A Prototype Manipulation System for Mars Rover Science Operations

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Abstract

This paper provides an overview of a new manipulation system developed for sampling and instrument placement from small autonomous mobile robots for Mars exploration. Selected out of the design space, two manipulators have been constructed and integrated into the Rocky 7 Mars rover prototype. This paper describes the design objectives and constraints for these manipulators, and presents the finished system and some results from its operation,

1 Introduction

In 1996, NASA launched the first of a series of spacecraft to revisit the planet Mars. This Pathfinder lander contains the mobile robot, Sojourner, a 12 kg six-wheeled mobile robot which will venture out from the lander, taking pictures and positioning a science instrument against designated soil and rocks.

Subsequent to this mission, there are plans to return to the surface of Mars every 26 months through 2005. Based on previous rover prototypes [3], Sojourner is designed to demonstrate the viability of mobile robot exploration of Mars. Already, longer range surface traversals with more instrumentation are planned for follow-on missions. Therefore, we are investigating next generation prototype rovers with more manipulation, mobility, autonomy, and general functionality [9].

This paper describes the dual manipulator system integrated into our latest prototype, Rocky 7, depicted in Figure 1. In the next section requirements and constraints for the manipulation system are provided, Given these bounds, Section 3 describes some of the conceptual designs developed. From these, two were chosen, and their mechanical details are provided in Section 4. Sections 5 and 6 detail servo and task level control, and Section 7 provides some experimental data from the system. Finally, Section 8 discusses some future extensions to this work.

[1] http://mpfwww.jpl.nasa.gov/

2 Requirements and Constraints

Mare mission constraints put severe restrictions on the design of rovers and their manipulation systems, Largely driven by cost factors, typical missions in consideration allow for a rover no larger than 50 kg and 0.5 cubic meters. Often a vehicle half this size is desired. Such a system should survive on the surface of Mars for several months, while traversing tens of kilometers across very rugged terrain, and collecting science data and samples. Among the tasks to be executed are:

- Digging: obtain soil samples, view soil layers, and bury a seismometer.
- Grasping: rock samples and instruments.
- Precise positioning: instruments such as spectrometers and cameras.
- High vantage-point imaging: from eye level for science reconnaissance and path planning.
- Vehicle self inspection: to check for damage or assess problems.

These tasks encompass the requirements of the system, The design of a system to accomplish them is greatly complicated

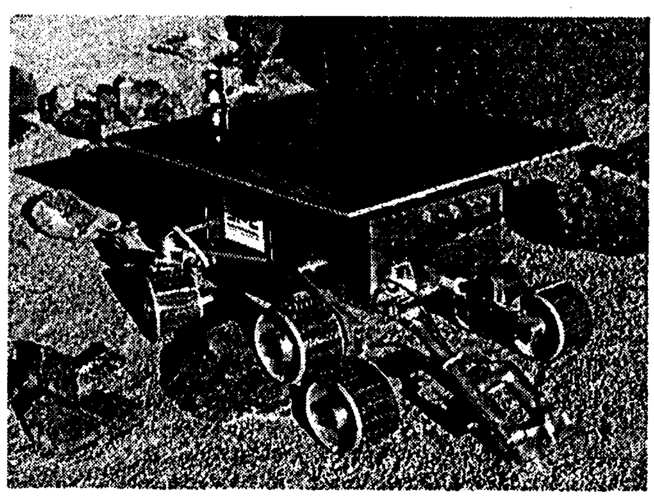

Figure 1: Rocky 7.

by the mass, power, and volume constraints on the rover. These constraints lead to a specific list of qualities that must exist in the manipulation system:

- Minimal degrees of freedom: reduced mass, power, and complexity.
- Low mass: typically less than 10% vehicle mass or about 1-3 kg.
- Compact storage: must not interfere with navigation sensing, solar power systems, or rocker-bogey mobility [1].
- High payload: carry samples and instruments on the order of the manipulator mass.
- Large workspace: minimize base motion requirements.
- Built-in versatility: enable sub-surface access and high vantage point stereo imaging, as well as dexterous and precise instrument positioning.
- Simple, robust control: for contact and non-contact mot ion.

