibrations of the flexible modes of the structure. The vibrations induced on the DSM by the slewing torque are shown in Figure 4 below, for Payloads 1 and 2 as described in Table 1.

Table 1. Payload physical characteristics

	Mass	Length	Width
Payload 1	200 Kg	100 cm	50 cm
Payload 2	350 Kg	150 cm	75 cm

The vibrations in Figure 4 can be seen to vary as the different slew torque switches are applied to the DSM. The vibration amplitude of each of the three distinct sections is dependent on the exact moment of the switch. In the plots it is also apparent the flexible deformation of the DSM (departure from the zero deflection line) as the manipulator is accelerated and then decelerated through the slew. The DSM finally returns to a steady tip vibration around a zero mean after the end of the slew. Since no structural damping has been included in the system's dynamic formulation the vibration levels after the manoeuvre will remain constant unless some form of active or passive vibration attenuation mechanism is introduced.

To damp out the vibrations of the DSM during and after a slew manoeuvre an output feedback control system based on Lyapunov's direct method has been formulated, basically guaranteeing error energy minimisation at all times. This is a well known method as described by Juang et al. (1989), Slotine and Li (1991), and Junkins and Kim (1993), among others. In most cases this control approach has been applied to single or double link flexible manipulators to ensure overall stability when traditional linear analysis methods of the control system do not apply, and following that research it is applied here to the time varying control problem of the DSM to cope with the feedback torque requirements as the manipulator's inertia changes.

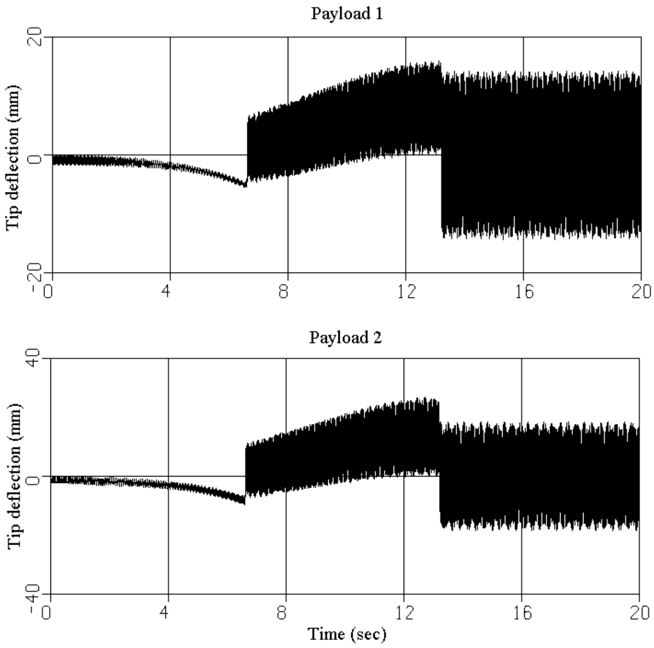

Fig. 4. DSM tip vibrations for a 50° slew

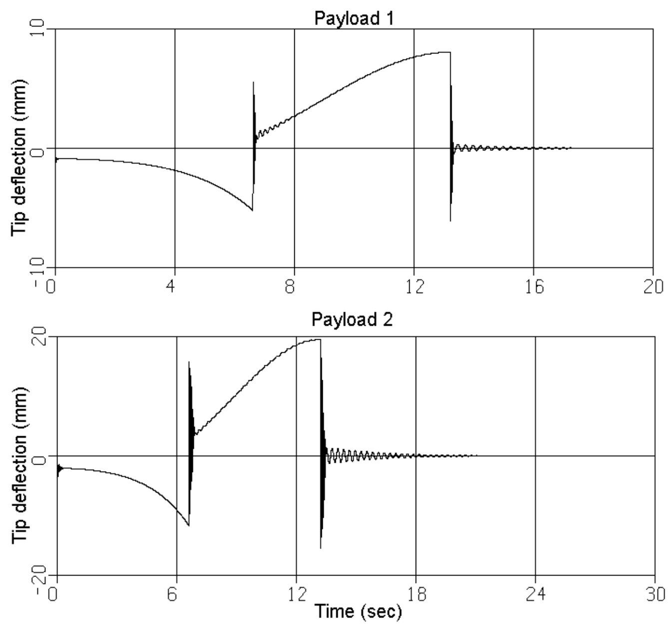

Fig. 5. Feedback control results for a 50° slew

The control actuators have been positioned as shown in Figure 1 above. There are two torque input devices, such as reaction wheel actuators, attached to the manipulator structure at the root and at the tip. Thus they produce feedback torques collocated with the output measurements, which are the measurable tip vibration deflection and speed, and the slew rotation angle and slew speed. The actuators are bound to 100 Nm and 10 Nm for the root and tip respectively.

The development of the control laws applied to the DSM can be found in Romero et al. (1999) which shows the complete development of the feedback control law formulas based on guaranteeing the reduction of the error energy of a simplified manipulator model:

root actuator feedback control law;

$$T_1 = -J_1\dot{q}_e - J_2 q_e - J_3\int_0^a r_2(L_1+x)\left[(L_1+x)\ddot{q}_e + \ddot{y}_2\right]dx - J_4 I_{yy}\left(\ddot{q}_e + \ddot{y}_2'(a)\right) - J_3 M_p(L_1+a)\left[(L_1+a)\ddot{q}_e + \ddot{y}_2(a)\right] \quad (5)$$

$$J_1 \geq 0 \quad J_2 \geq 0 \quad J_3 > -1 \quad J_4 > -1$$

tip actuator feedback control law;

$$T_2 = -\int_0^a \dot{y}_2\{r_2(L_1+x)\}dx - I_{yy}\dot{y}_2'(a) - M_p\dot{y}_2(a)(L_1+a) \quad (6)$$

The J_i quantities in equation 5 are tuneable gains, which must satisfy the conditions stated, the q_e quantities are the differences in the slew angle and speed between the observed and expected values. The control laws in Eqs. 5 and 6 are general output feedback control laws for the DSM, independent of a specific discretisation method for the manipulator flexible links. For the feedback control law application in the simulation environment, the manipulator's flexibility is substituted by Eq. 4.

