Robot manipulator technologies for planetary exploration

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ABSTRACT

NASA exploration missions to Mars, initiated by the Mars Pathfinder mission in July 1997, will continue over the next decade. The missions require challenging innovations in robot design and improvements in autonomy to meet ambitious objectives under tight budget and time constraints. The authors are developing design tools, component technologies and capabilities to address these needs for manipulation with robots for planetary exploration. The specific developments are: 1) a software analysis tool to reduce robot design iteration cycles and optimize on design solutions, 2) new piezoelectric ultrasonic motors (USM) for light-weight and high torque actuation in planetary environments, 3) use of advanced materials and structures for strong and light-weight robot arms and 4) intelligent camera-image coordinated autonomous control of robot arms for instrument placement and sample acquisition from a rover vehicle.

Keywords: Robot analysis, Ultrasonic motors, Rover-mounted manipulation, Autonomous sample acquisition, Autonomous instrument placement

1. INTRODUCTION

This paper describes the activities of the Planetary Dexterous Manipulators (PDM) task at the Jet Propulsion Laboratory in 1998. PDM is an on-going NASA telerobotics research effort to develop and demonstrate new technologies to enable or improve manipulation capabilities for planetary exploration. The target PDM space mission application is the NASA Mars Surveyor Program - a planned series of missions to explore the climate, geology, and possible biology on Mars over the next several years. Activities planned with rover vehicles on some of the missions include close-up viewing, analytic probing, instrument placement, sample exposure, and acquisition and collection. These activities require stowage and manipulation of instruments, tools and samples.

The PDM effort develops advanced algorithms, software, and hardware for lander- and rover-based manipulation with robotic arms and attached end effectors for planetary surface and near-surface exploration. PDM addresses the development and evaluation of new manipulator component and control technologies and design methodologies for reduction of mass, volume, power consumption and cost while extending the capability of dexterous robot arms consistent with planetary exploration needs. The specific path taken by PDM to achieve these goals is to design, fabricate, demonstrate and evaluate technologies for advanced and innovative implementations and applications of manipulator arms. The PDM task develops software design tools for manipulator analysis and optimization, develops component- and system-level manipulation systems and develops algorithms for intelligent autonomous sensor-guided control of manipulators for rover vehicles and landers. The areas of activity of the PDM task and their relationships are illustrated on Figure 1.

The four areas of activity in 1998 were:

- Development of robot design tools – a software package called Robot Computer Aided Analysis and Design (RCAAD) was developed to assist designers of robot arms for planetary rovers and landers to analyze and optimize their designs.

- Development of component technologies – finite-element modeling, prototype fabrication and testing of ultrasonic motors (USMs) was conducted to demonstrate their use as actuators for rovers and manipulators.
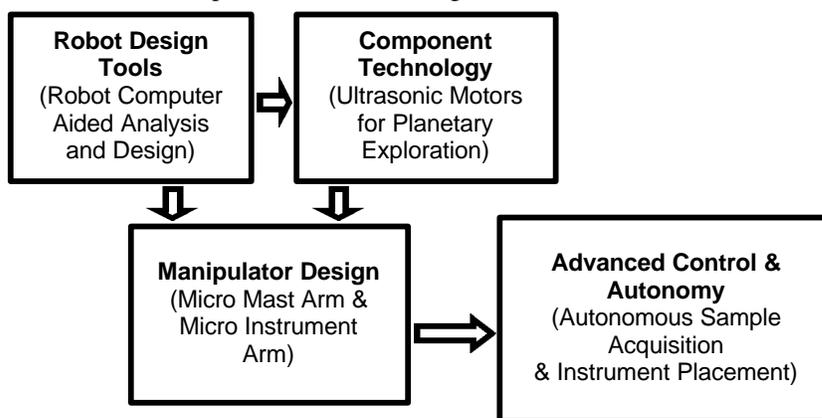

Figure 1 PDM task activities and their relationships.