These rigorous demands required that a new manipulation system be designed specifically for a Mars microrover. The next section will outline this design effort.

3 Design Concepts

Given the manipulation requirements for the rover system, and the constraints imposed on it, there is a greatly limited design space for manipulators. The common configuration of a six degrees-of-freedom (DOF) arm on an omnidirectional base [2, 5, 7, 4] violate many of the outlined constraints. To explore the allowed design space, a series of increasing complex manipulators have been considered, as shown in Figure 2. These arms have the following features:

(a) 2 DOF scoop

(b) 3 DOF scoop with two proximal actuators

(c) 3 DOF scoop with two distal actuators

(d) 4 DOF with scoop, flat gripper, and arched access to ground and utility tray

(e) 4 DOF with scoop, enabling front stowage, with scoop and curved gripper for instrument handling

(f) 4 DOF with scoop, flat gripper, and linear access to ground and utility tray

(g) 4 DOF for front or side stowage, with scoop and curved gripper for instrument handling

(h) 5 DOF, enabling planar access of ground, vehicle top, and horizontal utility tray.

(i) 6 DOF, enabling all but end effecter roll, and providing access to a tilted utility tray and cameras.

Rocky 7 includes two of these manipulator designs, as shown in Figure 3. The shorter sampling arm is cinematically

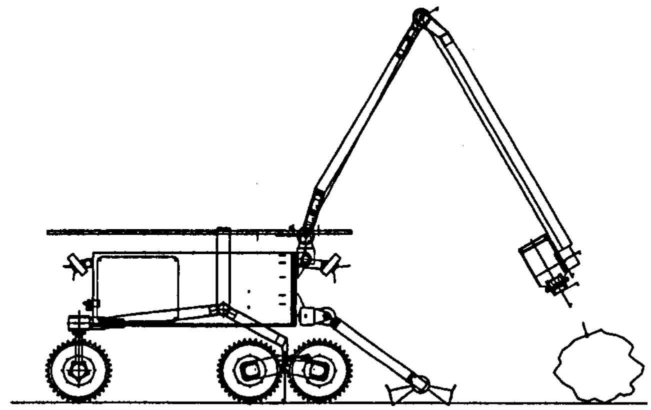

Figure 3: Selected arms for Rocky 7. The shorter arm can dig, grasp *instruments/samples,* and point a spectrometer. The *longer* arm serves as a *multispectral* stereo imaging mast, as *well as* a science instrument placement mechanism.

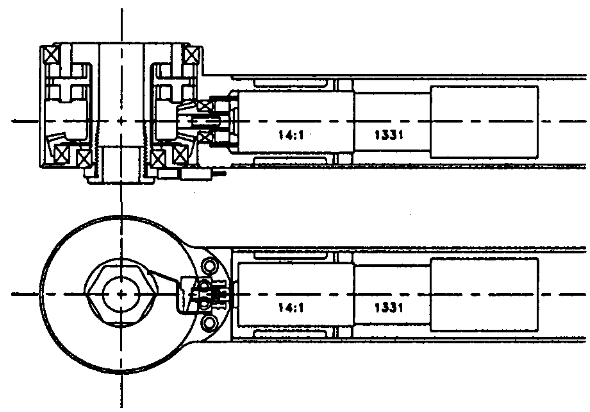

Figure 4: Modular planetary joint design

equivalent to design (e), while the longer instrument positioning arm is similar to (h). In the latter case, the scoops have been replaced with a science instrument.

4 Mechanical System

In order to create working manipulators from the chosen concepts, specific engineering solutions were required. This section outlines a new actuator design employed, as well as a detailed description of the two manipulators constructed.

4.1 Modular Joint Design

To provide compact, high-torque, backdriveable actuation for these manipulators, we have developed a new modular gearbox design which is used for all manipulator and steering DOFS on Rocky 7 [6]. As shown in Figure 4, this actuator design allows for rapid prototyping of the mechanical hardware with the following advantages over current off-the-shelf actuators:

- Allows for a wide range of gearing ratios.

