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SAMPLE ACQUISITION & INSTRUMENT DEPLOYMENT

(SAID)

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Perpared By:

Robert C. Boyd
SAID Program Investigator
Martin Marietta Astronautics
Payloads Sensors and Instruments

Prepared for:

Headquarters
National Aeronautics and Space Administration
Washington, DC

Prepared by:

Martin Marietta Astronautics
Payloads Sensors and Instruments
P.O. Box 179
Denver, Co. 80201

FOREWORD

This document was prepared in accordance with the requirements of NASA Contract NASW-4818, Section F.6(a), Annual Progress Report.

Introduction

This report details the interim progress for contract NASW-4818, Sample Acquisition and Instrument Deployment (SAID), a robotic system for deploying science instruments and acquiring samples for analysis. The system is being developed on the Planetary Instrument Definition and Development Program (PIDDP). The progress reported is for the period October 1993 through November 1994, the first year of contract effort. Significant progress has been made in the following areas:

- Systems Design:
  A baseline design has been achieved through analysis and trade studies of position sensors, motors, gear trains, brakes, shape memory alloys. The design considers environmental operating conditions on the surface of Mars, as well as volume constraints on proposed Mars Landers. Control issues have also been studied, and simulations of joint and tip movements have been performed.
- Wrist Development:
  A passively braked shape memory actuator with the ability to measure load has been developed. The wrist also contains a mechanism which locks the lid output to the bucket so that objects can be grasped and released.
- Wrist Testing:
  The wrist actuator has been tested for operational power and mechanical functionality at Mars environmental conditions. The torque which the actuator can produce has been measure. Also, testing in Mars analogous soils has been performed.

Systems Design

The most significant future opportunities for a sample acquisition and instrument deployment system are missions to the surface of Mars, although Lunar mission may also find the system beneficial. Design of the SAID system would take Mars environment factors into consideration, and draw on past studies, scheduled and proposed missions to the surface of Mars for functional requirements.

The surface of Mars is cold with equatorial temperature ranging from 205-225°K and polar temperatures of 200°K day time and 150°K for polar night time. The mean surface pressure is 6.1 mb, with a composition of 95% CO_2. Mars is generally 20 times dustier than Earth with global and local dust storms. Dust storms are estimated to raise the number of dust particles/cm^3 in the atmosphere near the surface to ~30 from a typical value of ~2.

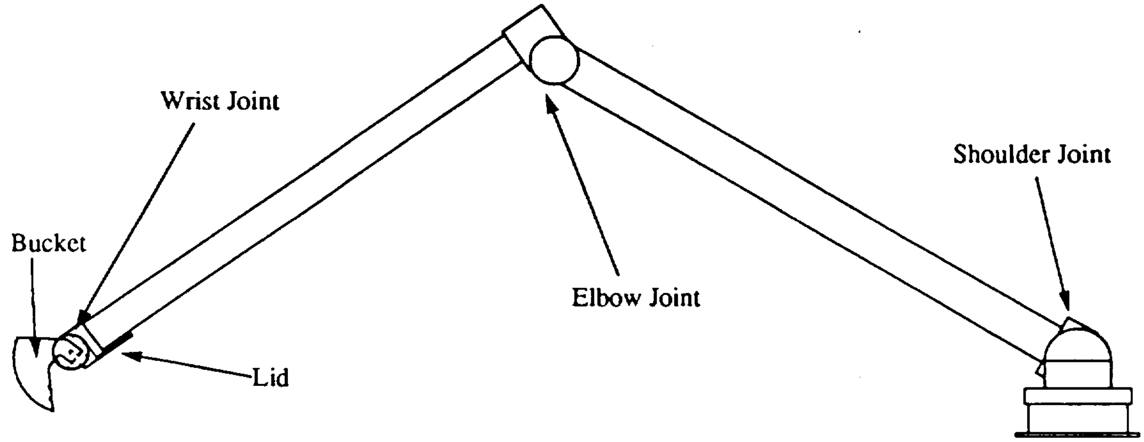


Figure 1 SAID System is a conventional arm with 4 degrees of freedom, and 2 meter length

The SAID system design is intended to satisfy requirements for operation from a MESUR Pathfinder type of lander, where the shoulder is mounted close to the ground. The first limb of arm extends upward and out from the shoulder 1 meter (see Fig. 1). The second limb connected by the elbow joint reaches back downward 1 meter, allowing the manipulator to reach over objects. This conventional arm style is generally heavier than the SCARA arm configuration which does not have the ability to reach over objects. The conventional arm can also be operated from an elevated shoulder position such as a Viking style lander or Mars rover. Stowage configurations and volumes for SAID onboard a MESUR Pathfinder type lander have been checked and approved by the Mars Polar Pathfinder Proposal Team.

Torque and positioning requirements for the SAID system have been driven by mass estimates of various instruments which have been proposed, and estimates of the Martian soil properties and the forces needed to dig in them effectively. Instruments benefiting from a SAID manipulator are listed below.

Instruments Requiring Soil Samples	Instruments Which Can Be Deployed
Differential Thermal Analyzer (DTA)	Alpha Proton X-ray Fluorescence (APX)
Thermal Evolved Gas Analyzer (TEGA)	Seismometer
X-ray Fluorescence (XRF)	Ground Penetrating Radar antenna (GPR)
Mars Aqueous Chemistry (MACE)	Camera, Stereo or Multispectral
X-ray Diffraction (XRD)	Rock drill, grinder or chipper

Selection of Upper-Arm Actuators

The nature and configuration of the drive systems of the various joints is fundamental to the capability of the arm. Operation in the cold Martian atmosphere plays a fundamental roll in the selection of actuators for the various joints.

For most 3 of the 4 degree's of freedom DC brushless motors with large gear reduction ratios of ~1000:1 seem to best fulfill the torque and positioning requirement. However, operation in the cold environment presents a problem for the gear reduction.

Unlike the bucket, the upper arm (i.e., the shoulder through the elbow) requires coordinated motion of three joints and relatively large torques, especially when an instrument is being carried at the end of the extended arm. Torques up to approximately 24 N-m (18 ft-lb_f) are required at the shoulder pitch joint and up to 11 N-m (8 ft-lb_f) at the elbow pitch joint to accelerate a 0.75 kg (1.7 lb) instrument upward in Martian gravity. Speed of motion is not a large issue. Baseline goals are for motion up to about 1.25 cm/s (0.5 in/s).

A variety of actuators can satisfy these requirements, but they differ in cost, size, weight, efficiency, compatibility with the Martian polar environment, and other relevant factors. Actuators commonly used in robotics and related applications include brushless and brush-type dc motors, ac motors, stepper motors, linear and rotary hydraulic actuators. Table 2 summarizes how these actuators compare in satisfying several evaluation criteria.

Table 2 - Actuator Selection Trade off Table.

Criterion	Weight	Brushless DC	Brush-type DC	AC	Step Motor	Linear Hydraulic	Rotary Hydraulic
Cost, Including Drive Elec.	10	7	10	5	10	3	3
Weight and Size, Including Drive Elec.	9	6	7	5	10	2	2
Life and Environment Compatibility	8	7	5	10	10	1	1
Power Consumption / Efficiency	6	10	10	7	5	5	5
Ease of Use in Feedback Control	4	10	10	7	6	3	5
Weighted Total Score		280	303	245	324	98	106

The cost of the drive circuitry was also considered, and for one-of-a-kind flight hardware, the cost of such circuitry is dominated by engineering costs, which varies with circuit complexity. The stepper motor's drive circuitry is hard to beat for simplicity, as it requires only computer-controlled switches. Brush-type dc motors can be just about as simple if pulse-width modulation is used. Their drive circuitry needs a pulse-width modulator but only half the number of switches. A brushless dc motor requires 50% more switches than a brush-type motor with pulse-width modulation, and commutation circuitry must be added, so the drive electronics becomes more expensive. In addition, the Hall-effect sensors usually used for commutation can be expected to increase the cost. The ac motor requires an ac source, which increases the cost of the drive electronics. Also, pulse-width modulation schemes are not attractive with ac motors, so there is the added cost of the circuitry to vary the ac voltage in response to computer command. These factors dominate over the difference in cost of the motor itself. While hydraulic actuators need not be expensive, they require voltage-controlled or motor-operated valves and a hydraulic pumps with their own motors, which greatly reduces their attractiveness.

Size and weight similarly favor the stepper motor, and for similar reasons. The support circuitry is minimal, so drive circuitry does not add much to the total weight.

AC and stepper motors were rated highest for life and environmental compatibility because they are rugged, contain no temperature-sensitive electronic parts, and have no contacts to wear out or get contaminated. The brushless dc motor has Hall-effect sensors whose operating temperature range may require some thermal control. Brush-type dc motors are subject to brush wear and contact contamination. Their life would be adversely affected by dust. Hydraulic actuators are least compatible. Normal hydraulic fluids are not suitable for the extreme cold, which also makes selection of suitable hoses or tubing difficult.

In power consumption and efficiency, dc motors perform well. However, the way the actuators are used has more to do with their overall efficiency than their inherent properties. For example, the assumption used in evaluating dc motors was that they would be used in a linear feedback control scheme employing pulse-width modulation of motor voltage, whereas steppers would be used for open-loop control. The feedback reduces drive to the dc motor to just what is required, whereas the stepper, operating open loop, gets full drive voltage at all times. This results in the stepper's being rated somewhat lower in efficiency.

Ease of use in feedback control was the last and least important evaluation criterion. Feedback control is desirable but not essential for producing accurate motion control. For this, dc motors are nearly ideal, as their output torque is readily varied with pulse-width modulation and their response is very nearly linear. For ac motors, continuous control requires more complex circuitry, and response is not generally as linear. Rotary hydraulic actuators can be made to have linear response, but the cost and complexity of driving the valves makes them less attractive. Steppers could, in principal, be used for linear feedback control but are most suitable for open-loop operation. Linear hydraulic actuators (pistons) have the disadvantages of their rotary cousins plus the problem of joint torque variation with joint angle due to the changing moment arm.

Although the precise-looking numerical results in the table reflect relatively imprecise subjective evaluations, the overall advantage of stepper motors for this application appears clear. One additional concern not mentioned is the gear reduction required for steppers vs. brushless DC motors. The stepper motors natural speed of rotation is at least 10 times slower then the brushless DC motors which makes achieving the necessary speeds of motion possible without providing gear reduction beyond what is required for achieving the needed torques.