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- Design, fabrication and demonstration of manipulators for planetary rovers – two robot arms were built and delivered to a rover technology integration and field demonstration project at JPL.
- Demonstration of advanced control algorithms and autonomous manipulation – autonomous acquisition of a small rock with a rover and robot arm from 1 meter away and autonomous placement of a science instrument on a target with a rover and a robot arm from 5 meters away were demonstrated.

In the following sections, we describe the specific developments and results from each of these activities.

2. ROBOT COMPUTER AIDED ANALYSIS AND DESIGN

The design of robot arms for planetary applications requires the designer to make trade-offs between many different performance criteria. These include increasing the dexterity, payload, accuracy, repeatability, stiffness and workspace of the arm, reducing its weight and power needs, and providing for efficient means of stowage, deployment and manipulation of science instruments and samples. This complex problem is usually solved sub-optimally using intuition and experience. The PDM task developed a software tool, RCAAD, to assist the designer visualize the performance of robot designs according to different criteria quickly.

There has been some work previously reported that relates to RCAAD. Low-level functions of use in the analysis of robot kinematics for the *MatlabÔ* and *MathematicaÔ* commercial packages were reported in [2] and [11] respectively. More recently, Hill [5] developed a analysis tool with goals similar to RCAAD. A related but more general system analysis and optimization tool was developed by Katragadda [6]. RCAAD runs within *MatlabÔ*, a commercial software package. When run, it displays a window on the computer monitor. The main window of RCAAD is shown on Figure 2. A pull-down menu under *File* is used for loading a previously created robot model, saving a modified or newly created model and quitting RCAAD. Items under the *Model* pull-down menu are used to create:

- the model of the robot,
- models of tools to be installed on the robot,
- a geometric model of a rover for mounting the robot arm,
- geometric objects and obstacles in the environment, and
- gravitational fields in which the analyses are to be performed.

Items under the *Analysis* pull-down menu select different analyses to be performed on the robot model. Analyses implemented in 1998 are manipulability, stiffness, accuracy & repeatability, tip force/torque to joint torque, and joint trajectory planning.

There are four panels in the display window. The top-left panel is a 3-D graphic display of the robot model and its environment. On the bottom-left is a move control panel to be used by

Figure 2 The main display window of RCAAD.

