CONTROL OF MOBILE MANIPULATORS INCLUDING VEHICLE DYNAMIC CHARACTERISTICS

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ABSTRACT

The dynamic interactions between a mobile manipulator and its vehicle are shown to lead to poor performance when conventional fixed-base controllers, which neglect these interactions, are used. An extended jacobian transpose control algorithm is developed, which accounts for dynamic vehicle motions caused by manipulator motions. It is shown to perform well, even in the presence of modeling errors and using only limited sensory data, such as would be practically available in highly unstructured field environments.

I. INTRODUCTION

In the future, robotic and telerobotic manipulators mounted on moving vehicles will play important roles in unstructured or hostile environments, performing such tasks as ordnance disposal, toxic waste cleanup, and fire-fighting.

A number of prototype systems are being proposed and developed for these applications[1-2], see Figure 1. However, due to the interactions between the manipulator and its vehicle, these systems present challenging control problems not found in conventional industrial manipulators mounted on stationary bases. The manipulator's motions and gravity will dynamically interact with the vehicle and its suspension to degrade the manipulator's performance. Such problems as excessive end-effector errors and poor system stability can result. To prevent these problems, and to ensure the success of future mobile manipulators, new control approaches are required.

To date there has been relatively little research on the control problems caused by the dynamic interactions between terrestrial mobile manipulators and their vehicles. Most studies of mobile robots have focused on obstacle avoidance and motion planning aspects of wheeled tracked or legged systems[3]. Generally, the systems are treated as simple vehicles without dynamics and/or without any manipulators[4,5]. Where the dynamic interaction of a manipulator and its vehicle have been considered, these interactions have been limited by assuming either a massive vehicle whose motion is unaffected by the manipulator and its payload[6], or by avoiding vehicle motion with the use of outriggers and limited manipulator motions[7]. A method for controlling manipulators on vehicles with suspension compliance, using endpoint sensing has been proposed. However, because of practical considerations such as limited sensor ranges and nonlinear manipulator properties this approach is applicable only to small manipulator motions, such as during the acquisition phase of manipulation tasks[8]. Obtaining practical endpoint sensing, 3 positions and 3 orientations, for large motions in fields environments is very difficult.

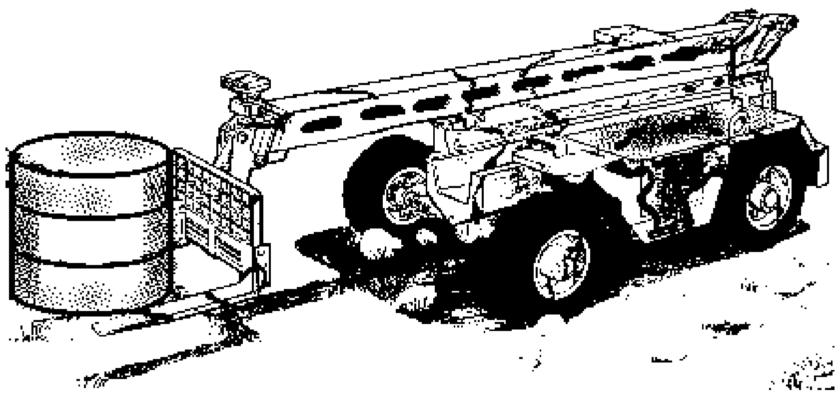

Figure 1. Example of a Mobile Manipulator System.

Clearly, there is a need to develop new control algorithms for mobile manipulators in field environments. This paper reports on an ongoing analytical and experimental study of the control of mobile robotic manipulator systems and it proposes such a new control method. This approach is shown to have the potential to provide good nonlinear large motion control, yet it relies only on easily available base sensory signals, rather than on difficult to obtain large motion endpoint sensing.