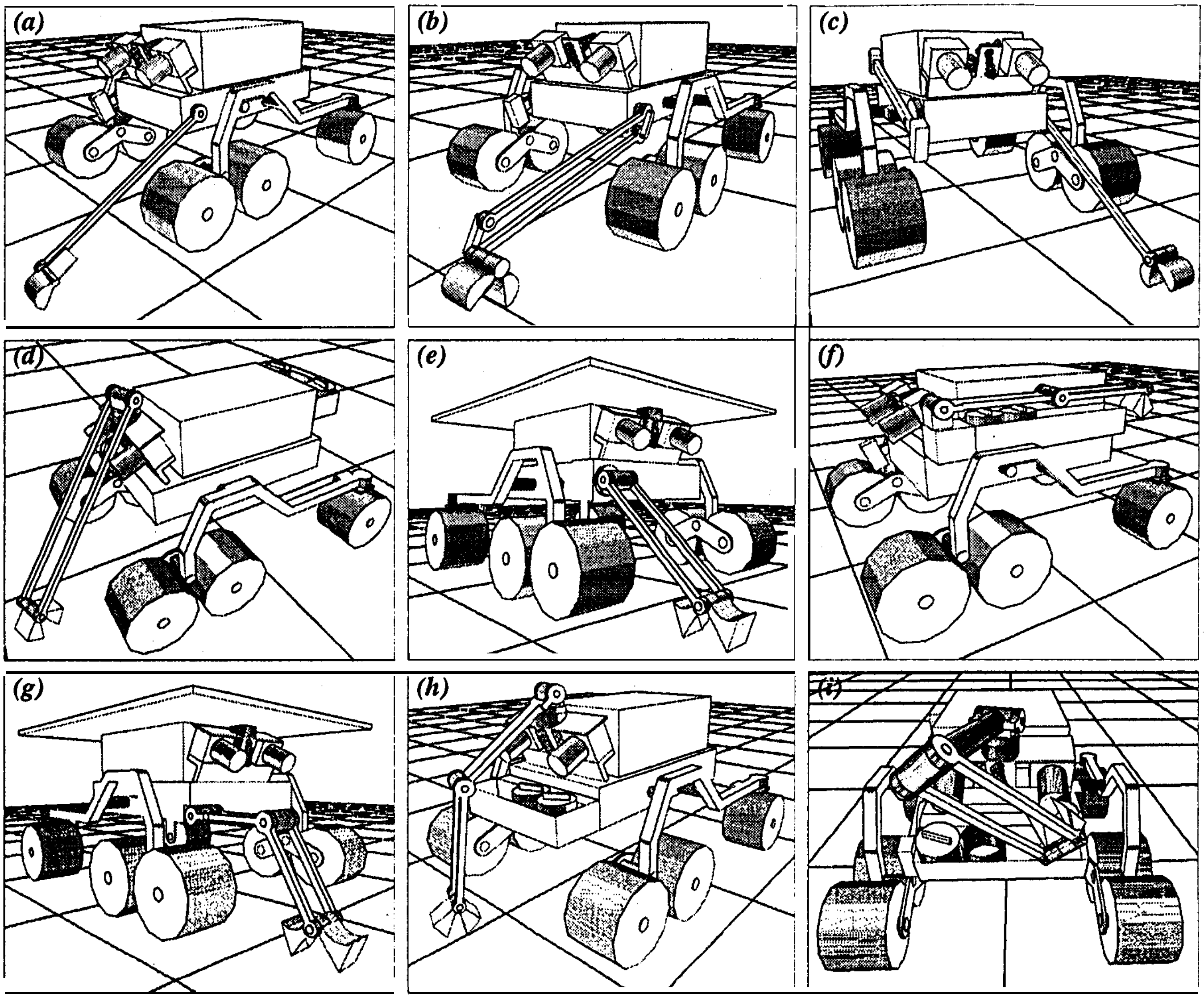

Figure 2: Rocky **7 arm** design concepts. See text for details.