the designer to specify the posture of the robot. It includes buttons and sliders to select modes of controlling motion of the robot. The bottom-right panel is used to control the view parameters of the 3-D graphic display. The panel on the top-right changes as the user selects different analyses to perform on the robot model. Each analysis has its own unique set of buttons, sliders, etc. that are used to perform its functions. In RCAAD, the designer creates a model of the robot design by specifying the geometry, material properties and sensors for the robot arm. The parameters entered are visualized as in a 3-D graphic display as component links of the robot arm are created.
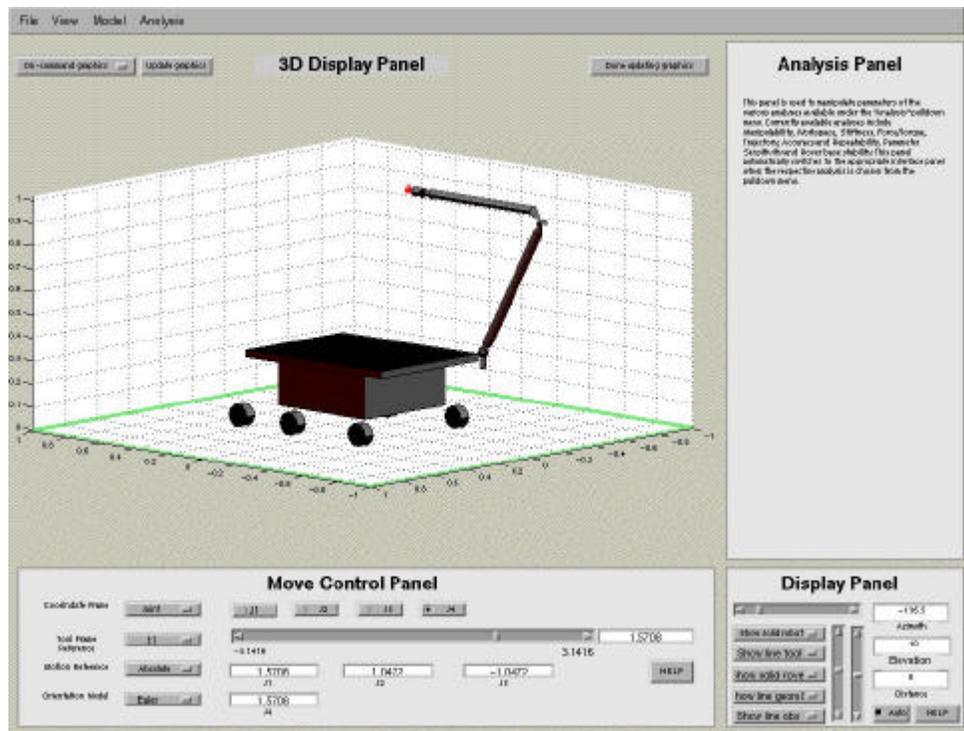
The model of the robot may be specified using either the Denavit-Hartenberg [3] notation or with detail geometric, material and sensor parameters for the links and joints. The display corresponding to the Denavit-Hartenberg (D-H) model is a stick-figure of the robot. A 3-D solid model is displayed if the detail information is entered instead. The models shown on Figure 3 illustrate the 2 displays. The robot model is created by specifying the parameters for each of its links. A link edit form – a window that pops-up when a new link is to be created or a previously defined link is to be modified – has edit boxes for the parameters of the link. The edit form can display a graphic preview of the link to confirm the values entered. Similarly, parameters for tools to be mounted on the robot, components of the rover, obstacles and geometric constraints in the environment can also be created, modified or deleted.
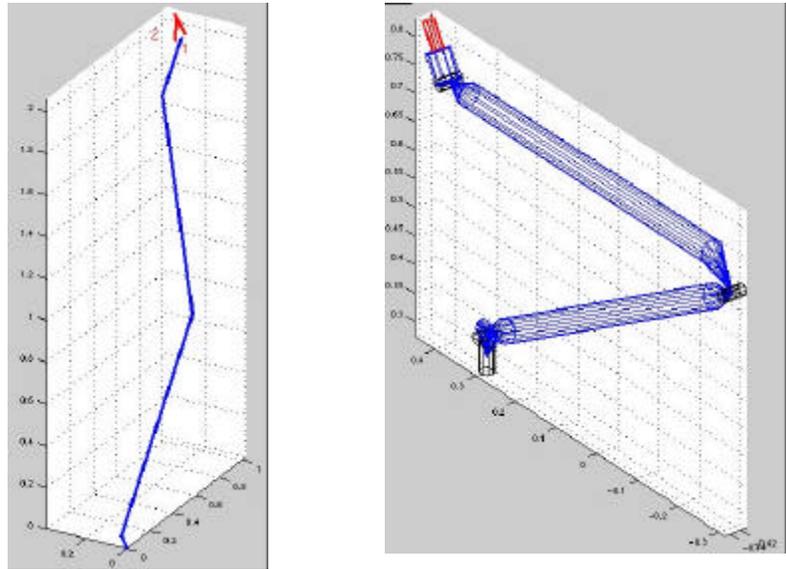
Figure 3 3-D gaphic of robot with D-H parameters (left) and detail geometric .parameters (right).

Once the robot is defined, its configuration can be specified by entering its joint angles or the position and orientation of a selected tool mounted on the robot. The configuration can be entered as absolute position of the respective parameters or relative positions with respect to the current position. This is done with the *Move* panel. The display panel is used to specify the view of the 3-D display of the robot and its environment. RCAAD can automatically determine the view to display. However, the user can specify the elevation, azimuth and zoom settings of the display manually.

