Extended Abstract: Applications of Mobile Camera Space Manipulation

Bill Goodwine Mike Seelinger J.D. Yoder Qun Ma
Steven B. Skaar
Aerospace and Mechanical Engineering
University of Notre Dame
Notre Dame, Indiana 46556
jgoodwin@nd.edu, mseeling@nd.edu, qma1@nd.edu,
Steven.B.Skaar.1@nd.edu

March 4, 1999

1 Introduction and Motivation

JPL mission planners are currently specifying the details associated with rover missions in 2003 and 2005 that will be focused on detailed *in situ* sample investigation, sample acquisition, and, ultimately, sample return to the Earth. One aspect of these rover missions is the deployment of a variety of science instruments on samples such as rocks or soil. Such science instruments include a microscope spectrometer (APXS) that was also carried on the Sojourner rover. These science instruments will be mounted at the end of a five degree–of–freedom manipulator arm and will be positioned against samples of interest. The target locations on these samples will be selected remotely by scientists via visual information returned by the rover cameras. One challenge to this operation includes the accurate positioning of the instruments against the target of interest. For some of the science instruments positioning requirements are very tight (1–2 mm range) due to instrument focusing issues. Concisely, therefore, the challenge is to develop and demonstrate the ability to accurately position rover–mounted manipulators using vision as the primary sensing modality when the target has been selected by a remote (earthbound) science operator.

Camera space manipulation ("CSM") is a proven method for using a vision–based control strategy to precisely control robotic systems. This paper presents some theoretical aspects of the extension of CSM to coupled holonomic – nonholonomic systems (such as the rover system envisioned by JPL) and presents experimental results related to a specific nonholonomic CSM implementation designed to be a preliminary "proof of concept" platform. The main goal is to demonstrate the autonomous capability outlined above using nonholonomic CSM and a "point–and–click" user interface to direct the remote holonomic –

nonholonomic system to engage a target with repeatable precision. The main results presented have been supported by a JPL Phase I SBIR grant. A Phase II SBIR grant has been awarded, and currently continues to support this research effort.

The primary difficulties with extending CSM to nonholonomic systems are two–fold. First, unlike its usual implementation [18, 19, 20], the class of nonholonomic systems we consider here has the cameras mounted on–board a mobile robot. In this scenario, a desired target location for the end effector does not remain fixed in camera space. This is in contrast to the holonomic case in which the cameras are fixed relative to the desired target point. Second, nonholonomic systems in general are more difficult from a control theoretic point of view than holonomic systems, and this characteristic carries over to the CSM context as well.

2 System Details

The simple experimental platform used to demonstrate the capability outlined in this paper is illustrated in Figure 1. Currently, a one degree–of–freedom arm is mounted on a mobile base along with two cameras. "Target" data are obtained either from a predetermined "cue" or by use of a remote, fixed laser pointer. The latter is particularly amenable to remote "point–and–click" teleoperation outlined subsequently.

The physical parameters appearing in the equations of motion of the system are illustrated in Figure 2. Referring to the figure, θ_1 and θ_2 represent the wheel rotations, and ω_1 and ω_2 represent their derivatives with respect to time, R is the radius of the wheels and b is half the distance between the two wheels.

In CSM, the primary objective is to superimpose the end effector (point "A") of the robot and a specified target location (point "B") simultaneously in two cameras, which guarantees coincidence of the end effector and target point in three dimensional space. Therefore, the kinematics of the system must be formulated in a way that specifies the response of target point B relative to the reference frame of the vehicle to which the cameras are attached, and are given by

$$\begin{aligned} \frac{dx_B}{dt} &= -\frac{R(\omega_1+\omega_2)}{2} + \frac{y_B R(\omega_2-\omega_1)}{2b} = g_1(x_B, y_B) \\ \frac{dy_B}{dt} &= -\frac{x_B R(\omega_2-\omega_1)}{2} = g_2(x_B, y_B) \end{aligned}$$

where (x_B, y_b) are the camera space coordinates of the target point, B in one of the cameras.

The stochastic form of these differential equations is

Figure 1. Holonomic–Nonholonomic CSM Experimental Platform.

$$\frac{dx_B}{dt} = -\frac{R(\omega_1+\omega_2)}{2} + \frac{y_B R(\omega_2-\omega_1)}{2b} + w_1(t) = g_1(x_B, y_B) + w_1(t)$$
$$\frac{dy_B}{dt} = -\frac{x_B R(\omega_2-\omega_1)}{2} + w_2(t) = g_2(x_B, y_B) + w_2(t)$$

where $[Q] = E[w(t)w(t)^T]$.