II. THE SYSTEM

For purposes of this study, a system was designed to be representative of a system performing human scale material handling tasks in a hostile environment[9]. The system consists of a three link 125 kg manipulator with a 25 kg payload. It has a hydraulic actuator at each manipulator joint, and a total of nine degrees of freedoms (DOF), including the position and orientation of its 500 kg, four-wheel vehicle. The system has a total reach of 1.9 meters. Its lowest structural resonance is at approximately 30 Hz. The manipulator's maximum static endpoint deflection with payload, due to link elasticity and gravity, assuming locked actuators and excluding base deflection, is less than half a millimeter. The manipulator can be modeled as a rigid link system[10].

The vehicle's suspension is modeled as four identical passive quarter car suspensions resulting in combined vehicle/manipulator natural frequencies of approximately 1 Hz in the vertical direction and 2.5 and 10

Hz in the forward and sideward horizontal directions. The suspension is designed to give effective damping ratios in the 0.5 - 0.6 range, depending on manipulator configuration and payload.

As a performance requirement, it was assumed, that the system should move a payload from rest to its final stationary position in two seconds, with less than a 20 mm maximum end-effector tracking error, less than a 10 mm steady state endpoint error, and less than a 0.4 seconds settling time at the end of the motion. The settling time is defined to be the time after the end of the commanded motion required for the end-effector to stay within 0.5 mm of its steady state position.

The performance of this system, using a well designed conventional joint control algorithm of the type found in most industrial systems, proved to be quite unsatisfactory compared to the above specifications. Consider the simple planar trajectory, shown in Figure 2. Link 1 is stationary for this trajectory. The velocity profile is a simple sinusoid. The base is assumed to be initially at rest with the manipulator in its initial position.

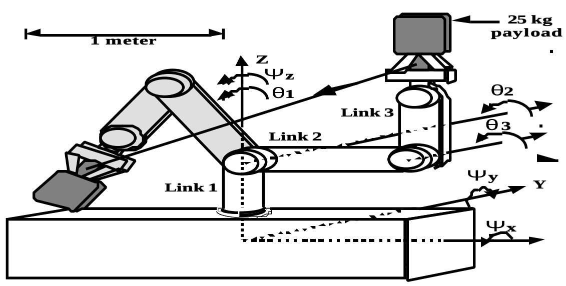

Figure 2. Initial & Final Endpoint Positions on Straight Line Trajectory.

A conventional proportional-derivative controller is chosen for the manipulator with a 4-10 Hz bandwidth, depending on the system configuration, and a 1.0 to 2.0 damping ratio. This ensures that the system bandwidth is well below the first structural resonance. When the controller is applied to the manipulator with its vehicle held stationary the maximum dynamic endpoint error is 8.5 mm, and the steady state error is 5.5 mm, due to gravity. However, when the vehicle is permitted to move in response to gravity and to the dynamic forces exerted on the vehicle, the manipulator takes more than a second to settle, and the errors are larger by an order of magnitude, as shown in Figure 3.

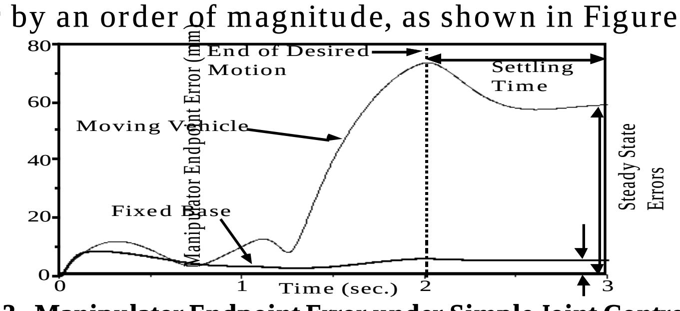

Figure 3. Manipulator Endpoint Error under Simple Joint Control

This error is due principally to the interaction of the manipulator and its vehicle, including dynamic, gravity and suspension effects. Figure 4 shows the linear vehicle motion during the manipulator move. The vehicle also experiences significant pitch motion. Clearly, the interaction of the manipulator and its vehicle significantly degrades the system performance, and better techniques are required for satisfactory large motion control. In this work a number of such algorithms were developed and evaluated. Here, an extended jacobian transpose control algorithm is presented for mobile manipulators, and shown to offer some substantial advantages for their control where model uncertainty is high and sensory information is limited.