In using steppers, it should be taken as a fact of life that steps will be missed. This means that control based purely on counting of steps of a stepper motor will eventually get "off track," so some form of absolute joint-angle sensing is required to provide periodic corrections for missed steps.

Of course actuators using feedback control would also require these sensors, the point to be noted here is that use of stepper motors does not eliminate the need for them as it might at first appear.

Shape Memory Actuators

The shape memory actuator provides torque to a joint from the force of the shape memory muscle's contraction much like the muscles in a human arm. The muscle is composed of a number of strands of shape memory wire (NiTiCu Alloy) secured at each end mechanically and electrically. When power is applied the wires heat up; once their phase change temperature is reached (70°C-120°C depending on load) they undergo martensitic transformation, contracting about 3% of their length. When power is then removed the wires cool below their phase change temperature and return to their original length. At the joint end of the muscle a pulley is attached which is used as a turnbuckle to double the length which the muscle can pull. One end of the cable looped through the turnbuckle is attached to the hub to provide rotary motion; and the other end is attached to a rap spring brake trigger. When the muscle begins pulling the force on the rap spring trigger removes the braking force allowing the hub to rotate in one direction. Once the brake is release and the rap spring trigger contacts it's stop, all of the force of the muscle is transferred into the hub. Two muscles and two rap spring brakes are required for rotary motion in both directions. Also it is necessary for the working muscle to reload the other muscle to it's prestrained condition. The phase change occurs slowly enough in a multistrand muscle that the speed of the rotary motion is at a controllable level.

Shape memory metal rotary actuators developed and tested at Martin Marietta have several advantages over motor/gear drives for this application: 1) lower mass 2) no gears 3) no lubricants 4) tolerant to dust contamination 5) operates at very low temperatures 6) simple drive electronics. Disadvantages include: 1) power consumption 2) positioning control 3) volume consumed by ~80 cm muscle length.

The advantages for shape memory metal in this application are significant. The high power consumption and poor positioning control eliminate this type of actuator for use in the shoulder or elbow joints, where high torque's and accurate positioning are required. However, the wrist pitch joint requires much smaller torque's which can be achieved with reasonable power budgets. Also, positioning requirements for the wrist pitch joint are less severe, ($\pm 1^\circ$ - wrist vs. $\pm 0.1^\circ$ - shoulder) which we believe to be feasible with the shape memory actuator. The volume for the muscle length can be accommodated in the forearm link of the arm which will be constructed of a 6 cm diameter composite tube approximately 100 cm long.

Gear Reduction

To satisfy torque and positioning requirements for the upper arm joints a large gear reduction of ~1000:1 will be required. Gear-trains being considered include spur, planetary, worm and harmonic gear sets. Planetary gears are the least compliant but have the greatest mass. Worm gear systems sized for this application have less than half the mass of planetary gears but have an order of magnitude greater backlash and compliance which would make it difficult at best to obtain the desired positioning abilities of the upper arm. Spur gears and harmonic gears are the best choice for this application. The highest ratio available in harmonic gear sets is 160:1. To reach the ~1000:1 reduction desired a spur gear with a reduction ratio of ~8:1 would be used for the input to the harmonic drive. The harmonic drive with the input spur gears and appropriate bearings saves more than 400g over a comparable drive using only spur gears. The difficulty with harmonic drives is in satisfying lubrication requirements at very cold temperatures while holding the efficiency to an acceptable level. It may be necessary to actively heat the drive before operation at temperatures below -10°C. We are studying alternative lubricating techniques for the harmonic drives which will produce greater efficiencies at the cold temperatures, and hopefully eliminate the need for any active heating. We are confident that harmonic drives with small spur gear reductions on the input side will produce the most functional drive system for the upper arm joints.

Drive System Design

After studying various drive systems for this application a hybrid arm seemed to make the best use of the advantages of the various types of drives while minimizing their disadvantages. Stepper motors with harmonic gear sets can best supply the high torque and tight positioning accuracy needed for the upper arm joints (elbow and shoulder). Motors will be 45°, bi-polar driven steppers to provide the maximum torque possible at low pulse rates and minimize wiring to the motors. Gear-trains have been selected to provide the necessary torque's and also to provide a step resolution which results in tip positioning of 1.3 - 1.1 mm with the arm fully extended. Shape memory muscles can save mass and best tolerate the cold and dusty environment, and will be used for the wrist actuator. 1° of motion at the wrist joint results in 1.6 mm at the tip in accuracy which we believe to be achievable with a shape memory actuator. Table 3 details the drive system components for the 4 joints being built for the SAID program.

Table 3 - Actuators selection for SAID

Joint	Angle of Motion	Actuator Torque	Actuator Type	Gear Ratio and Mass	Motor Torque and Mass	Actuator Mass
Wrist Pitch	180°	4.2 N-m (3.1 ft-lbf)	shape memory muscles	1:1 ratio pulley mass = 44 g	184 g for both muscles	228 g (0.50 lbs)
Elbow Pitch	180°	16.9 N-m (12.5 ft-lbf)	stepper motors, harmonic & spur gearing	HD-100:1 Spur-7:1 Total-700:1 287 g	5.9 N-cm (8.4 in-oz) 88 g	357 g (0.79 lbs)
Shoulder Yaw	360°	5.7 N-m (4.2 ft-lbf)	stepper motors, harmonic & spur gearing	HD-100:1 Spur-12:1 Total-1200:1 307 g	1.1 N-cm (1.7 in-oz) 37 g	344 g (0.76 lbs)
Shoulder Pitch	90°	30.8 N-m (22.7 ft-lbf)	stepper motors, harmonic & spur gearing	HD-160:1 Spur-8:1 Total-1280:1 457 g	14.8 N-cm (21 in-oz) 170 g	627 g (1.38 lbs)

The drive systems are designed with enough stiffness that the dynamic loads expected during movement will not add so much deflection to the joint that the absolute position sensor and logic confuse the deflections with missed steps. Static deflection for the arm from shoulder and elbow pitch actuators under different load in Mars gravity are show in Table 4a. This table does not consider deflection from bearings or arm links and assumes the maximum allowed current to the motors. Table 4b summarizes vertical deflection vs. arm extension in Mars gravity while carrying a 0.75 kg load at the tip of the arm. Joint torques for the above loads varied from 10.8 N-m (8 ft-lbf) to 19.8 N-m (14.6 ft-lbf) at the shoulder and from 3.1 N-m (2.3 ft-lbf) to 8.7 N-m (6.4 ft-lbf) at the elbow.

Table 4a - Total Actuator deflection with load.

Load in Bucket (kg)	Total Deflection (mm)
0	1.001
0.25	1.202
0.50	1.394
0.75	1.560
1.00	1.706
1.25	1.852
1.50	1.987

Table 4b - Total Actuator deflection from extension carrying a 0.75 kg load.

Arm Extension (m)	Total Deflection (mm)
0.30	0.031
0.50	0.089
0.75	0.217
1.00	0.403
1.25	0.646
1.50	0.947
1.75	1.295
1.79	1.355

Description of Control Scheme

Coordinated Control and the Control Hierarchy - The arm is controlled with a hierarchy of control algorithms, each level uses the next lower level to implement its functions. At the highest level, chains of commands, or macros, can be executed for such common functions as fetching or storing an instrument. This level does some rudimentary path planning to avoid bucket contact with the petals and other lander structure and produces a chain of straight-line motion segments, pauses, re calibration operations, and bucket-positioning commands. This level of control is one of the two primary levels through which commands from Earth will be executed.

The next lower level, also directly commandable from earth, executes the primitive motion commands from the top level. These commands, chained together in a linked list data structure, are executed in sequence until the end of the list is reached, after which the current position is maintained until a new list is received, either directly from uplink or from the top control level. The principal command executed at this level is a "move to" command, in which the arm is to move the bucket in a straight line from its current position to a new position at a specified rate.

To execute a "move to" command, the control computer first measures the current joint angles, then determines what the joint angles will be at the end of the line segment by using inverse-kinematic calculations. The change in joint angle is then calculated for each joint, and the time allocated for the line segment is calculated by dividing the length of the segment by the commanded velocity.

If all joints are to rotate less than 100 mrad (approximately 6°), each is simply stepped at a constant rate, generally different for each joint, that will result in reaching the new arm "pose" at the end of the allocated time.

There is, however, a maximum allowed stepping rate. This maximum is imposed to minimize problems with missed steps, which result from a joint's having to react to torques caused by acceleration of other joints. For example, consider what happens if the arm is straight, parallel to the ground, and holding a camera and the shoulder pitch (elevation) joint moves the arm up. The elbow must apply a relatively large torque just to keep the arm straight. Reaction torques have been computed for representative arm motions, and the calculations suggest that stepping rates should be no higher than about 10–30 steps per second to allow the elbow to "catch up" to the shoulder between steps. This step rate corresponds with bucket velocities on the order of 1 cm/s when the arm is near the middle of its range of extension.

The step rate is therefore modified to limit the step rate of the fastest joint, and the rates of the other joints are decreased in proportion. The motion will then take the intended path, although at a slower pace than commanded.

When one or more of the joints must move more than 100 mrad, uniform-rate joint rotation would produce a bucket path deviating significantly from a straight line. This is undesirable, because it complicates path planning and collision avoidance. In this case, the control algorithm calculates what fraction 100 mrad is of the total rotation for the joint that must rotate farthest. It then sets up an intermediate goal a fraction of the total commanded distance from the starting point. This "chunk" of the commanded motion can then be handled in the same way as small moves. When the arm reaches the end of the "chunk," the control algorithm treats the remainder of the move as a new command, starting where it left off. The result is motion that closely approximates uniform-rate straight-line motion with a series of small arcs as shown in Figures 2 and 3. These figures consider only errors due to the algorithm and do not reflect other sources of error such as dynamic response and arm "sag" due to gravity and compliance of the arm.