Note that, as the terrain's unmodeled variability increases, the diagonal elements of $[Q]$ should increase. Considering the purely kinematic nature of the above equations of motion, time "t" is not the best choice of independent variable. One reason for this lies with the unreasonable effect that, even as the vehicle remains stationary ($\omega_1 = \omega_2 = 0$), the diagonal elements of $[P]$ would generally grow. Much more reasonable would be a growth of uncertainty with "distance traveled". Toward this end, we recast the governing equations using "α" rather than "t" as the independent variable, where $\dot{a} = \frac{\dot{\theta}_1+\dot{\theta}_2}{2}$. Thus

$$\frac{d(\cdot)}{dt} = \frac{d(\cdot)}{d\alpha}\frac{d\alpha}{dt}$$

$$\frac{d\alpha}{dt} = \frac{v}{R} = \frac{\omega_1+\omega_2}{2}$$

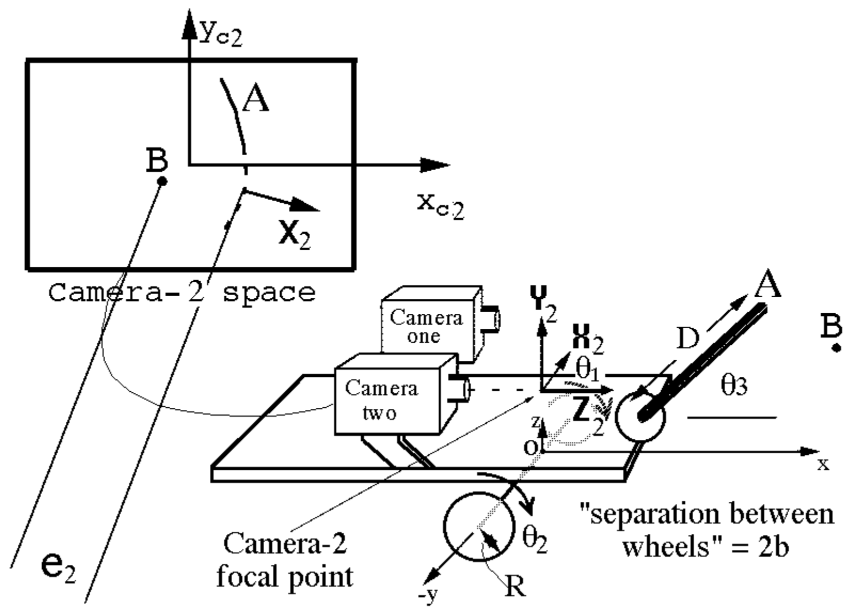

Figure 2. Physical parameters for holonomic–nonholonomic system.

where v is the speed of the point of the cart located at the midpoint between the two wheels.

The stochastic state equations become:

$$\begin{aligned} \frac{dx_B}{dt} &= -\frac{R(\omega_1+\omega_2)}{2} + \frac{y_B R(\omega_2-\omega_1)}{2b} + w_1(t) = g_1(xB, yB) + w_1(t) \\ \frac{dy_B}{dt} &= -\frac{x_B R(\omega_2-\omega_1)}{2} + w_2(t) = g_2(xB, yB) + w_2(t). \end{aligned}$$

CSM is distinct from servoing vision based robot control techniques in that it is fundamentally open–loop. A nominal trajectory is determined, which can be updated as new information from visual signals is obtained. It is important to emphasize the nature of "updated" information (occurring at discreet points in time) as opposed to a continuous feedback signal required for servoing. In CSM, robustness is obtained by means of appropriate estimation and filtering techniques that compensate for model uncertainty (including, among other things, shortcomings of idealized camera models). CSM is particularly suited for nonholonomic systems because of the limitation of feedback control for certain classes of nonholonomic systems. In fact, as shown by Brockett [2], for classes of systems (including cart–like robots), there **does not exist a smooth feedback law which asympotitically stabilizes the system to an equilibrium point.** As such, servoing techniques would have to resort to "time–varying" techniques, which generally result in oscillatory solutions for nonholonomic systems. In contrast, the open–loop nature of CSM is perfectly amenable to nonholonomic problems in that the trajectory for the system can be determined either by optimal control techniques or other simple open–loop path generation techniques.