The analyses currently implemented in RCAAD are manipulability, stiffness, accuracy & repeatability, tip force/torque to joint torque, and joint trajectory planning of the robot model. The analysis to be performed is selected by picking it out from the *Analysis* pull-down menu. The selected analysis has a corresponding unique panel display that appears on the tip right of the RCAAD window. For example,
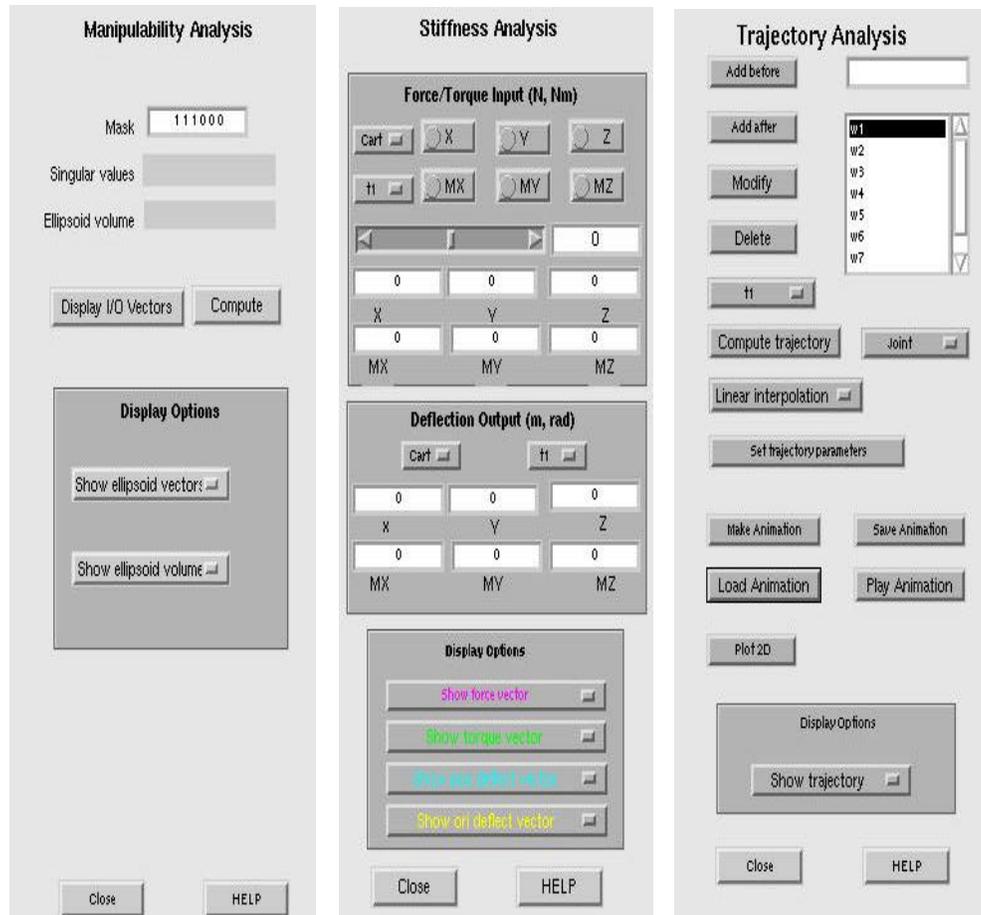

Figure 4 Manipulability (left), stiffness (middle) and trajectory (right) analyses panels.

the stiffness analysis panel has buttons, sliders and edit boxes for specifying the force and torque on a specified tool and for displaying the resulting deflection due to the applied force and torque and gravity acting on the tools and the links of the robot arm. The applied force and torque vectors are graphically displayed on the 3-D model of the robot as are the resulting position and orientation deflection.
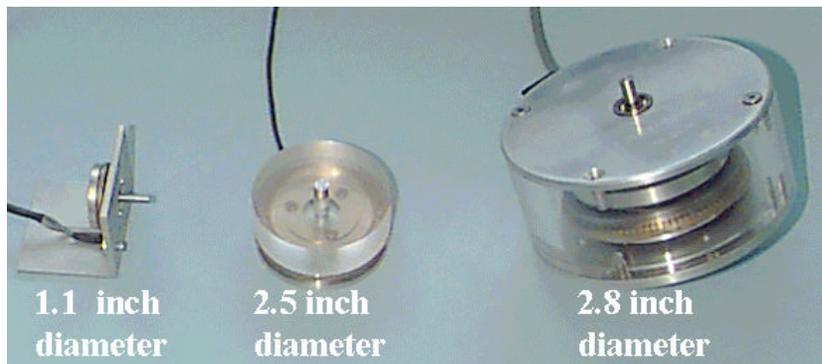
3.   ULTRASONIC MOTORS