- Incorporates a passageway through the axis of rotation.
- Includes an adjustable homing scheme.
- Has high torque capacity and high torque-to-weight ratio.
- Incorporates high capacity output bearings.
- Allows for easy mechanical interfaces.
- Is **backdriveable.**

On Rocky 7 these actuators have housing diameters of **3.5** cm and employ one, two, and three-stages planetary gearing to provide up to 0.86 **N.m** of output torque in a 0.15 kg package (including **motor/encoder/gearhead).** As currently configured these joints have gear ratios from 1161:1 to 7128:1, although the design can accommodate values from **50:1** to **25,000:1,** with torque capacities to match.

Two features of thie joint that are of particular value to robotics applications are its hollow axis and **backdriveability**. The former is valuable since robots typically employ serial chains of actuators, and the hollow axis allows wiring to pass through each joint without service loops. It has also proven useful on Rocky 7 for an optical pathway, as described below. The latter is valuable since **backdriveable** joints accommodate reaction forces during contact operations, enabling better sensing and control. Also, from a practical standpoint, during development the manipulator may be manually moved when unpowered.

4.2 Sampling Arm Design

Figure 5 shows three views of the sampling arm on Rocky **7**. As broadly described by the variable positions of the scoops shown in Figure 6, this arm is designed for:

- Digging to a depth of 10 cm, to enable subsurface sampling and seismometer burial. The shorter length of this arm reduces link flexing and actuator torque requirements.
- Capturing, sieving, and stowing a soil or rock sample. During stowage, the arm does not block the navigation cameras, impede the motion of the rocker-bogeys, or reduce ground clearance.
- Grasping a payload up to 1 kg while horizontally extended in Earth gravity.
- Pointing of a an aperture which is connected through an integrated optical pathway to a spectrometer housed in the vehicle chassis, as shown in Figure 7. The aperture is only open when the scoops are back to back.
- Deployment and stowage of an unactuated spectrometer calibration target by **pushing** it around the scoops' axis of rotation.

The sampling arm may be mounted to the chassis of the vehicle such that the first joint haa a horizontal or vertical axis. As shown in Figure 5, the arm is currently mounted with first axis horizontal. This configuration enables it to sweep cones about the same axis, and point the spectrometer normal to the surfaces of these cones. In this way, the arm can adjust the pointing direction to accommodate the approximately spherical shape of rocks, aa well as the available sun lighting angle. The alternate vertical axis mounting is designed to enable the end-effecter to reach an arc on the ground while keeping the scoops normal to the surface. This configuration is better suited to repeated digging operations, such as for instrument burial.

Another option immediately available to this design is the addition of an elbow, merging the design of Figure 2(e) with that of **2(g).** An elbow **would** effectively double the reach of the arm, for greater depth in digging or to enable access

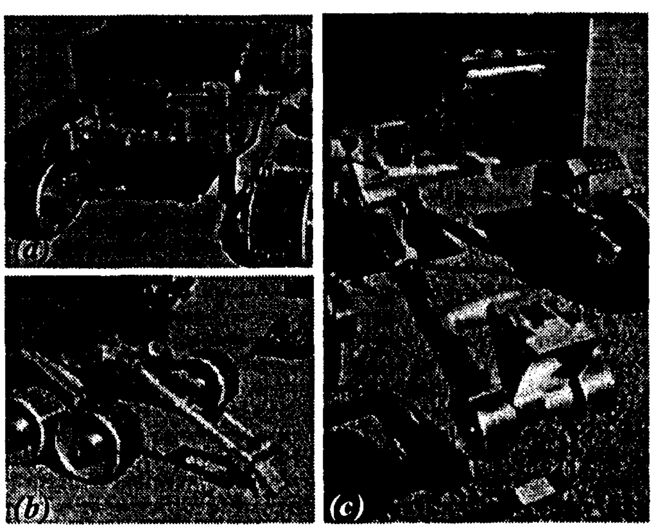

Figure **5**: Rocky 7 arm: (a) stowed position, (b) digging, ***(c)*** spectrometer pointing with calibration target ***deployed.***

above the plane of the solar panel. Since the spectrometer optical path can be augmented with that of a boroscopic imager, this upward increase in reach will allow this arm to double **as** a periscope. In lieu of demonstrating this functionality on this manipulator, we have chosen to incorporate it in a second manipulator, described next.