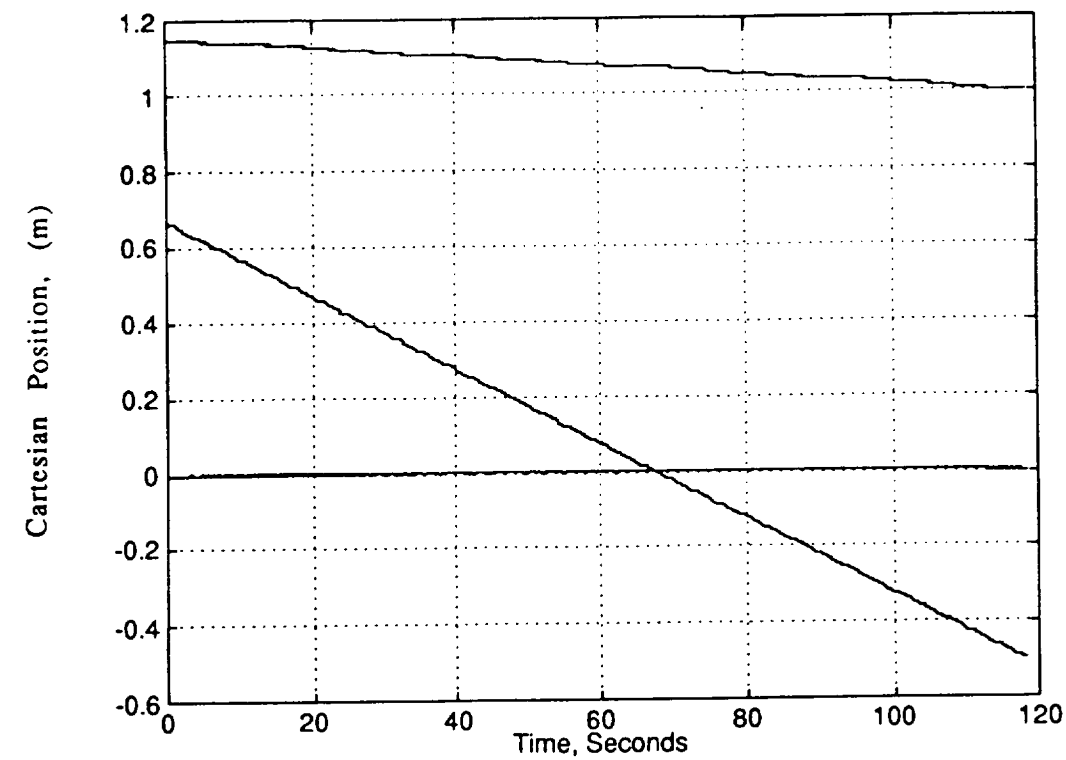


Figure 2 - Cartesian Coordinates of Bucket vs Time for Line Segment Requiring "Chunking"

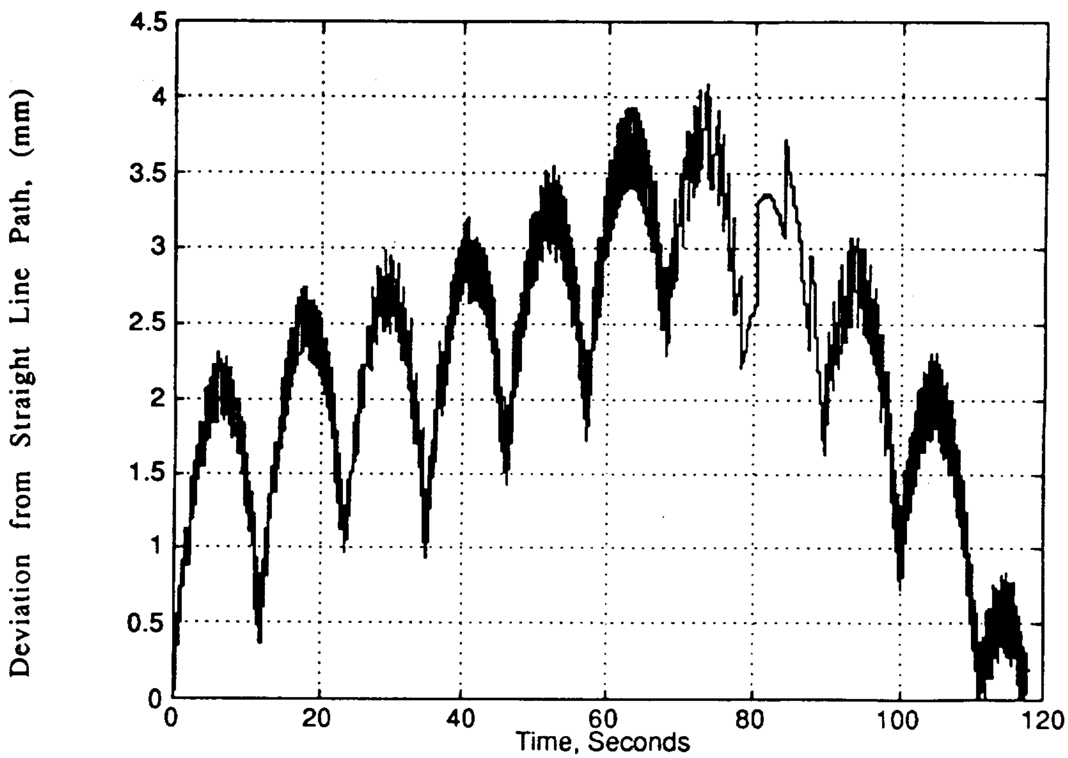


Figure 3 Error from Straight-Line Path for Motion of Figure 2

Upper-Arm Joint Control - Joints in the upper-arm, from the shoulder yaw joint through the elbow roll joint, are controlled by stepper motors, with position sensing via Resolvers (discussed in the next section). This section describes how these motors are controlled within a "chunk" of motion, as defined in the previous section.

Commands from Earth directly to this level will be possible but are not expected to be used for common operations. The position sensors will not be used in a traditional feedback control scheme. Rather, for simplicity, stepper motor steps will be timed to provide the desired rates, and steps will be counted to stop at the specified angle. The position sensors will be used periodically as a "sanity check" on the step counts, because it is expected that steps will occasionally be missed and because the weight of the arm and loads will cause sag due to arm compliance. At least at the end of each motion segment, the true positions of the joints will be sensed after arm settling. Steps will then be added to move to the intended position and realign the step count with the position sensor readings. Control is therefore fundamentally open-loop with periodic recalibration. Where positioning is critical, small motion commands will ensure frequent recalibration. Zero-length motion commands can be used to force the recalibration without changing from the last commanded position.

A function in the software coordinates the steppers to move the arm in a straight line at a uniform rate without servicing interrupts at a different rate for each motor. Furthermore, although the computing burden would be reduced somewhat and the code simplified by use of a programmable interrupt timer, interrupts can be set up to occur at a fixed interval, independent of the motion being executed, provided that this interval is short compared to the fastest stepping interval. If a fixed interrupt interval is used, the interrupt service routine maintains a "wait count" to cause it to pass over a specified number of interrupts before acting on one. A one-millisecond interval worked well for this fixed interval in simulations, but rates ten time slower might be used.

The interval at which interrupts are acted upon is calculated in the setup function before motion begins for a new "chunk." The interval is simply the time allocated for the chunk divided by the number of steps in the chunk for the motor that requires the most steps, rounded down to an integer multiple of the interrupt interval.

At each acted-on interrupt, the computer calculates the ideal number of steps each motor should have taken. If, for any motor, the actual number of steps differs from the ideal by more than half a step, that motor is stepped once in the direction that reduces the difference. The ideal count is simply the total number of steps in the chunk for the motor times the fraction of the allocated time that has elapsed. A variable in the software keeps track of elapsed time, in units of the interval between acted-on interrupts. The resulting joint motion versus time and Cartesian motion of the bucket versus time are shown in Figures 4 and 5, which are from a kinematic simulation model. The joint motion is monotonic and a close approximation to constant angular rate, although steps do not occur at regular intervals. Cartesian motion is not monotonic because a single step from one joint may contribute more motion to one Cartesian axis than multiple steps from a different joint. Nevertheless, deviations from a constant Cartesian rate are small over time intervals much larger than the stepping interval.

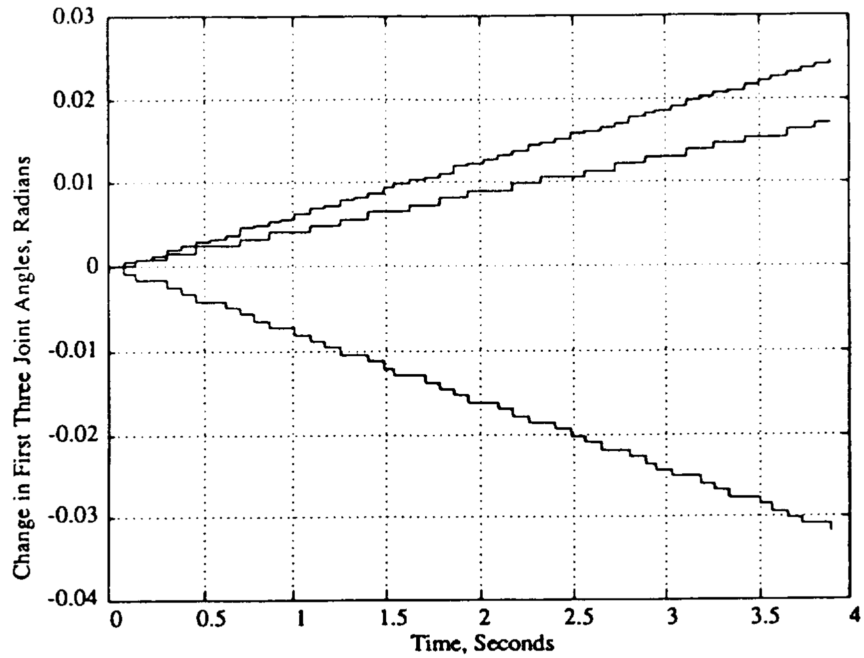


Figure 4 Change in Shoulder Joint Angles and Elbow Pitch Joint Angle for Motion of Figure 2, First 100 Steps