Application of the feedback control torques together with the slew torque produce the results shown in Figure 5, the vibrations both during and after the slew are quickly attenuated, decreasing the high vibration environment for the manipulator and payload during a slew manoeuvre.

GPS AS FEEDBACK SENSOR

In the initial phase of the study presented above, the issue of sensors selection was not considered in detail, the main aim was to produce a stable output feedback control system that could guarantee good vibration attenuation performance for the DSM. The sensors were assumed to be strain gages or accelerometers to measure the flexible deformations of the manipulator plus a standard optical angle encoder to measure the overall angular motion of the DSM.

Currently the idea has been proposed to look at using GPS antennas working in differential mode to sense all of the output quantities necessary for DSM feedback control. The advantage of GPS technology is that it is non-intrusive in the manipulator, small antennas could be installed throughout the manipulator or at specific points with little fuss. The application of this technology for these purposes has been studied in some detail by Teague et al. (1996), for the control or a large suspended flexible structure, with very encouraging results. The application here would not be substantially different, except that the frequencies of vibration are considerably higher in this application so suitability has to be studied and the performance evaluated by simulation.

The idea would be to use the GPS signal carrier and make differential measurements between different antennas to determine the variations in position. The principle is highlighted in Figure 6. Basically a number of full cycles, h, plus a portion of a cycle, f, will be detected by a receiver in differencing mode having all the antennas as input and using Antenna 1 as the reference antenna. This will produce a baseline distance measurement between each of the antennas. Thus, making continuous measurements the relative positions of each antenna could be found to centimetre level accuracy.

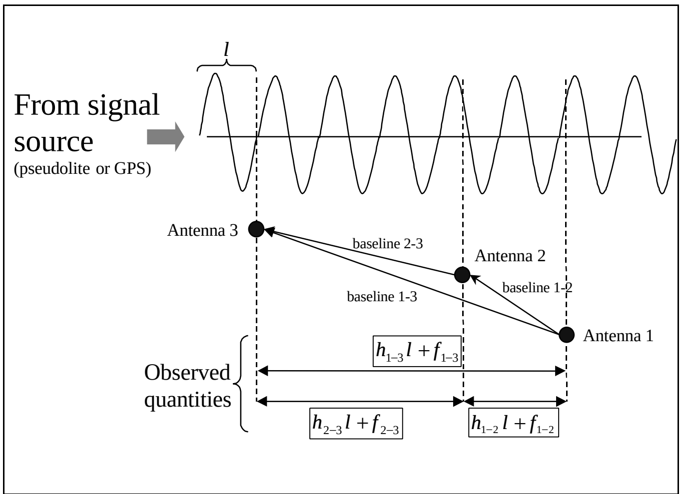

Fig. 6. Carrier differential GPS observable concept

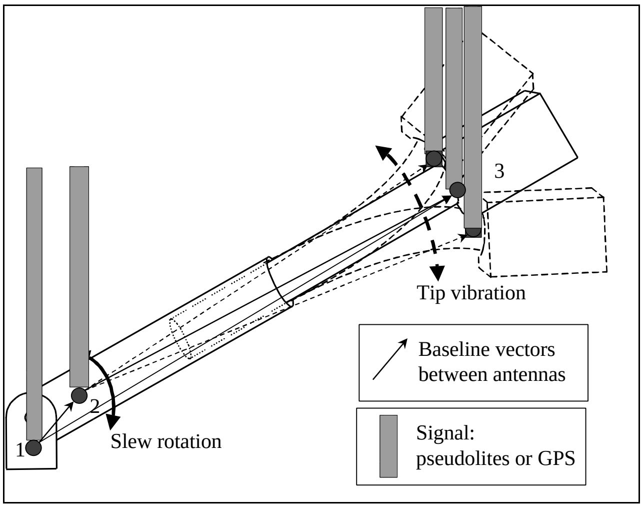

Fig. 7. GPS antenna positions on the DSM

It is assumed here that Antenna 1 is at the base of the DSM, Antenna 2 close to the root of link 1, and Antenna 3 at the tip of the DSM (Figure 7). Since the antenna positions are well known a priori, any variation in their relative positions will indicate either a rotational motion, indicating a slew, or DSM flexible vibrations.

This use of GPS technology as a deformation sensor in a flexible structure will measure reliably dynamic responses below 10 Hz and deflections around the centimetre level (Teague, et al. 1996). This would clearly not capture all of the dynamic information of the DSM vibrations, only the slewing motion and the first mode of vibration, but nonetheless together with the Lyapunov–based output feedback control law presented above it is hoped that a stable and reliable control system can be demonstrated.

CONCLUSIONS

The dynamics of a novel manipulator system have been shown, the vibrations during slewing have been discussed and an output feedback control strategy has been presented based on Lyapunov's direct method. Using GPS antennas the sensor for the DSM has been discussed and a preliminary study suggests the idea is worth pursuing but understanding that some limitations exist for this technology in this application and therefore the performance of the control law developed will be degraded from the results reported.

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