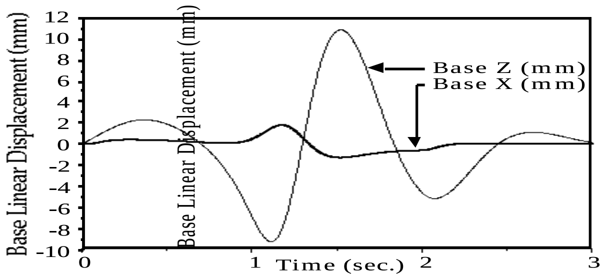

Figure 4. Linear Vehicle Motion during Joint Control Move.

III. THE MOBILE MANIPULATOR CONTROL ALGORITHM

The development of the extended jacobian transpose algorithm for mobile manipulators recognizes that a manipulator on a vehicle has a non-square jacobian. However, the extra degrees of freedom do not have control actuators, and hence one cannot simply resolve the redundancy, for example by locking one or more actuators. As discussed below, themobile manipulator jacobian (MMJ), can be partitioned into two sub-jacobians, $\mathbf{J}_v$ and $\mathbf{J}_m$, where $\mathbf{J}_v$ multiplies the vehicle velocities corresponding to the uncontrolled degrees of freedom, and $\mathbf{J}_m$ multiplies the manipulator joint velocities corresponding to the controlled degrees of freedom. For a n DOF mobile manipulator on a 6 DOF vehicle:

$$\dot{\mathbf{x}}_e = \begin{Bmatrix} \dot{\mathbf{r}}_e \\ \omega_e \end{Bmatrix} = \mathbf{J}\,\dot{\mathbf{q}} = [\,\mathbf{J}_v \mid \mathbf{J}_m\,] \begin{Bmatrix} \dot{\mathbf{x}}_v \\ \dot{\mathbf{q}}_m \end{Bmatrix} \qquad (1)$$

where $\dot{\mathbf{x}}_e$ is the 6 x 1 vector of end-effector linear and angular velocities, $\dot{\mathbf{r}}_e$ and ω_e, respectively. The vector $\mathbf{q} = [\mathbf{r}_v, \theta_v, \mathbf{q}_m]^T = [x, y, z, \psi_x, \psi_y, \psi_z, q_1, \ldots, q_n]^T$ is the 6+n by 1 generalized position vector, which includes the vehicle position and orientation as well as the manipulator joint displacements $\mathbf{q}_m$. The vector $\dot{\mathbf{x}}_v = [\dot{\mathbf{r}}_v, \omega_v]^T$, where $\dot{\mathbf{r}}_v$ is the vehicle linear velocity vector and ω_v is the vehicle angular velocity vector. It has been shown, that the MMJ sub-matrices $\mathbf{J}_v(\mathbf{q})$ and $\mathbf{J}_m(\mathbf{q})$ can be written as[9]:

$$\mathbf{J}_v(\theta_v, \mathbf{q}_m) = \begin{bmatrix} \mathbf{I} & \mathbf{R}_v(\theta_v)\ [{}^v\mathbf{r}^v_e(\mathbf{q}_m)]^\times\ \mathbf{R}_v^T(\theta_v) \\ \mathbf{0} & \mathbf{I} \end{bmatrix} \tag{2}$$

$$\mathbf{J}_m(\theta_v, \mathbf{q}_m) = \begin{bmatrix} \mathbf{R}_v(\theta_v) & \mathbf{0} \\ \mathbf{0} & \mathbf{R}_v(\theta_v) \end{bmatrix} \mathbf{J}_{fb}(\mathbf{q}_m) \tag{3}$$

$\mathbf{I}$ is the 3 by 3 identity matrix and $\mathbf{R}_v(\theta_v)$ is the 3 by 3 rotation matrix, which relates the orientation of the vehicle frame to the inertial frame. The term ${}^v\mathbf{r}^v_e(\mathbf{q}_m)$ is the 3 by 1 position vector of the manipulator end-effector with respect to the vehicle frame expressed in vehicle frame coordinates. $[\mathbf{a}]^\times$ is the cross product matrix for the vector $\mathbf{a}$, defined as:

$$[\mathbf{a}]^\times = \begin{bmatrix} 0 & -a_z & a_y \\ a_z & 0 & -a_x \\ -a_y & a_x & 0 \end{bmatrix} \tag{4}$$