Efficient miniature actuators that are compact and consume low power are needed to meet the NASA needs of future missions. Ultrasonic rotary motors are an emerging actuation technology that offer compact, light motors with many advantages for robotic applications including self-braking. These motors have high torque density at low speed, high holding torque, simple construction, can be made in annular shape (for optical application, electronic packaging and wiring through the center), and have a quick response. To assure the compliance of this materials with the harsh and demanding space applications, rigorous analytical tools as well as adequate attention are need to determine the effect of extreme temperatures and vacuum [1]. Generally, ultrasonic motors can be classified by their mode of operation (static or resonant), type of motion (rotary or linear) and shape of implementation (beam, rod, disk, etc.). Despite the distinctions, the fundamental principles of solid-state actuation tie them together: microscopic material deformations (usually associated with piezoelectric materials) are amplified through either quasi-static mechanical or dynamic/resonant means. Obtaining the levels of torque-speed characteristics of USMs using conventional motors requires adding a gear system to reduce the speed, thus increasing the size, mass and complexity of the drive mechanism. The emphasis of the current efforts is on rotary type motors. In Figure 5 the principle of operation of an ultrasonic motor (flexural traveling wave ring-type motor) is shown. A traveling wave is established over the stator surface, which behaves as an elastic ring, and produces elliptical motion at the interface with the rotor. This elliptical motion of the contact surface propels the rotor and the drive-shaft connected to it. Teeth on the top section of the stator are intended to form a moment arm to amplify the speed.   The operation of USM depends on friction at the interface between the moving rotor and stator, which is a key issue in the design of this interface for extended lifetime.
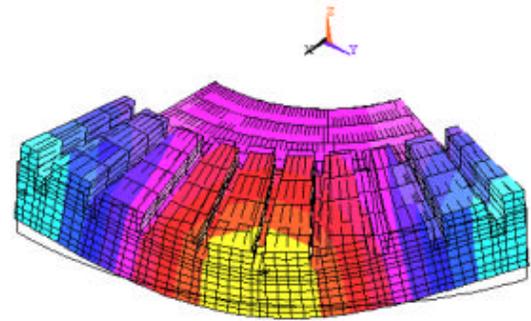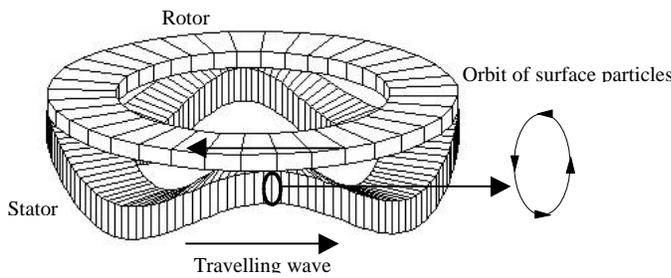
Figure 5 Principle of operation of a rotary travelling wave motor.

**Figure 6** A segment of a 3d finite element model of a USM stator showing two stages.

Recently, a 3-D finite element analytical modeling was developed to examine the excitation of flexural plate wave traveling in a rotary piezoelectrically actuated motor (Figure 6). The model was used to predict the excitation frequency and modal response and it incorporates the details of the stator, which include the teeth, piezoelectric crystals, stator geometry, etc. The theoretical predictions were corroborated experimentally for the stator. Parallel to this effort, USMs are made jointly with QMI (Costa Mesa, CA) and they are incorporated into the robotic arms as well as being programmed for computer control. Examples of the motors that were developed jointly with QMI are shown in Figure 7.   The different diameters allow various torque-speed levels.   In addition, the effects of low temperatures and vacuum were investigated it was shown that a motor with a novel actuation can be operated at temperatures as low as -150°C and 16-mTorr pressure (see Figure 8).