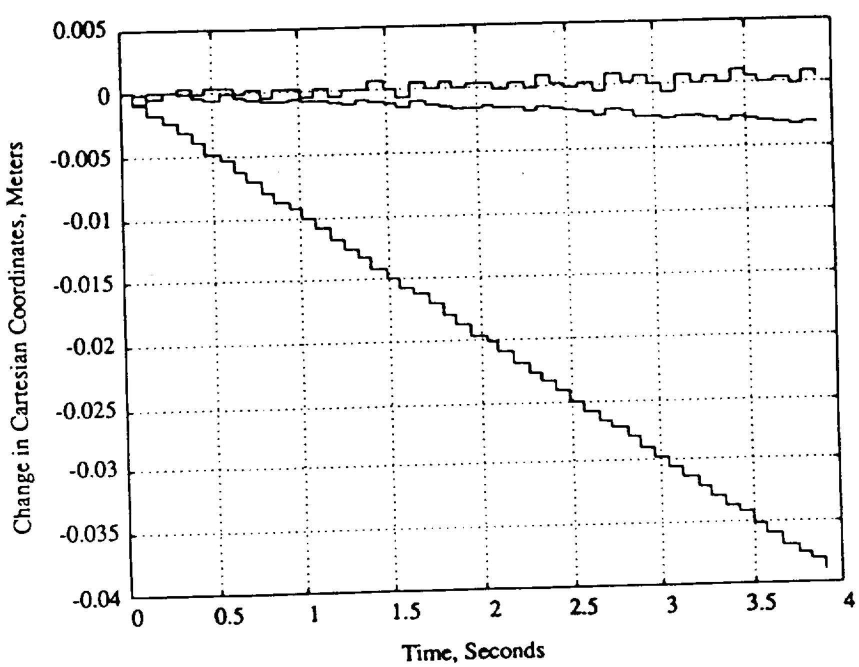


Figure 5 Cartesian Motion Corresponding to Figure 4

The dynamic simulation software was also used to generate the following graph (Fig. 6) which defines the predicted force and load capabilities for the SAID manipulator. Keeping in mind that soil sampling will occur at distances greater than 0.5 m, the graph indicates that the estimated forces produced by the arm are well matched for the task of digging and manipulating science instruments.

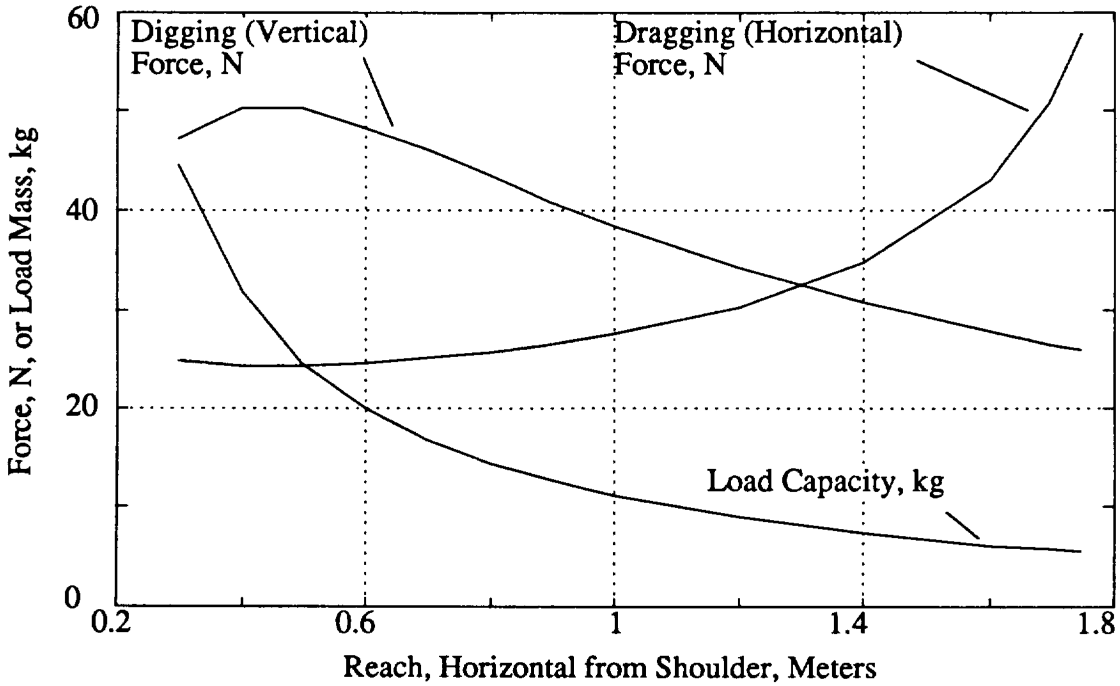


Figure 6 Load and Force Capacity.

Selection of Upper-Arm Joint-Angle Sensors

Some of the anticipated tasks for the arm, e.g., fetching and storing the camera, require positioning the bucket with the upper-arm joints to an accuracy of about 5–10 mm (0.2–0.4 in). Achieving this accuracy will require sensing joint angles accurately. The relationship between joint errors and position errors is defined by a Jacobian matrix, which varies with all the joint angles. Fully extending the arm, for example, makes vertical positioning errors most sensitive to shoulder joint angles but makes errors in position along the line of the arm very insensitive to errors in the shoulder joint angles. The pose in which the camera is fetched and stored, however, does not produce the greatest position error for a given joint error. An analysis based on representative poses and reasonable assumptions about additional error sources suggests an accuracy requirement of approximately 0.1° at the shoulder joints.

Any of a number of sensor types could be used to read the joint angles with the required accuracy, so a trade study was conducted to select the most appropriate device. Table 5 summarizes the results. Some other sensors, like Inductosyns, were not selected for the trade study because either they added complexity for accuracy that was not needed or their suitability for the application was questionable due to their size or other reasons. Inductosyns, for example, can provide accuracy to 0.5 arc seconds, over 700 times better than the requirement. Some others, such as capacitive and inductive sensors and sensors based on eddy currents were rejected at the start of the study because of angle range constraints or concerns about linearity and the complexity of support electronics.

Table 5 - Joint Angle Sensor Selection Tradeoff Table

Criterion	Weight	Resolver	Absolute Optical Encoder	Incremental Optical Encoder	RVDT	LVDT	Potentiometer
Cost, Including Computer Interface	10	8	10	10	4	4	9
Weight and Size, Including Computer Interface	9	9	10	10	6	6	9
Life and Environment Compatibility	8	10	6	6	10	10	8
Ease of Reading Absolute Angle	7	10	10	3	10	8	10
Power Consumption, Including Computer Interface	6	8	8	10	6	6	8
Weighted Total Score		359	356	319	280	266	353

As with the actuators, overall cost was the chief concern. For some of the sensors, the cost of the sensor itself is misleading. Whereas the optical encoders can interface to a computer almost directly, Resolvers, LVDTs and RVDTs require an ac excitation supply and digitizing circuitry to interface to the computer. Even a potentiometer requires a dc supply voltage for excitation and an A/D converter. (To achieve 0.1° accuracy with a potentiometer, the voltage across the device must be used as the reference voltage for the A/D converter, which somewhat complicates the circuitry, and even then, this accuracy may be difficult to achieve). Similarly, the LVDT and RVDT have outputs proportional excitation amplitude, so excitation amplitude would have to be measured unless 500 ppm stability of the excitation could be assured. Even the suitability of these devices for the application is difficult to assess, inasmuch as they are not primarily designed as absolute-position sensors. For Resolvers and potentiometers, R/D and A/D converter modules are readily available components, so design time would be minimal for the interface. Differential transformer interfaces could be made with RMS-to-dc converters followed by A/D conversion, but achieving the required 0.05% accuracy with this approach would be difficult at best. Transicoil Inc. makes dc-to-dc LVDTs, which avoid the conversion circuitry, but their linearity is only 0.25%, which translates to errors over twice the budgeted limit.

Weight and size parallel the cost, because the interface circuitry strongly influence both. The high score given to optical encoders assumes that devices with built-in interface circuitry can be used. For this application, this may or may not be practical. However, even if only a read-station is provided in the encoder, the added circuitry for computer interfacing is straight-forward and small.

Life and compatibility with the environment favor devices with no internal electronics, since it is desirable to minimize power use for heating in the arm. In addition, the non-optical devices are more rugged, and the potentiometer and optical devices are more affected by the potential for dust contamination than the other sensors.

The whole reason for providing the angle sensors is to read absolute angles as a sanity check and calibration for the step-counting control scheme. As a result, incremental encoders were ranked low, since they count from a reference scribe rather than providing a direct readout of absolute angle. If the count becomes suspect, the joint must be moved past the reference scribe for recalibration, and if that is to be done, the motor counts can just as easily be recalibrated; much of the value of the sensor is lost. The LVDT has a reduced rating because its output is a nonlinear function of joint angle. Some processing would be required in the computer to convert its reading.

Finally, power consumption was considered. Again, the interface circuitry is a large factor. The incremental encoder is hard to beat, since its only significant power use is in the light source. The differential transformers were rated lowest due to the power required by their excitation and digitizing circuitry.

The results show that Resolvers have a slight advantage over absolute encoders and potentiometers, but that all three are reasonable candidates for the application. However, the technical risk in use of potentiometers is higher, inasmuch as the required accuracy will be difficult to achieve. Absolute optical encoders also may be risky in that their internal electronic parts may prove inadequate for the cold environment. If it is found that this makes internal parallel-to-serial conversion impractical, an absolute encoder would require routing approximately 15 wires per joint back to the computer through the arm, which is highly undesirable.

It should be noted, however, that 0.1° accuracy is at the edge of what is achievable with a single-cycle Resolver. Typically, a single-speed Resolver has accuracy of about 3–7 arc minutes (0.05 to 0.1 degree), and errors in the R/D conversion can degrade that accuracy further. R/D converters are available with 16-bit output (e.g., Analog Devices' AD2S80A), but for the average Resolver, the least significant two or three bits are essentially random. Any tightening of positioning requirements will require reassessment of the suitability of these sensors. At this point, Inductosyns become attractive despite their size (1½–2-inches diameter for an unhoused unit that mounts on the joint axis directly). In principle of operation there is little difference between a Resolver and an Inductosyn, but the latter is capable of very high accuracy and resolution. However, an Inductosyn sensor would also require routing approximately 19 wires per joint back to the computer through the arm, which is highly undesirable. These considerations led to selection of Resolvers for the upper-arm joint angle sensors.