The MMJ, $\mathbf{J}(\theta_v, \mathbf{q}_m) = [\ \mathbf{J}_v(\theta_v, \mathbf{q}_m)\ |\ \mathbf{J}_m(\theta_v, \mathbf{q}_m)\ ]$, as can be seen in equations (2) and (3) is a 6 by 6+n matrix dependent only on the manipulator joint displacements and the vehicle orientation.

The equations of motion for the n DOF mobile manipulator are[9]:

$$\mathbf{H}(\theta_v,\mathbf{q}_m)\,\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}}) + \begin{Bmatrix} \mathbf{0} \\ \mathbf{V}\,\dot{\mathbf{q}}_m \end{Bmatrix} + \mathbf{G}(\theta_v,\mathbf{q}_m) = \begin{Bmatrix} \mathbf{F}_{vs}(\mathbf{x}_v,\dot{\mathbf{x}}_v) \\ \tau_m \end{Bmatrix} = \tau \tag{5}$$

The 6+n by 1 vector τ consists of the forces and torques exerted on the vehicle by its suspension, $\mathbf{F}_{vs}$, and the manipulator's joint torques, τ_m. $\mathbf{H}$ is the 6+n by 6+n inertia matrix and is a function of the vehicle orientation θ_v. $\mathbf{V}$ is the n by n manipulator viscous joint friction matrix, $\mathbf{C}$ is the 6+n by 1 nonlinear torque vector due to coriolis and centrifugal terms, and $\mathbf{G}$ is the 6+n by 1 gravitational torque vector.

Jacobian transpose control methods, such as stiffness control[11], and operational space control[12], use the standard fixed based jacobian, $\mathbf{J}_{fb}$, to compute τ_m as:

$$\tau_m = \mathbf{J}_{fb}^T(\mathbf{q}_m)\ \mathbf{F}_e \tag{6}$$

where $\mathbf{F}_e$ is the vector of forces and torques reflected to the end-effector.

To develop an algorithm for the n DOF mobile manipulator on a 6 DOF vehicle, one must use the MMJ given by equations (1-3). In parallel with equation (6) one can write:

$$\tau = \begin{Bmatrix} \mathbf{F}_v \\ \tau_m \end{Bmatrix} = \mathbf{J}^T(\theta_v, \mathbf{q}_m)\,\mathbf{F}_e = \begin{bmatrix} \mathbf{J}_v^T(\theta_v, \mathbf{q}_m) \\ \mathbf{J}_m^T(\theta_v, \mathbf{q}_m) \end{bmatrix} \mathbf{F}_e \tag{7}$$

By adding a gravity compensation torque to the term for τ_m in equation (7) in order to eliminate steady state errors, and by applying equation (3), an extended jacobian transpose control algorithm can be defined as:

$$\tau_m = \mathbf{J}_m^T(\mathbf{q}_m, \mathbf{F}_{e}des) + \mathbf{G}(\theta_v, \mathbf{q}_m)$$

$$= \mathbf{J}_{fb}^T(\mathbf{q}_m) \begin{bmatrix} \mathbf{R}_v^T(\theta_v) & \mathbf{0} \\ \mathbf{0} & \mathbf{R}_v^T(\theta_v) \end{bmatrix} \mathbf{F}_{e}des + \mathbf{G}(\theta_v, \mathbf{q}_m) \tag{8}$$

where $\mathbf{F}_{e}des$ provides endpoint position, $\mathbf{x}_e$, and velocity, $\dot{\mathbf{x}}_e$, feedback by setting it as:

$$\mathbf{F}_{e}des = [\,\mathbf{K}_p]\,\{\mathbf{x}_{e}des - \mathbf{x}_e\} + [\,\mathbf{K}_d]\,\{\dot{\mathbf{x}}_{e}des - \dot{\mathbf{x}}_e\} \tag{9}$$