4.3 Instrument Positioning Arm Design

Figure 8 shows three views of the instrument positioning manipulator. This arm is also referred to as "the mast", due to the pose shown in Figure 8(c). The design hsa the following features:

- Carries an integrated sensor package ("masthead") as shown in Figure 9. The masthead has stereo cameras with counter rotating filter wheels, and an instrument canister currently outfitted with a **gimbaled** close-focus camera. The canister size and mast payload specifications (0.5 kg) are designed to allow the replacement of the close-up **imager** with a science instrument, such as a **Mossbauer** spectrometer.
- Extends to a height of 1.4 meters from ground level and rotates 360 degrees to provide panoramic imagery.
- Stows through a slot in the solar **panel.** When stowed the arm does **not** cast a shadow on the solar panel, block the

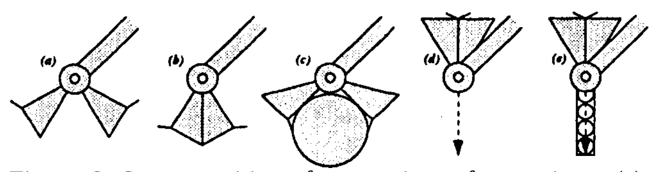

Figure 6: Scoop positions for a variety of operations: (a) digging and dumping, ***(b) sample*** enclosure, ***(c)*** instrument grasping, (d) spectrometer pointing through opened ***aper-***t ure, ***(e)*** spectrometer calibration target deployment.

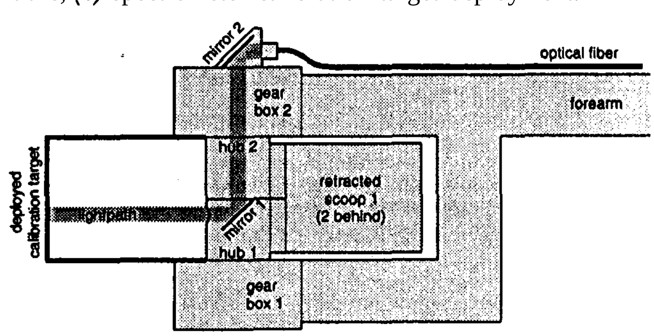

Figure 7: The ***lightpath*** for the spectrometer through the dual scoop end-effecter. The aperture in hub 1 is only open when the scoops are back to back. The calibration target is ***usually*** stowed in the inner perimeter of the forearm. When the scoops are rotated together though 360 degrees, a tab on the target support (near the hub) is caught by one of the scoops, forcing it to depJoy. A reverse motion stows the target.

navigation cameras, or impede the motion of the rocker-bogeys.

- Has a large workspace for instrument positioning on soil and rocks,
- Enables visual vehicle self-inspection from all directions,

5 Electrical System

To control the motors in the manipulators (as well as wheels) of the rover, we have developed a customized independent joint control system. While similar capability can be obtained from off-the-shelf hardware, limitations in mass, power, and volume, required the development of custom electronics.

Asshown in Figure 10, each motor is moved by a pulse-width-modulated (PWM) signal created by H-bridges that regulate battery voltage at a28 KHz duty cycle. The pulse width and polarity is governed by magnitude and sign values provided by the National Semiconductor LM629™ motor control chip. These signal values are determined from a comparison of measured motor position to reference position, and a Proportional/Integral/Derivative control law in the LM629. The reference signal, as well as preset parameters for the control law are provided by Rocky 7's CPU, through the Digital IO board in the 3UVME system. Since there are 15 copies of the motor control circuitry (one for each DOF), selection circuitry is used to connect the host to one LM629 at a time.

