Rover-arm Based Coring with Slip: Technological Development and Control Approach

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***Abstract*—Technology to enable core sample acquisition from a low-mass rover on slopes is being developed. A rotary percussive coring tool was integrated onto a low-mass rover and sensing, control, and simulation technologies are being developed. Initial results indicate that coring with modest rover slippage will be feasible.**

I. INTRODUCTION

Technology to enable core sample acquisition from a low-mass rover on slopes is being developed. The current state-of-the-art in coring and drilling from a planetary rover arm-mounted tool, represented by the Mars Science Laboratory mission, assumes that the rover is a stationary platform. Future missions could benefit by enabling arm-mounted drilling or coring where the rover may experience modest slippage during the drilling or coring operation. To enable such a scenario, a rotary percussive coring tool is being integrated onto a rover and sensing, control, and simulation technologies are being developed. The rotary percussive coring tool has mass and impact energies similar to expected future planetary coring tools and it is being integrated onto an 85 kg six wheel rocker-bogie rover. Sensing includes sensing to detect slippage and sensing for control to accommodate slippage during the coring operation. Slip will be detected using measurements of filtered force and torque values, coring tool current, and visually detected rover motion relative to the environment. It is assumed that the rover slippage will be slow relative to the speed at which the arm can be reconfigured to accommodate the slip. If the rover slips at a greater rate, then a separate recovery action will be taken. The arm will be automatically reconfigured to accommodate the rover slippage using control based on force-torque and motor current feedback. If the arm reaches the edge of its workspace, then the rover will autonomously drive to place the arm back into its operational workspace and the arm, with tool remaining in the rock, with be reconfigured accordingly. A simulation environment is being developed to simulate the coring operation. An example of the Rocky 8 rover on a slope in the JPL Marsyard is shown in Figure 1.

Figure 1. Rover Slope Slip Test

II. OPERATIONS SCENARIO

For the work described in this paper, it is assumed that any rover slippage will be slow compared to the rate at which the arm can be reconfigured to accommodate the slip, to allow the coring tool to remain in the coring hole during reconfiguration. For example, the rover might slip 20 cm during an hour long coring operation. The operational scenario for coring and accommodation of rover slippage during coring is described below.

1. The rover drives onto a slope so that a science target is within the workspace of the rover-mounted manipulator. The rover could approach the target from any direction.

2. The arm is deployed and the coring tool is placed on the target and coring is initiated.

3. While the coring operation is active, sensing is active to detect rover slippage.

4. If rover motion relative to the coring hole is detected, then the arm is automatically reconfigured to accommodate the slip if the rover

slip is within a safe bound. The rover is not actively moved. If the slip is beyond a safe bound, then the coring operation is stopped and the tool is removed from the hole.

5. If the arm approaches the edge of its workspace due to accommodation of rover slip, then the coring tool is turned off and the rover is moved so that the target is back near the center of the arm workspace. Then the coring operation is continued.

III. SLIP SENSING

Several sensing approaches will be active during the coring operation to detect motion of the rover relative to the coring hole. A six-axis force-torque sensor will detect binding of the coring tool as lateral forces between the coring tool and hole and as torques on the tool perpendicular to the tool axis. Coring tool current and rotation speed will be monitored to detect binding of the tool – increased current or reduced speed will be indicators of tool binding. Absolution Motion Visual Odometry (AMVO), described below, will measure absolute motion of the rover relative to its pose at the start of the coring operation.

IV. ABSOLUTE MOTION VISUAL ODOMETRY

Absolute Motion Visual Odometry (AMVO) is a technique for measuring the motion of a rover to sub-millimeter precision for relatively small motions of the vehicle (< 50 cm). We use this technique to accurately detect and measure the slippage that a rover undergoes while collecting a sample from the environment.

AMVO uses the exact same algorithm as visual odometry (VO) [2, 3] but it uses the concept of a "reference image pair" to avoid the well established measurement drift associated with VO. We are able to use the technique because we expect that the rover will not slip a significant amount (up to ~50 cm) before we choose to stop sampling or to accommodate the slippage.

The "reference image pair" is taken before the sampling is started. Then the each subsequent image pair taken for motion estimation is processed along with the reference image pair using the visual odometry algorithm. We will briefly describe the visual odometry algorithm here, for a more in depth explanation see [2, 3]. VO takes two image pairs as inputs (in our case, the reference image pair and the motion image pair). Initially, it finds a set of features in the first image pair based on an interest operator (i.e. Forstner). Then it localizes each of the features in 3D using stereo triangulation. Next, it finds a set of features in the second image pair (using an estimate of their image location from an estimated motion input) and performs stereo triangulation on these as well. It then attempts to match features from each of the image pairs with one another. Finally it estimates 6-DOF motion using a two step process. The first step is a rough motion estimate using a singular value decomposition technique called Schonemann motion estimation. The second step is a maximum likelihood motion estimation that refines the first estimate.