Figure 7 Three sizes of ultrasonic motors that were made using flexural traveling wave as a drive mechanism.

Also, a USM that was tested in thermal cycles of 0 to -90°C over a period of 210 cycle did not show any significant change in performance. The use of segmented ring for the actuation of the motor showed a significant improvement in the longevity of the motor with about 6 time longer durability as compared to a continuous ring drive. Currently, issues associated to the interface, longevity, efficiency and miniaturization are being studied.
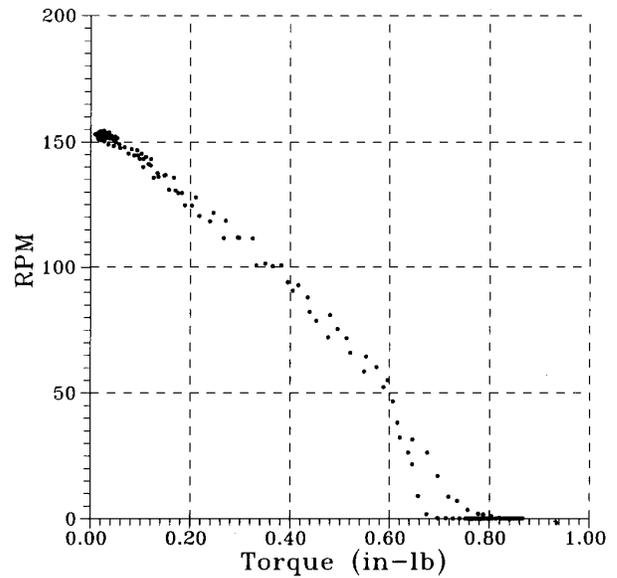

Figure 8 Torque-speed performance of a JPL/QMI USM subjected to 150°C and 16 mTorr.

4. MICRO MANIPULATORS FOR PLANETARY ROVERS

The PDM task designed two robot arms for the Exploration Technology (ET) Rover task, a collaborating rover technology integration and demonstration effort at JPL. The ET Rover Task will perform integration of new technology and field tests on a prototype vehicle to demonstrate concepts for the Mars `03/`05 rover missions. The specifications for the Mars `03/`05 rover require it to have an instrument carrying robot arm to deploy and place up to four science instruments against soil and rock samples for analysis and a mast-like arm for panoramic viewing and self-inspection. The arms developed by the PDM task towards these specifications are the Micro Instrument Arm (MIA) and the Micro Mast Arm (MMA).

The approach taken with the design of the two robot arms was to share as much as much as possible in their components. Consequently, there are a number of similarities between the two arms. They both have four degrees of freedom (DOF) – a shoulder yaw joint, a shoulder pitch joint, an elbow pitch joint and a wrist pitch joint. The joints are all fabricated of aluminum. The links between the shoulder and elbow and the elbow and wrist are a 1.5 inch diameter graphite-epoxy tubes.