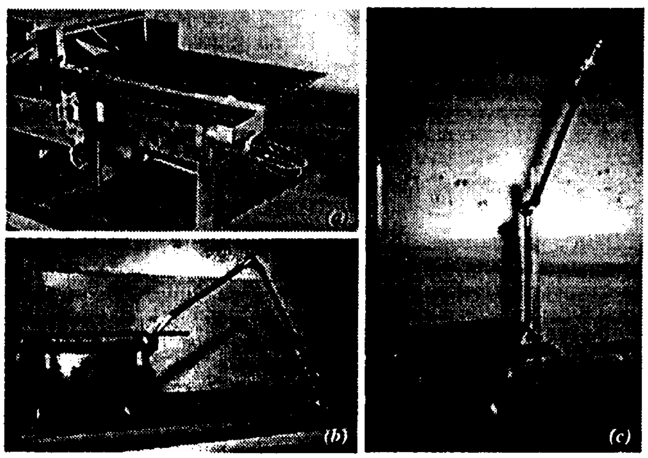

Figure 8: Rocky 7 mast attached to a mock-up chassis: (a) stowed position, (b) science instrument deployment, *(c)* panoramic image acquisition.

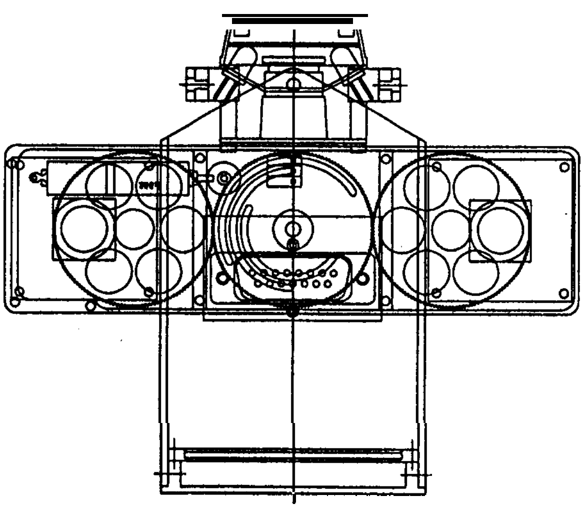

Figure 9: Rocky 7 masthead with stereo cameras, *filter* wheels, *and close-up imager* instrument canister.

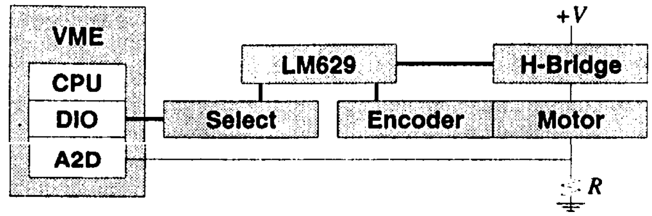

Figure 10: Block diagram *of servo* level motor control.

As a protection against high currents during motor stall, and to provide a measure of motor current, a limiting resistor has been placed in each motor circuit, The voltage drop across the resistor is also read by the host computer through an Analog to Digital converter to provide a crude measure of exerted forces.

In addition to position and current monitoring, the manipulators have switches for homing and contact. The homing switches are located on the outside of the joint gearbox shown in Figure 4, and activated by a cam on the output shaft. Contact switches are used on the end of the mast to aid in placement of the close-up imager. As shown at the top of Figure 9, three switches are located beneath a pressure plate, and activation of any causes mast motion toward the target rock to stop.

6 Task Level Control Techniques

The chosen manipulator designs introduce some important control requirements for the rover system. Unlike the lower level servo control described the last section, this section describes the higher level planning and operations issues addressed within the system,

6.1 Tethered Instrument Deployment

Typically, the arm and mast must be stowed before the rover moves. In the case of the mast, the long thin design with a relatively large payload will subject it to intolerable dynamic loading if the base moves. Also, as the vehicle tilts or turns, shading of the solar panel is inevitable. In the case of the arm, it obscures the obstacle detection capability of the stereo cameras above it, and it is subject to collision with the environment as the vehicle turns.