This control algorithms is shown in Figure 5. Note that in general the 6 by 1 vector $\mathbf{F}_v$ in equation (7) consists of a combination of active control and passive suspension forces and torques acting on the vehicle. In this study it is assumed that the vehicle has no suspension actuators and hence $\mathbf{F}_v$ consists solely of the passive terms, $\mathbf{F}_{vs}$ in equation (5). The difference between the desired $\mathbf{F}_v$ and its actual value, $\mathbf{F}_{vs}$, is a disturbance to the system.

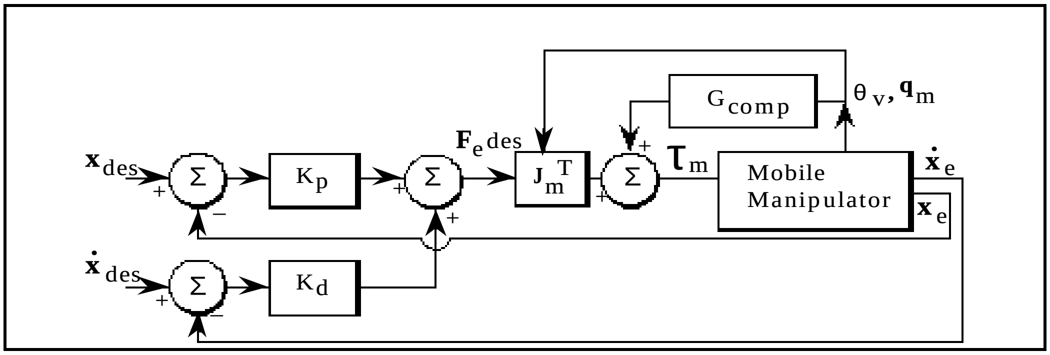

Figure 5. The Jacobian Transpose Control Block Diagram.

IV. PERFORMANCE OF CONTROL ALGORITHM

A. The Ideal Case and the Case with Modeling Errors

Assuming, in the ideal case, that all the sensing and modelling requirements are met, the jacobian transpose algorithm has a 3.7 mm maximum endpoint error, and settles in 0.12 seconds, see Figure 6. This performance satisfies the requirements of less than 20 mm maximum endpoint error and 10 mm steady state error, and less than 0.5 sec. settling time, see Figure 6. Thus it performs very well, particularly when compared to conventional PD approach shown in Figure 3, which had a 73 mm maximum endpoint error and took over a second to settle.

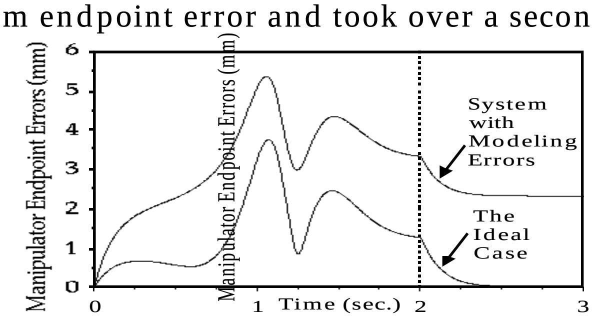

Figure 6. Endpoint Error With and Without Modeling Errors.

In reality, however, the mass properties of field systems and their payloads may not be well known. Figure 6 shows the how the performance of the jacobian transpose algorithm deteriorates under the assumption of a 10 % error in system masses, and an unmodelled 25 kg payload. The performance deteriorates by about 2-3 mm, giving it a maximum error of 5.3 mm and a steady state error of 2.3 mm, which still meets the performance specifications.

B. Limited Sensory Information

It was shown above, that the jacobian transpose algorithm has good performance, with regard both to transient and steady-state errors and to settling time, even in the case of substantial modeling errors. However, the above results use both manipulator endpoint, as well as vehicle orientation, sensory data. In practice, a mobile manipulator often operates in highly unstructured environments. Consequently, vehicle sensing may be limited due to a lack of good environmental reference points. In addition, although it may still be possible to perform endpoint sensing in the close vicinity of the target[8], imagine the difficulty of performing accurate 6-dimensional endpoint sensing, three positions and three orientations, along the entire trajectory of large motions.