The elbow joint configurations, however, of the arms are different. The two tubular links of the Micro Instrument Arm are side-by-side in the stowed configuration while they are one-above-the-other in the MMA. Two distinct types of joint designs are used throughout each system. The first is a yoke and clevis
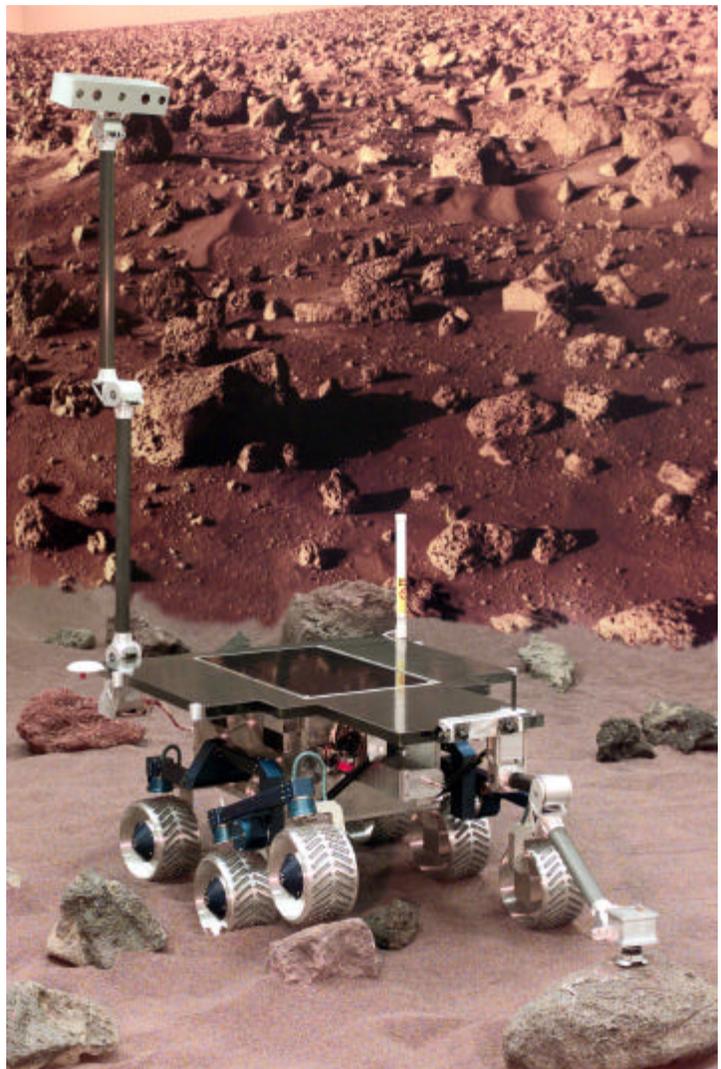
Figure 9 Micro Instrument Arm (front middle) and Micro Mast Arm (back left) mounted on the ET

joint. This joint consists of a stationary clevis, which houses the actuator and gear train, and a yoke, which surrounds the clevis on both sides and provides the output of the joint. The second joint configuration is an internal stator arrangement. In this configuration, the stator hardware remains on the interior of the joint, while the rotor output rides on the outside. The yoke and clevis joint was used on the shoulder, elbow, and wrist pitch joints of the MMA as well as the shoulder and wrist pitch joints of the MIA. The internal stator arrangement was used in the shoulder yaw joint of both arms as well as the elbow pitch joint of the by the PDM task MIA.

Joint angle sensing on all joints of the two arms is with potentiometers and magnetic encoders. For both arms, the gear ratios of the shoulder yaw joints are 6600:1, shoulder pitch joints are 19800:1, elbow pitch joints are 19800:1 and on the wrist joints are 6600:1. The joints were designed to allow for the internal routing of up to fifty-five 26AVG teflon insulated cables. The MIA weighs 2.35kg. and the MMA weighs 2.42kg. The load carrying capacity of the arms is 20 Newtons for the MIA and 10 Newtons for the MMA.

These designs are the result of previous experience from the design of robot arms for rover vehicles [12,13] and of new innovations made to increase performance and meet tight design specifications. The use of harmonic drives in the joint gear reduction, the implementation of internal cable routing, the use of graphite-epoxy tubular links and the arm joint configuration are legacies of the Micro Arm I and Micro Arm II designs developed at JPL. The concept of a mast arm on a rover for panoramic viewing and self-inspection was first demonstrated on the Rocky 7 rover [15]. Innovations implemented in the MIA and MMA are:
- greater mechanical robustness needed for rugged field testing,
- increased range of motions on the joints and corresponding increased workspace,
- greater capacity for internal cable routing,
- incorporating hard stops on the joints range limits,
- increased payload capacity, and
- modular joints and corresponding cable layout for ease of disassembly and repair.

The mounting of the MIA and the MMA on the ET Rover is shown on Figure 9.The MIA is mounted on the front of the rover under its solar panel. It stows under the panel and deploys to reach beyond the panel as shown on Figure 9. The MMA is mounted on the rear side corner of the solar panel and it stows along the back edge of the solar panel. It deploys vertically above the corner of the solar panel and reaches a height of 1.9 meters.