Briefly, the control algorithm is as follows. Initially, the target location is determined in both cameras (either by use of some visual cue or a laser spot controlled by the point–and-click user interface discussed subsequently). Robustness in CSM is a result of estimating a particular set of parameters relating, in part, to the camera model for the system. Using the current estimates for these camera parameters (which may contain significant error), an estimation of the location of the target point in physical space is computed, and a trajectory for the cart to follow is computed, either via optimal control or a simple polynomial trajectory planner. As subsequent images are acquired, the estimation parameters are updated using the new information and an appropriate weighting method, and the target location in space is recomputed, along with an updated trajectory. This process is repeated until the end effector successfully engages the target location.

Using the above control methodolgy, on flat terrain the cart is currently able to repeatedly engage the target location within the $1 - -2$ mm accuracy desired by JPL. A typical engagement is illustrated in Figure 3, where the target location was in the center of the circular "cue." For scale reference, the manipulator arm has a square cross section with one inch sides.

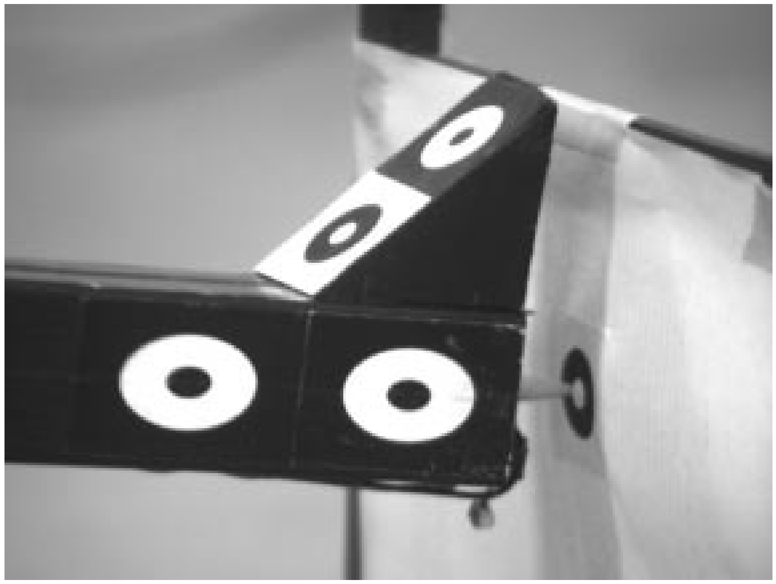

Figure 3. Typical engagement accuracy.

3 User Interface

It is important to produce a strategy for the basic Graphical–User–Interface (GUI) "point–and–click" capability. This basic capability entails presentation of the camera's image to the user on the monitor, followed by user selection of the particular pixel that represents the desired physical target for our pointer. As we have discussed, it will be important to leave an icon on the monitor, superimposed onto an image of the scene, indicating the camera–space location of the selected juncture. It will also be important to be able to read in, automatically, to the controlling program, the pixel address (x_c, y_c) of the selected target.

With the surface points of interest selected in the selection camera, a separate laser–pointer–bearing pan/tilt unit is actuated in such a way as to create laser–spot locations on or near the prescribed locations in two–dimensional selection–camera space. This is accomplished in any of a variety of ways; however it generally involves adaptive identification and use of the two–by–two Jacobian matrix of partial sensitivities of increments in camera–space spot–center coordinates to increments in pan/tilt angular coordinates. With adequate convergence of the laser–spot center onto each selection–camera point, the CSM cameras likewise detect the corresponding spot centers in their own camera–spaces thereby permitting a local mapping from selection–camera space into CSM–camera space. The current implementation has the laser pointer mounted on a fixed pan/tilt unit separate from the cart. We intend to add the laser pointer to the cart so that it moves with it in a subsequent embodiment of the system.

4 Other Potential Application

Although extraterrestrial rovers are a primary motivation of this research, the means of control described in this paper has broad application to most mixed holonomic–nonholonomic autonomous systems. Examples of potential applications include:

- automated forklifts, where a remote user can specify by simply pointing and clicking on an appropriate image, the pallet or other object for the forklift to engage;
- mining robots, where the location of the robot to remove material can be specified remotely by a supervisor;
- earth moving, construction and demolition robots, again, where points of engagement for the robot can be specified remotely via a vision system;
- etc.

Clearly, the "substance" of this technology that allows for a "one–time" specification of the target location, followed by autonomous, dextrous action by the robot lies with the theoretical aspects of CSM. Full details of this control methodology, including contrasts with visual servoing and calibration methods for vision–based robotic control, can be found in references [17, 1, 3, 21, 4, 6, 5, 11, 12, 16, 18, 19, 20, 22, 15, 8, 9, 7, 10, 13, 14].

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