Despite base orientation and endpoint sensory information, the jacobian transpose control algorithm can be applied by estimating θ_v, $\mathbf{x}_e$, and $\dot{\mathbf{x}}_e$, based on a fixed-base manipulator model and joint sensing, for use in equation (5). However, the resulting performance is unsatisfactory[9]. One could also use a model of the system mass properties and suspension characteristics to compensate for the static gravitational error by estimating the quasi-static vehicle orientation[9]. This approach reduces the maximum transient error as well as the settling time. Still, the result does not meet the performance specifications. Furthermore, it requires a good knowledge of the payload and manipulator weights. Errors in these quantities will cause the performance to degrade further.

Our studies show that the effectiveness of the jacobian transpose methods and other algorithms such as resolved acceleration comes from the use of endpoint sensing. As discussed above, this is very difficult to obtain in practice. Here the use of sensors to measure the vehicle's motion and to use this information to replace the endpoint sensing was investigated. As discussed below, this proved to be an effective approach.

Although it was recognized that complete vehicle motion sensing may not be feasible, limited vehicle sensing is practical. Pitch and roll sensing can be performed using inexpensive inclinometers that exploit gravity, although yaw motion is difficult to measure. Note that these motions are major contributors to the end-effector errors. Similarly, it is relatively easy to measure the heave (z) motion of the vehicle, since the ground surface provides a reference plane for ultrasonic range sensing. However, there are often no similarly convenient references for sensing lateral motions. Fortunately, a vehicle’s suspension will typically be least stiff in the heave direction, to isolate rough ground vibrations during travel, and thus this motion will be substantially larger than lateral motions of the vehicle. Hence, sensing to replace endpoint sensing was limited to easily measured data.

The jacobian transpose control algorithm yields good transient and steady state endpoint errors as well as a good settling time of 0.13 seconds in simulation, if one uses only the relatively easily measured vehicle motions (z, ψ_x, and ψ_y), and assumes that non-measurable vehicle variables are zero. In fact, as Figure 7 shows, the performance approaches the ideal performance of the jacobian transpose control algorithm with complete endpoint and vehicle sensing. With modeling errors, endpoint errors increased in the order of those shown in Figure 6 for the jacobian transpose control with endpoint sensing, approximately 3 mm.

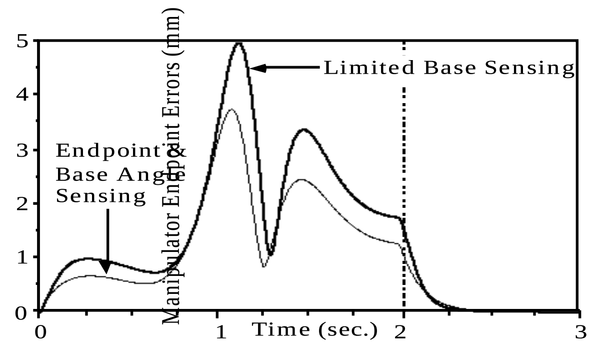

Figure 7. Endpoint Error with and without Endpoint Sensing.

VI. CONCLUSIONS

Conventional fixed-base joint controllers do not perform well on terrestrial mobile manipulators due to vehicle motions produced by gravity effects and due to the dynamic interactions between a manipulator and its vehicle. Here an extended jacobian transpose control algorithm is developed that compensates for these effects. The jacobian transpose control algorithm performs well with endpoint sensing even in the presence of modeling errors. However, in practice, in remote unstructured environments, endpoint sensing is not practical for large motion trajectories. But it is shown that with practical and cost-effective vehicle sensors, such as inclinometers and ultrasonic sensors, endpoint sensing can be replaced and the performance of the jacobian transpose control algorithm approaches that achieved by ideal endpoint sensing.

VII. ACKNOWLEDGEMENTS

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