Wrist Development

Soil Acquisition

Most of the soils expected to be encountered on Mars are relatively weak in strength as far as soils go. However, on Mars there is an excellent chance of encountering much stronger materials also, for example, water lane deposits, permafrost soils or polar ice deposits can be expected to have considerable strength. It is also, desirable to have the ability to measure the strength of the soil while sampling with the acquisition device. The soil bucket design that seem to provide the best chance of satisfying these desires is a simple backhoe with tapered sides so that the bottom of the bucket comes to a point (see Fig. 7a-7b). This way the leading tip of the bucket would be very pointed for scratching at or plowing through high strength materials. Also, the bucket capacity increases rapidly when being pulled through weaker materials at a greater depth, which would allow trenching operations in weaker materials to be feasible. The maximum capacity is 125 ml. The buckets profile is pushed forward so that the leading edge provides clearance for the trailing portions of the bucket. The shape memory muscles are monitored with load cells to prevent over straining. These load cells can also be used to monitor the cutting resistance of the material being sampled. Alternative designs such as a clamshell or three pedal sampler require more than one blade surface to be pulled through the material, which makes strength measurements more complex and requires more force from the actuator.

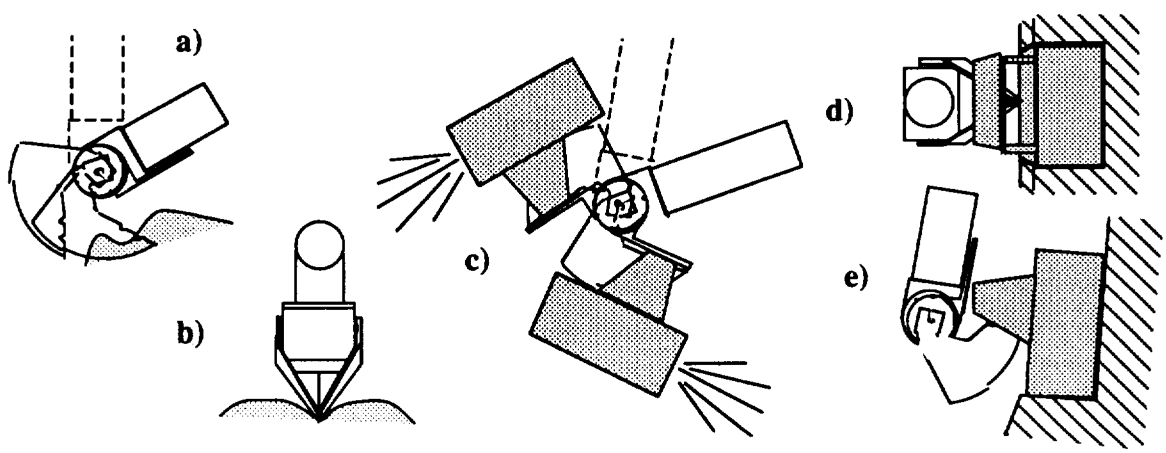


Figure 7 Soil acquisition and instrument depolyment concept: a) Bucket shown in acquisition and dumping positions. b) Front view showing pointed tip for acquisition in high strength materials. c) Range of angles which instruments can be deployed. d) Top view of grasping or stowing an instrument. e) Side view of grasping or stowing an instrument.

Grasping System

Concept - The pointed bucket shape is appropriate for capturing objects of different shapes much the same as a hook. Also, the pointed tip allows for misalignments when attempting to capture the inverted U-shaped handle envisioned for instrument deployment (Fig 7d-7e). By having a lid on the wrist assembly which can act as an opposing thumb, objects can be held. If the lid can hold itself tightly to the bucket the wrist actuator can be used for grasping, as well as a degree of freedom which can rotate the end effector. A mechanism was devised which could lock the lid to the bucket when the bucket reached a position 45° from fully closed. At this point the mechanism would allow the bucket to continue to close on the lid while the mechanism's ratcheting action would prevent the bucket and lid from separating. This way objects 4 cm or less can be captured and grasped between lid and bucket when the bucket is near the fully closed position. Once grasped the wrist actuator can rotate to any position(see Fig 7c). When the bucket is returned to within 45° of fully closed the mechanism releases the lid for stowage. 45° from fully closed was chosen for a grasp and release point because it is ideal for deploying instruments and these positions are not particularly useful for soil acquisition.

Mechanical Design - The design of a passively activated locking/releasing mechanism was appealing for one main reasons, it does not require an additional actuator when the wrist actuator can easily provide the needed actuation force. This saves mass at the end of the arm, wiring through 3 of the 4 joints, and power for an additional actuator. However, it does confine grasping and releasing operations to within 45° of fully closed.

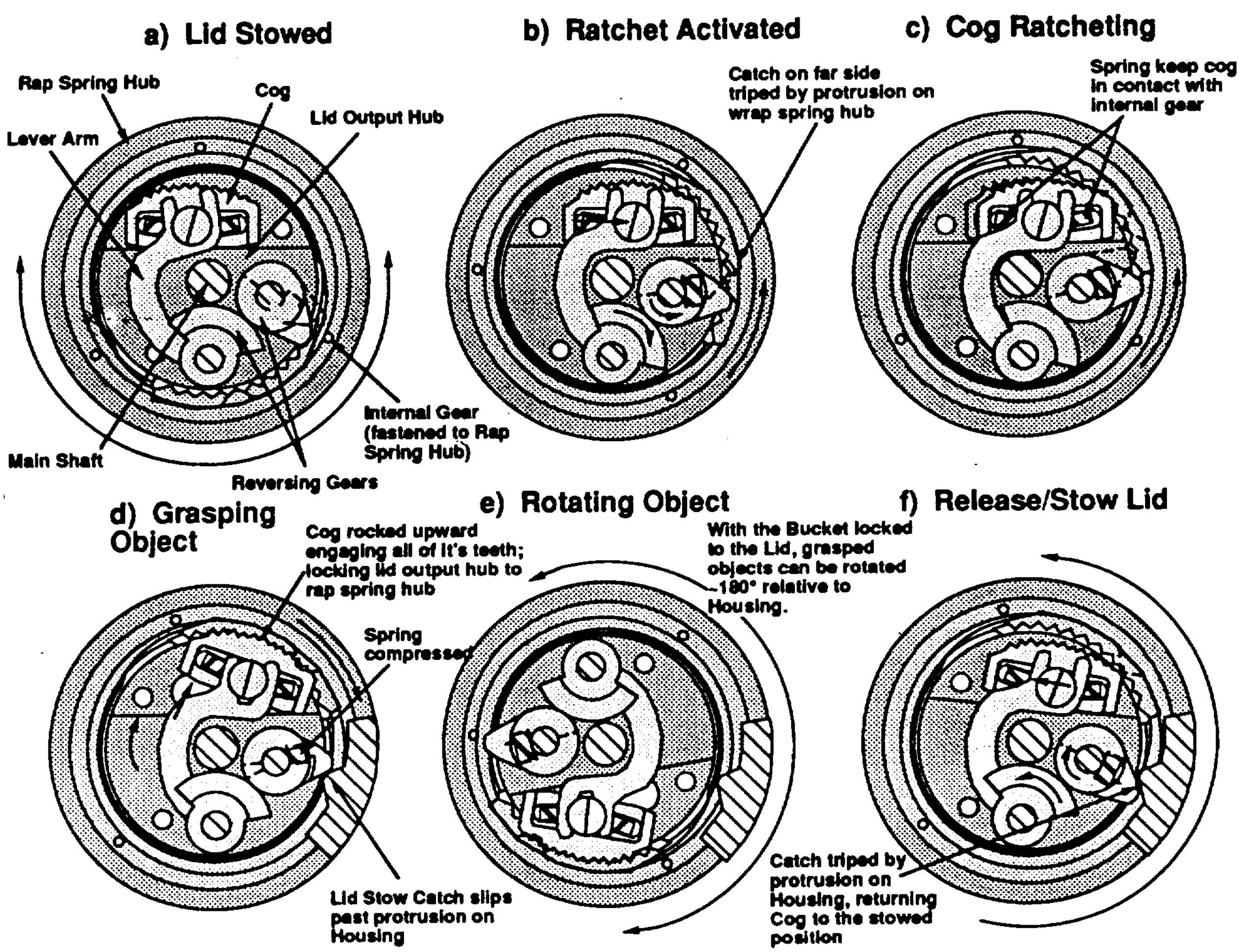


Figure 8 Lid Lock/Release Mechanism Sequence

Design of the mechanism centers around a small cog with teeth which when moved into position engages the teeth of an internal gear. The cog is spring loaded which allows the internal gear to ratchet past in one direction. When the internal gear is moved in the other direction the cog's end most tooth catches rocking the cog upward until all of the teeth are engaged preventing the internal gear from rotating without also rotating the cog and associated hub. The internal gear is mounted inside the wrap spring hub and therefore mechanically connected to the bucket output. The hub which the ratcheting cog resides on is also located inside the wrap spring hub were it can revolve freely around the main shaft. The ratcheting cog's hub is mechanically connected to the lid assembly. The sequence is illustrated in Fig. 8.

The mechanism is actuated by two small catches on the ratcheting cog's hub which are mounted to a common shaft. The catches protrude beyond the diameter of the ratcheting cog's hub. When the bucket is rotated in the closing direction to the 45° position a protrusion on the rotating portion of the wrap spring hub engages one of the catches which turns two small gears reversing the mechanical motion and moving the cog into ratcheting position. Upon returning to the 45° position for releasing the other catch engages a protrusion on the stationary portion of the wrap spring hub which returns the cog to the stowed position, thereby releasing the grasped object. The catches are spring loaded so they can move past the protrusions in one direction of rotation while catching in the other. The ratcheting cog's hub is machined from Torlon which has a very low coefficient of friction 0.06. Torlon is used as a bearing surface for the shafts, and it also allows the cog to slide freely. Torlon also has a coefficient of thermal expansion (CTE) which is within 1.1 µm/mK of stainless steel. Therefore the shafts, cog, reversing gear, and internal gear have been machined from stainless steel, so that the mechanism can function over a wide range of temperatures.

Wrist Mechanical Assembly (see Fig 9)
The completed housing assembly is sealed from dust by Teflon spring-energized seals between the housing and lid outputs (1.5" ID rotary seal) and between the lid output and the bucket output (.25" ID outside face seal). These seals have skived edges for maximum protection from dust with a minimum of sealing force (1 lb. per linear in.). The housing sides also have glands for a Teflon seal that mates with the housing cover to prevent dust from contaminating the wrap springs and associated mechanism. The bearings for lid and bucket outputs are nested inside the housing sides, and are sealed from dust. For redundancy the bearings are also of the sealed variety with no lubricant, and are commonly available as Mil Spec bearings.