There is one scenario in which it is desirable to keep the arm deployed during vehicle motion: deploying a tethered instrument, such as a seismometer, from the lander. In this case, the instrument will be grasped and held away from the vehicle and wheels as far as possible, while navigation is restricted to forward motion with the steering wheels in front. Minimal turning is also needed to prevent the tether from getting caught in the vehicle wheels, as well as creating a convoluted path along which the cable will snag on a rock, After reaching a desired deployment location, the arm may drop the instrument and bury it, then stow and enable resumption of normal operation.

6.2 Arm Collision Avoidance

Before the arm is deployed to perform a dig, dump, grasp, or spectrometer read, the area immediately in front of it must be checked for clearance. This is especially true if Rocky 7 approaches a site with the arm side forward, or when there is a rotation in place just before a manipulation operation,

Using either a specified manipulation task point, or a queue of default test points, a collision check is made. This operation is performed within a concave volume with vertical sides, and a perimeter demarcated by the vehicle chassis and the swept area of the arm deploying at the task point.

If a collision will occur, the next task point on the queue is tested. If no other points exist, an error is indicated.

6.3 Surface Texture Analysis

In the case of digging, after the test is made for collision prevention, there is a second test for soil at the dig point. Currently this is a simple test that considers low texture areaa to be soil, and high texture areas to be rock. Future extensions may employ more elaborate analysis to do terrain classification. If the dig point does not pass this test, the manipulation system will begin testing a new task point for arm collision.

6.4 Image Differencing

Even after visual testing of the terrain, it is possible that the dig operation may fail to extract soil from the terrain. This is usually due to the presence of extremely hard soil or rocks. To detect this failure, imaging of the scoops is performed immediately before and after the digging procedure, A difference in the images indicates the presence of soil, meaning success. The same test is performed during dumping operations to confirm the reverse.

6.5 Joint Position Error

After each trajectory segment of the manipulation operations a check is made between the desired and measured positions of the joints of the arm. Typically errors occur in the position of the scoops due to obstructions during digging or scoop closure. This is particularly problematic for scoop closure, since it can lead to soil samples leaking out during arm stowage. Another common area of failure is jamming of the scoops against a rock during an unsuccessful dig. In each case, an error trajectory is activated to dump the scoops and stow the arm, and failure is reported.

6.6 Surface Normal Extraction

Both the visible-light spectrometer on the arm, and the close-up imager (or Mossbauer spectrometer) on the mast, benefit from being oriented in a desired configuration with respect to the surface under investigation. A perpendicular orientation is often desired, but angled configurations can be necessary. For instance, angling the visible-light spectrometer might alleviate shadowing. Since the close-up imager has a passive gimbal, utilizing a non-normal approach can reduce base motion needed for positioning the sensor.

Therefore, prior to planning the positioning of the instrument, it is valuable to have the surface position and the normal at that point. This information is extracted from the stereo image processing, and currently provided to the operator during task point selection. Autonomous task point selection using this information is under development.

7 Experimental Demonstration

Both the arm and mast are fully operational systems on the Rocky 7 Mars rover prototype. As an example of their function, Figure 11 shows the measured joint angles, angular errors, and measured currents for the arm during a digging operation.

As described elsewhere [9], all control is performed using ***Real-Time Innovations'*** ControlShell™ [8] running under the ***Wind River*** VxWorks™ real-time operating system. The trajectory shown in Figure 11 is created by transitioning through the 'dig' sequence of the 'manipulation' finite state machine. This sequence performs the following operations:

1 Unstow the arm.

2 Move to the inspection position and image the empty scoop.

3 Position one scoop downward and move to contact while monitoring joint currents.

4 Stop the arm when the large current spike is measured.

5 Back-off the arm and reposition the scoops for the dig.

6 Swing the bottom scoop through the soil.

7 Move back to the inspection position and image the full scoop.

8 Difference the images and confirm a successful dig.

9 If successful close the second scoop over the full one and stow.

10 If unsuccessful, do a safety dump of the digging scoop and stow. (This step is not shown by the data.)

Similar sequences are used for all arm and mast operations and similar trajectory data is seen.