5. AUTONOMOUS SAMPLE ACQUISITION AND INSTRUMENT PLACEMENT

The PDM task also developed algorithms for autonomous sample acquisition and science instrument placement in 1998. The demonstrations performed were the acquisition of a small rock sample designated by an operator autonomously from one meter away using the Rocky 7 rover and the placement of a science instrument on a target designated by the operator autonomously from five meters away. These capabilities enable a rover-manipulator system to perform science operations with minimal input from the operator. In the Mars planetary exploration scenario, each command cycle between the Earth and the rover on Mars occurs over one Mars *sol* – the equivalent of approximately an Earth day. Reducing the number of command cycles required to perform science operations can greatly increase the accomplishments of the mission.

Related developments in visual guided manipulation reported for similar applications includes work at MIT [14] and at the NASA Ames Research Center [16]. The algorithms we developed use stereo processing algorithms developed by Matthies and colleagues[8,9]. The advances made in our implementation of the sample acquisition and instrument placement capabilities are modeling the operation on a realistic mission scenario[*], performing all the autonomous computation on-board the rover and performing the operations in relatively fast times.

The approach taken in the development of the autonomous manipulation capabilities in the PDM task was to design and implement a control architecture to support high-speed visual guidance. The implementation of the capability addressed only the demonstration of the autonomous behavior without considering other high-level functions of a planetary rover, for example, obstacle avoidance or navigation functions. The sensory inputs used to perform the autonomous operations were limited to those available on most rover platforms, i.e. odometry and black & white stereo vision. The portable, extendible and re-useable object-oriented algorithms were designed to be easily ported to other platforms. The demonstration was

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[*] Sensors available on Mars rover missions include B&W cameras mounted on the rover and wheel odometry. The data is of poor quality due to noise and wheel slippage.

successfully implemented on the Rocky 7 rover (see Figure 10). This development is retorted in greater detail in [7] and [10]. Rocky 7 was developed at JPL as a technology demonstration platform for future NASA Mars planetary exploration missions [4].

The features of the development are:
- No assumptions were made that would prevent the use of the algorithms on NASA's planned Mars rover missions to explore the planet Mars.
- On-board cameras were used for vision.
- Noisy odometry was used for traverse estimates.
- The target location and an intensity threshold from one camera image are the inputs needed.
- Target designation can take place from anywhere in the world because the image and target positions are communicated via a TCP (Internet) link.
- The autonomous software is all on-board the rover.
- The algorithm does not require a continuous view of the target.

Figure 10 The Rocky 7 rover completing the small rock acquisition (left) and the science instrument placement (right) procedure.

The algorithms successfully demonstrated autonomous sample acquisition and instrument placement using the Rocky 7 rover platform at operator designated targets from one meter and five meters away respectively.

6. CONCLUSION

These innovations extend the capabilities of robotic systems for a wide range of planetary exploration environments. The activities reported above are continuing in 1999. The modeling of joint backlash will be included in the analyses performed in RCAAD. Improved and faster 3-D visualization is also planned to provide real-time graphic updates of the robot models and their environments. Analysis of lander or rover tilting from forces exerted during manipulation will be found. This feature of RCAAD is expected to assist in the mission operations of the MVACS manipulator arm on the Mars `98 lander mission.

Our USM development will analytically and experimentally study the effects on operation longevity, variance in behavior and the effect of vertical and tangential mechanical loads on USM performance. A finite-element model of the rotor-stator interface and a miniaturized electronic driver and compact ultrasonic motor will be developed.

Replicas of the MMA and MIA robots will be installed on a rover mock-up. A control system for the arms will be developed and research will be conducted into coordinated control of the arms to improve robustness and functionality. The autonomous sample acquisition algorithm developed in 1998 will be extended to acquiring up to 3 samples autonomously from targets designated by the operator from 1 meter away. One technology advance needed to enable this capability is a robust visual odometry system for recovering the location of targets after loss of their view in the camera images.

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