The precision potentiometer used was manufactured as a custom part by McCulley Inst. Corp. for the SAID contract. It is similar to those manufactured by McCulley for space qualified gyro assembles and is unhoused with a total mass of only 1.6 g. There are two wipers which make contact, one on each side of the resistive element of the potentiometer. In the SAID application one wiper would be used for the bucket's position and the other for the lid's position sensing. The resistive element is mounted to the housing with alignment screws.

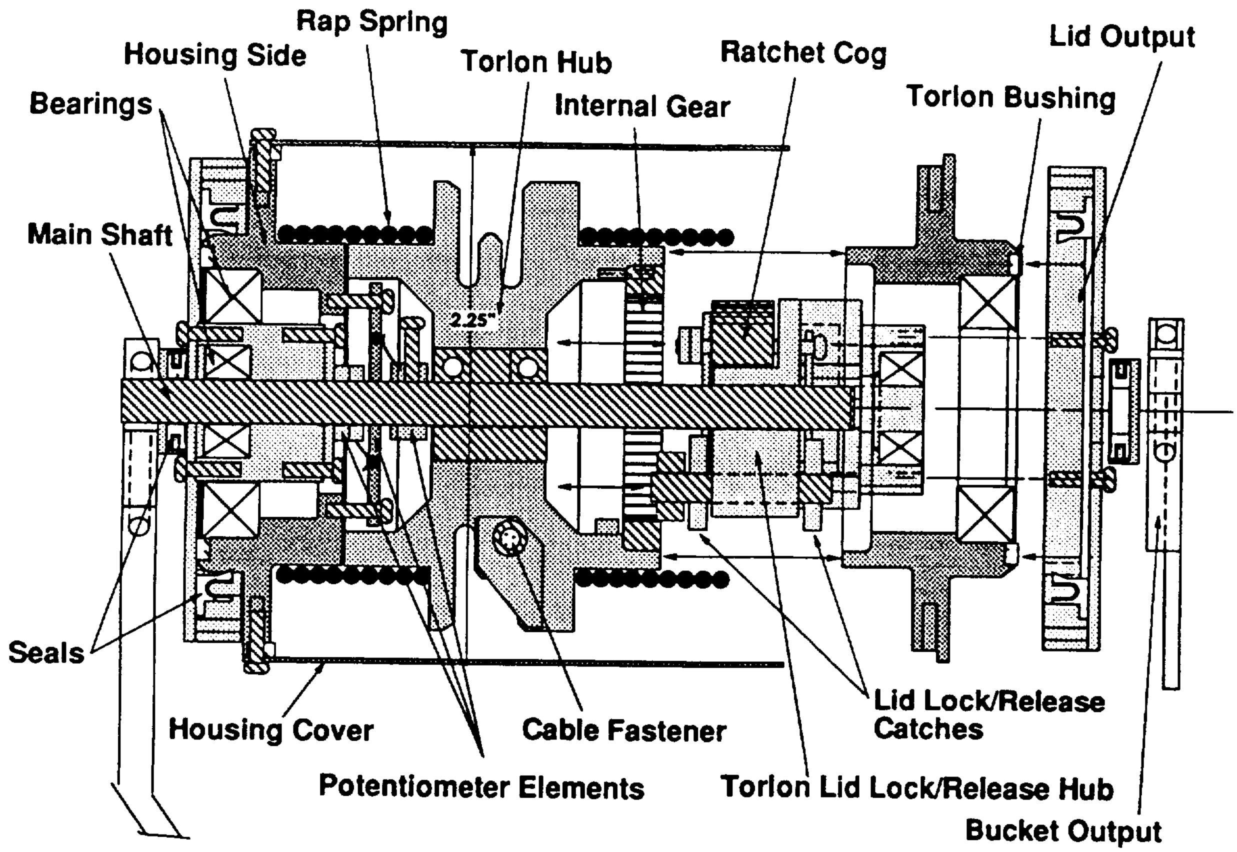


Figure 9 Cross Section of SAID Wrist Mechanism

The wrist assemble has been machined from aluminum (housing elements, lid and bucket assemblies), stainless steel (shafts, bearings, lid lock/release gears and cog), and Torlon 5030 (muscle pulley, lid lock/release hub, lid output bushing). Torlon after machining was recurred as specified by the manufacturer for 21 days ramping up to 500°F. It should be noted that assembling and disassembling the unit has not been as easy as we had hoped, and requires some skill of the technician. Alignment of the potentiometer elements is perhaps the most difficult, however we have been able to assemble and disassemble the unit many times without damaging or having to replace any of it's components.
Table 6 summarizes the major components of the lower arm and their mass.

TABLE 6 Actual Mass of SAID Forearm, Wrist and End Effector

Wrist, End Effector & Forearm Assemblies	Assembly Mass (g)
Lid Lock/Release	31.07
Rap Spring Brake	90.54
Pulley, Main Shaft & Coupler	68.23
Bearing	50.21
Seal	8.40
Position Sensor	1.60
Muscle	124.70
MLI Blanket	120.40
Housing	111.67
Bucket End Effector	94.50
Lid for Bucket	83.49
Forearm Composite Tube	200.00*
Total	**984.81**

*Estimated mass

Wrist Testing

The End Effector, Wrist, and shape memory muscle actuator assemblies fabricated for the SAID program have been tested for operational power, torque output, and soil sampling capabilities. For testing, these assemblies where mounted into a fixture which could hold the assemblies in the proper positions for testing and also function as the forearm structural member, which has not yet been fabricated (see Fig 10). LabView Software was used to control the wrist and acquire data. The software monitors lid and bucket position, load on the muscles, voltage and current draw by the muscles, and load from an external load cell used to measure tip force. It controls the Wrist end effector with a simple algorithm which allows setting of the desired position, an initial current level for warming up the muscle, a Ø2 allowing a separate current setting for movement, and Ø3 allowing a third current setting for slowing the motion just before the desired position is achieved. We have had good success stopping the Wrist to within ± 2°. A more sophisticated version of the algorithm has been developed but not yet implemented. It should allow greater position control, and hopefully allow us to achieve or goal of ± 1° accuracy or better.

Power Testing

The shape memory muscles power utilization is dependent upon the temperature and pressure of the environment in which it is operating. For these reasons the system needed to be tested in a vacuum chamber at cold Martian temperatures, and low pressures. The move toward a vacuum environment lowers the power required by the muscles, however the colder temperatures have the opposite effect. The muscle built by Martin Marietta before this contract used 24 wires and required 1.4 watt-hrs for 90° of motion in the up (open) direction at nominal Martian temperature and pressure. We had hoped that the 8 wire muscle built for SAID would greatly reduce the total energy as well as the required current. Unfortunately, the current required for efficiently warming the SAID muscles below -60°C is 2.35 amps, virtually the same as the 24 wire muscle. The energy required for motion was reduced by 40-60%.

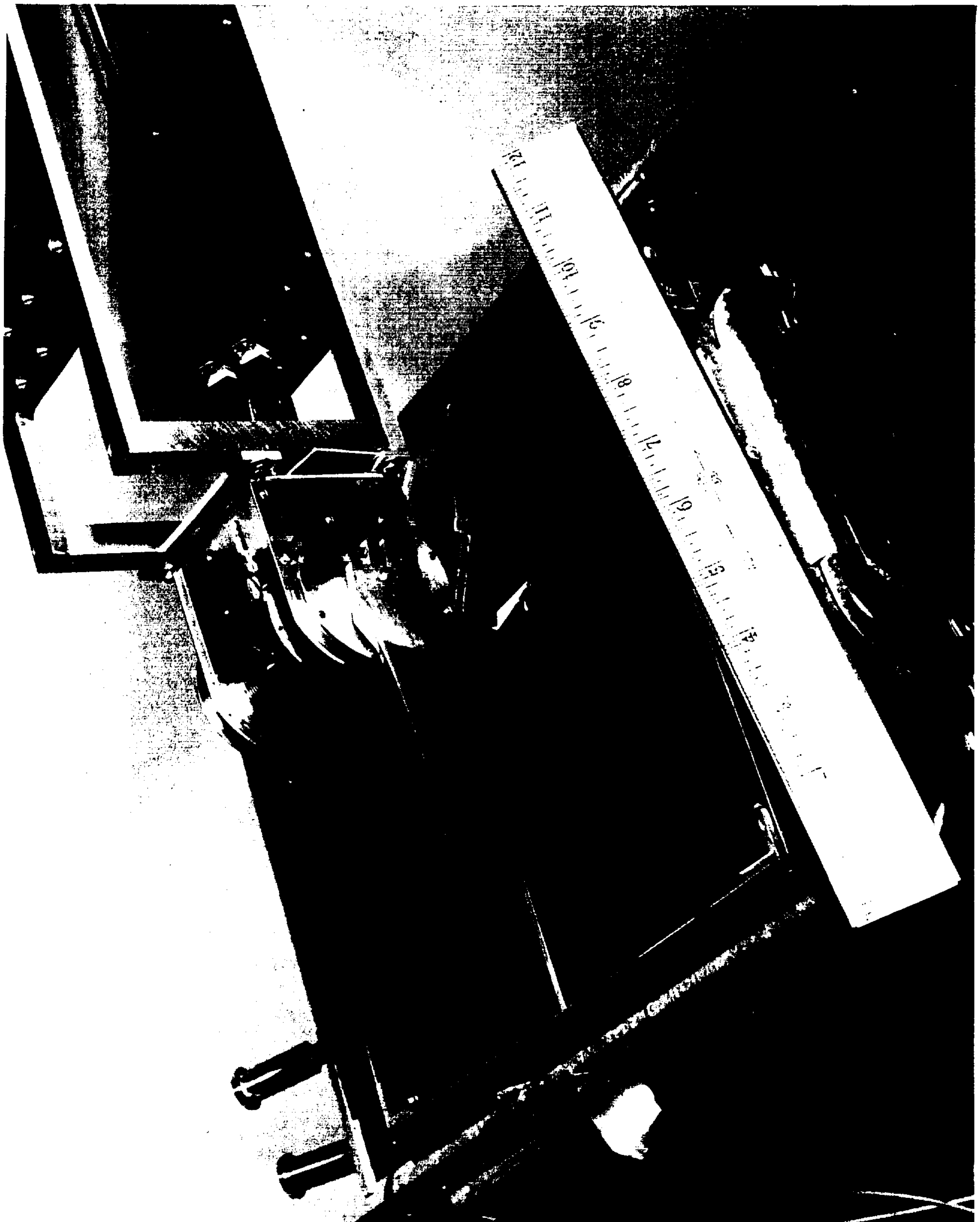


Figure 10 SAID Wrist Assembly Mounted for testing. Housing Cover has been Removed to Show Rap Spring Triggers and Brake. Shape Memory Muscles are Visible Extending out of the Picture on the Right Side.