8 Future Extensions

Since the current system is only able to store one sample in the scoops, it is not suitable for the long range Mars sample acquisition missions now being proposed by NASA. To address this problem, we intend to investigate the following additions to the system: off-board rock fracture by a spring load hammer, on-board rock crushing and separation, on-board sample transport to several discrimination sensors, and on-board packaging and containment of selected samples. Current mission plans require a single 1 kg sample cache be created, consisting of individual 10 gram rock samples packed in soil. It is likely that the sample container will be retrieved by a second rover long after the sampling rover has died, Therefore, the sample container and manipulation system must be designed to enable access from on and off board the rovers.

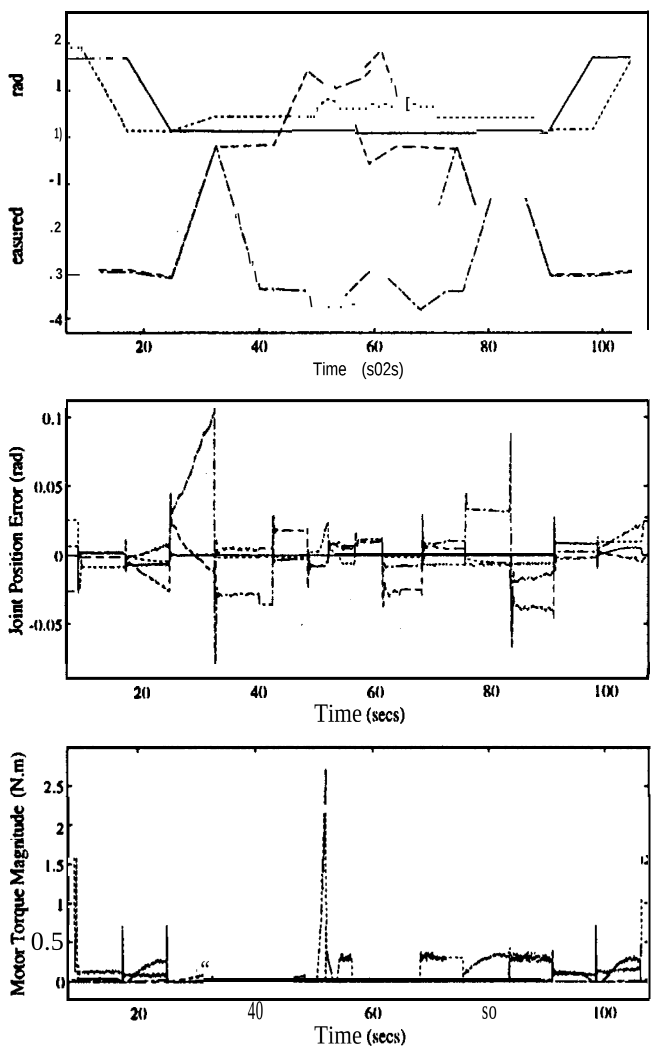

Figure 11: ***Joint angles, errors,* and *torques during* a *dig.***

9 Summary

This paper has described a new manipulation system designed for sample acquisition and instrument positioning from very small mobile robots during exploration of other planets. To satisfy two major requirements of soil/rock sampling and panoramic imaging, we have developed two types of manipulators. The first is a short arm with scoops that stows across the chassis side, and enables digging, grasping, and optical instrument pointing. The second is much longer, and acts as a camera mast for panoramic imaging. Deploying through a slot in the solar panel, its much larger workspace also enables easy science instrument placement around the vehicle, as well as self-inspection operations. This paper has provided an overview of the design considerations leading to these manipulators, as well as details of their mechanics and control. We have also discussed some task-level control issues, and provided experimental data from system use. Finally, possible future extensions to the system have been provided.

10 Acknowledgments

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