The muscles are wrapped in Multi-Layer Insulation (MLI) blankets, which improve the power characteristics by 65% or more depending on temperature and pressure conditions. Since it is not possible to monitor the temperature of the shape memory wires without shorting them, the temperature of the blankets was monitored along with the air temperature inside the chamber. During operation, after the initial muscle warm up blanket temperatures can be expected to stay well above the air temperatures for hours after the muscle has been turned off, as was the case with the SAID tests (Fig. 11). Figure 12a and 12b show the energy used for various blanket temperatures at Martian pressures. Start-up power is included in the 90° and 180° measurements.

Figure 11   Air Temperature vs. Blanket Temperature

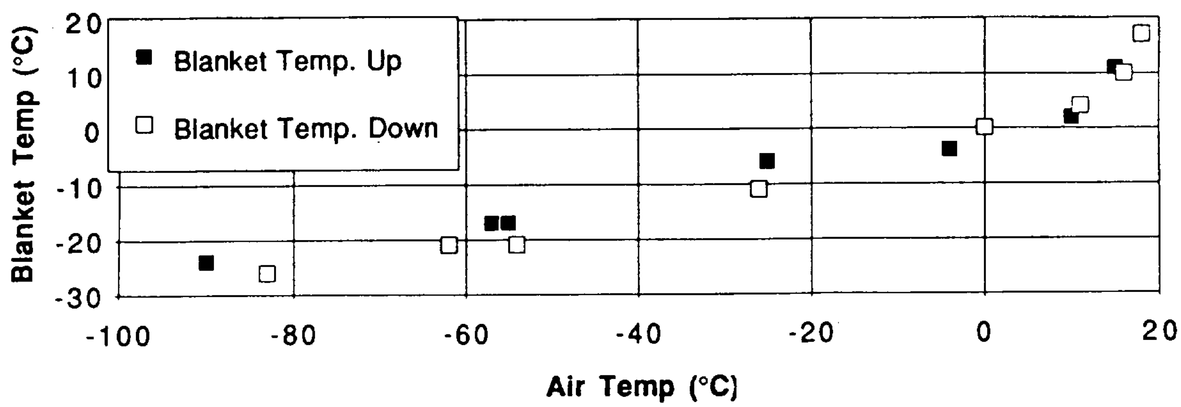


Figure 12a   Energy for Down Motion

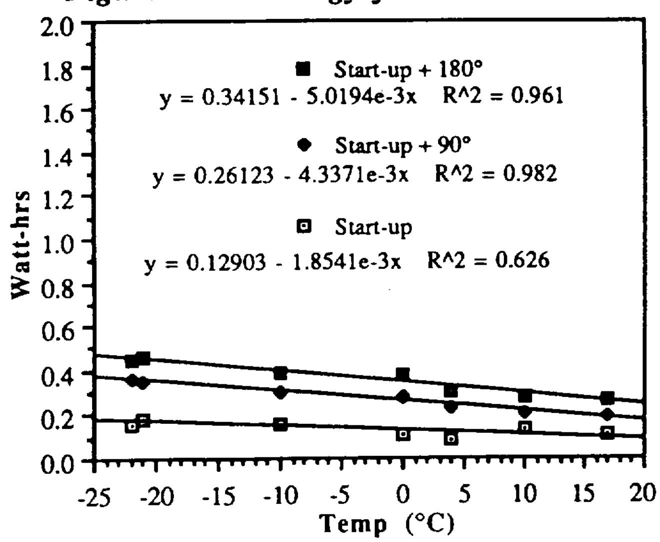
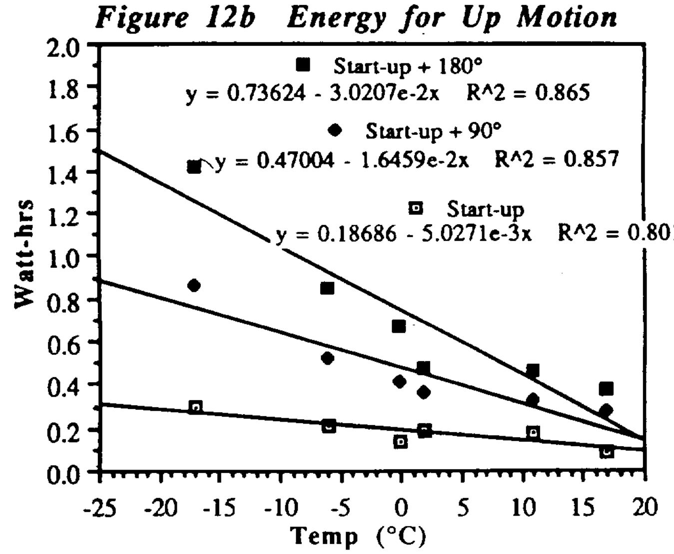


Figure 12b   Energy for Up Motion

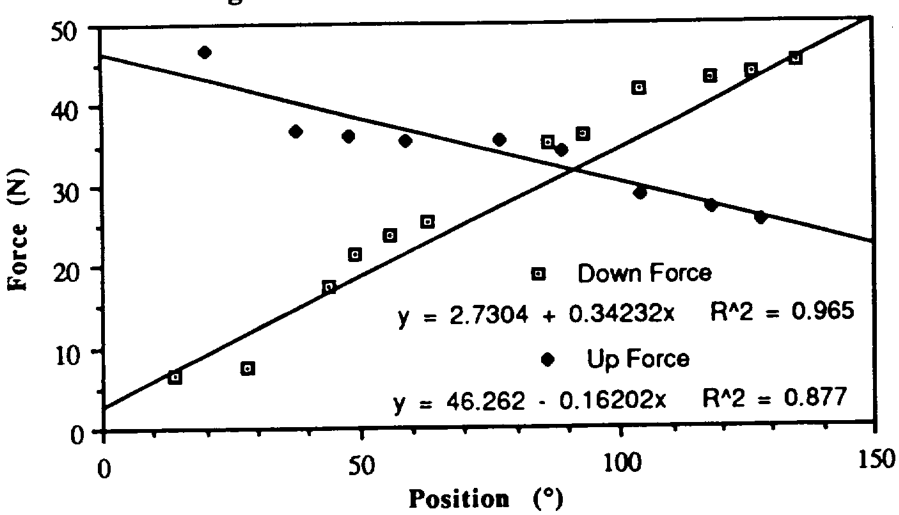


The mechanisms has worked smoothly in the thermal/vacuum chamber down to the coldest temperature tested, -90°C. We did experience drop-outs in position readings from the potentiometer at temperatures below -60°C, which we have attributed to an undiagnosed CTE problem. Except for these drop-outs the sensor has been 100% reliable through 100's of cycles at temperatures above -60°C.

Torque

The torque which the muscle can supply is a function of position. This is because the activated muscle is reloading the other muscle when moving. The lowest torques are when the bucket position is near fully closed or fully open (see Fig 13). This works out well since these positions are not generally used for digging, lifting or other functions requiring high torque.

Figure 13 Wrist Force with Position



Soil Sampling

Soil sampling tests were performed to verify the mechanisms designed ability to acquire soil samples and explore the systems ability to make measurements of the soil properties during an acquisition. The load cells which monitor each of the muscles, to prevent over straining, can also be used to monitor loads from cutting resistance when the bucket is pulled through soils. The additional load from the soil work can be subtracted from the normal loads produced when one muscle reloads the other. If the loads on the bucket can be measure in this manner with enough resolution and accuracy, then perhaps determination of the physical properties of the soil being sampled could be estimated.

Soil samples were prepared by the PI, which were analogous to Martian soils. Because of the uncertainty of the Martian soils properties and mineralogy, a variety of samples were prepared. The samples were tested by the USGS Soil Testing Lab in Golden Colorado so they could be accurately reference and compared to other soils. The testing involved the direct shear method which defines both the cohesion and the angle of internal friction of a sample. Mineralogy and densities of the soil was also recorded along with the method used to compact the soil. A summary of the soil types used for testing SAID can be found in Table 7.

Table 7 Soil samples tested by the USGS, and used for SAID soil testing.

Soil Sample	Composition	Grain Size	Density	Cohesion	Angle of Friction	Shear Vane
#1	Clay-Nontronite, Compressed	1-100 µm	1.41	43.1	31.8	7.0-7.6
#3	Cinders-Volcanic Dust	10-150 µm	1.47	66.0	27.3	7.5-9.1
#4	Clay-Nontronite	1-100 µm	1.25	7.7	38.5	2.5-3.0
#5	Sand-Quartz & Feldspars	250 µm to 2 mm	1.44	7.0	31.3	0.8-1.5

The bucket was pulled through each of the soil types at 4 different depths, although only the deepest 3 samplings produced useful data. While acquiring the samples, position and muscle load were recorded with time. This data is plotted with data from pulling the muscle through air (see Fig 14). The time at which the bucket first makes contact with the soil is recorded as well. The load associated with the soil resistance is plotted for different depths for all of the samples tested (see Fig 15). Clearly the SAID system was able to distinguish the weaker soils (sample #4 and #5) from the stronger one (sample #1 and #3).

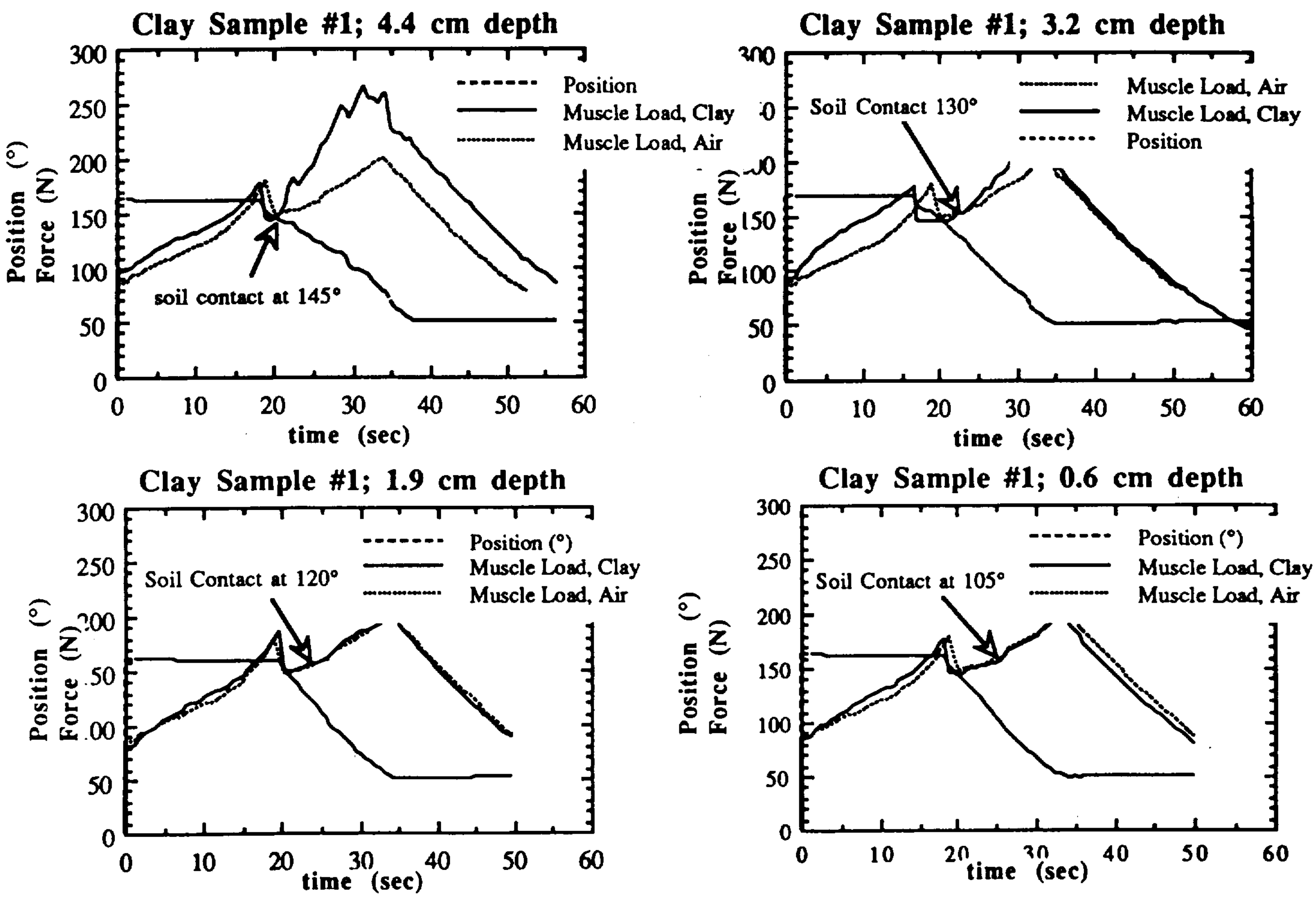


Figure 14 Sample Acquisition in Clay, Sample #1 at Various Depths Compared with No Load Acquisition through Air.

We are encouraged to see that the system can record meaningful data even in very weak soils such as sand. Also encouraging was the comparison between sample #1 and sample #3, which have similar cohesion's and different angle's of internal friction. The steeper angle of the load building up on sample #1 may be reflecting the higher angle of internal friction measured by the USGS. After reducing this data it was observed that the signature of the curve building up force until the soil suddenly fails from shearing may correspond more closely to the signatures produce during the direst shear testing failures This may be a more useful method of determining the soil's properties than comparing the reduced results of the direct shear test which report cohesion and angle of internal friction.

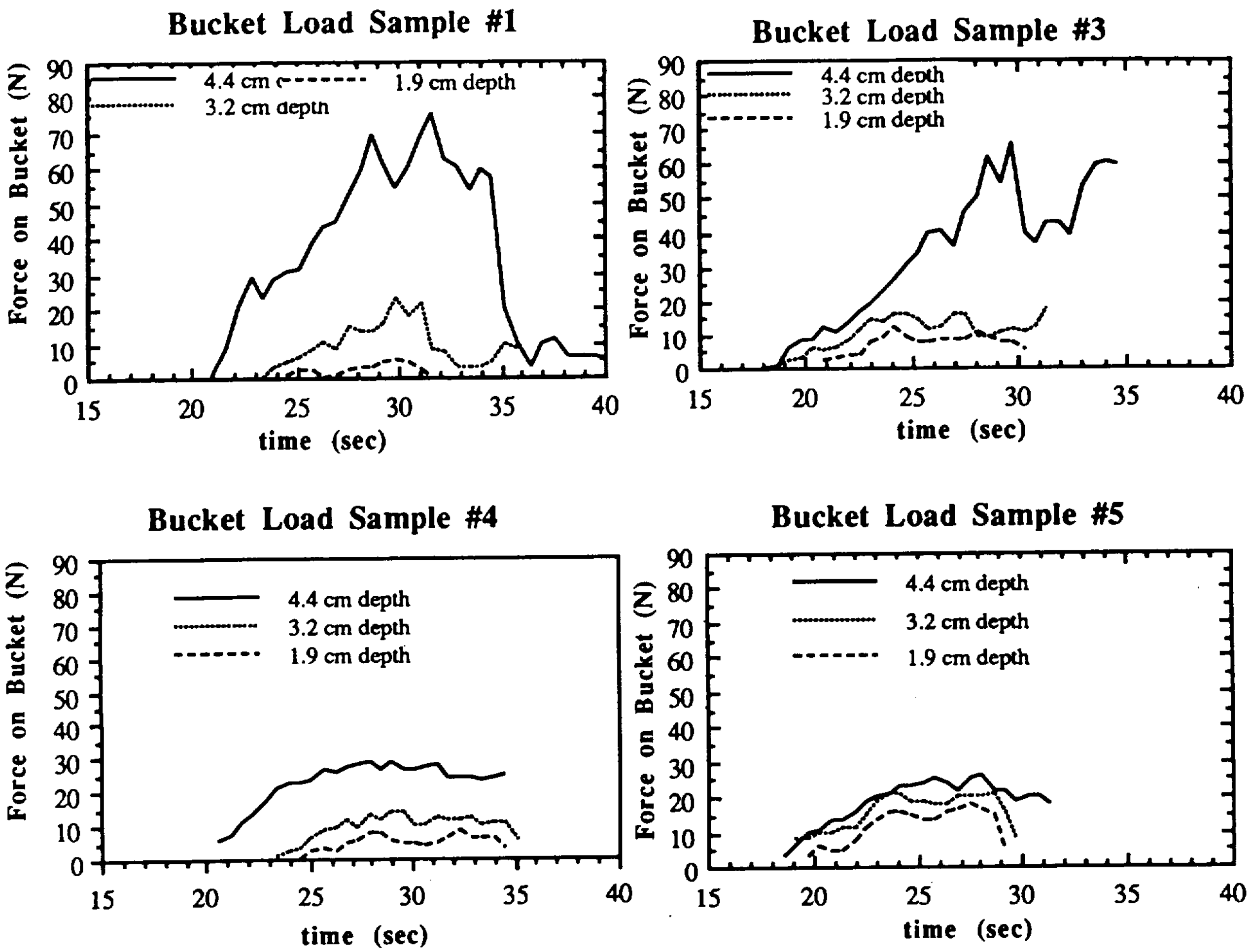


Figure 15 Load on Bucket from Sampling Operations at Various Depths for the 4 Soil Types Described in Table 7.

Although we have not taken enough data or performed enough analysis of the cutting properties of this bucket design to devise an accurate method of determining soil properties from the sampling, we have shown that these measurements are feasible with the SAID system. Quantitative correlation's will require much more soil testing, so that repeatable results are confirmed, and theoretical analysis are developed so that greater understanding of how the bucket interfaces with the materials being sampled can be achieved. The magnitude of this effort is out of scope with the present contract funding level.

Grasping

We were not able to test the lock/release mechanism's ability to provide grasping and releasing functions for the wrist and end effector. Although the device required significant development after the initial assembly, all aspects of the mechanism are now performing as designed except for one. The Cog assembly is not ratcheting smoothly past the Internal Gear when the Bucket closes on the Lid. This resulted in failure about 50% of the time, causing us to remove the mechanism from the wrist assemble so that other tests could be successfully completed. We are still very confidant that the mechanism can be made to work reliably. There are two modifications which will help the mechanism perform more reliably: 1) use of a dry lubricant on the internal gear, instead of no lubricants; 2) angle the teeth on the Internal Gear and the Cog so that they slip past each other in one direction and catch in the other direction. The present design has symmetric teeth so that the Cog could catch in either direction. One direction was to be for locking the Lid to the Bucket and the other was for stowing the Lid. We have since discovered that the Lid seals provide enough holding torque to retain the Lid assembly in the stowed position, so the Cog doesn't have to do this job.

Conclusions

Although we are pleased with the wrist and end effectors ability to measure soil properties and function in the Martian environment, the following known short comings of the system should also be mentioned: 1) The system requires higher current and more power than expected; 2) Although there is some mass savings by using the shape memory muscles for actuation it is not nearly as much as was originally believed - perhaps because of a lack of understanding of the additional components necessary to enable the muscle system to work efficiently; 3) Control has always been seen as a challenge for the shape memory devices, however in light of the minimal mass savings provided by shape memory it is apparent that small motors could produce much greater positioning control for nearly the same mass.

Planned Activities for the remainder of the SAID contract

- Wrist Mechanism Grasping Tests
- Final Component Selection
- Build Drawings Finalized
- Upper Arm Fabrication
- Upper Arm Development
- Upper Arm Performance Testing

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13. ABSTRACT

This report details the interim progress for contract NASW-4818, Sample Acquisition and Instrument Deployment (SAID), a robotic system for deploying science instruments and acquiring samples for analysis. The system is a conventional 4 degree of freedom manipulator 2 meters in length. A baseline design has been achieved through analysis and trade studies. The design considers environmental operating conditions on the surface of Mars, as well as volume constraints on proposed Mars Landers. Control issues have also been studied, and simulations of joint and tip movements have been performed. A passively braked shape memory actuator with the ability to measure load has been developed. The wrist also contains a mechanism which locks the lid output to the bucket so that objects can be grasped and released for instrument deployment. The wrist actuator has been tested for operational power and mechanical functionality at Mars environmental conditions. The torque which the actuator can produce has been measured. Also, testing in Mars analogous soils has been performed.

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