By using the reference image pair for each motion estimate we get an estimate of the "absolute motion" of the rover and we are able to avoid the drift that occurs from integrating the relative estimates associated with standard VO, thus enabling extremely precise motion estimation.

In the first experiment, a sequence of 500 image pairs were taken with the rover hazcams without any rover motion to find 'minimum bound' of slippage estimation during sampling using the AMVO technique (see Figure 2). Sub-mm (potentially <0.1 mm) motion detection can be achieved using this technique (the 3σ variance of this signal is 0.089 mm). For MER class manipulators this would correspond to <5 Newtons of tool force which is of a similar accuracy as most force sensing techniques.

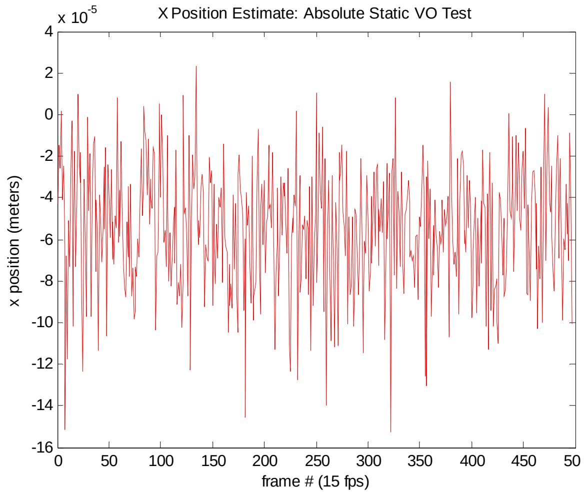

Figure 2: AMVO Minimum Bound Test

A second experiment was to command the rover the smallest possible motion. This resulted in a motion estimate of 0.54 mm (see Figure 3), which was easily detected by AMVO.

A third experiment was to simulate sample collection on a sandy slope by attaching a vibration motor to the rover while on a slope of 16.2° (pitch) and 6.2° (roll). With AMVO, a slip of 1.6 mm was detected. A picture of the slope taken by the front hazcam is shown in Figure 4. Results of the experiment are shown in Figure 5.

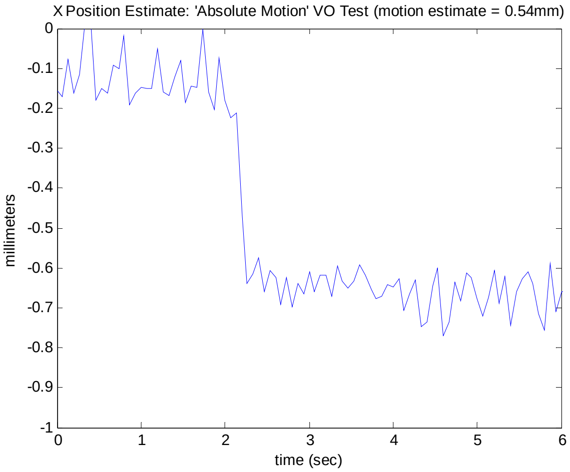

Figure 3: AMVO Small Motion Test

Figure 4: Picture of Slope Taken by Front Hazcam

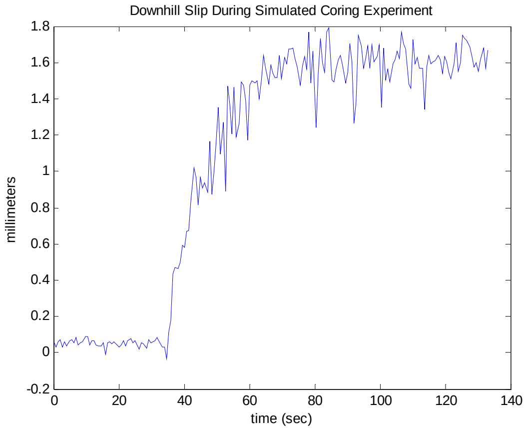

Figure 5: AMVO Slip Measurement

V. DRIVING

Driving the rover back into the arm workspace will require measurement and accommodation of rover slip during the drive. The goal of the rover drive subsystem is to drive the errors of the three controllable DOFs of the rover to zero [2]. The three controllable DOFs of the rover are x, y, and yaw. When the rover slips to the edge of the arm workspace, the sampling process will pause and this driving with slip correction algorithm will be invoked. Simultaneously, the arm will accommodate the rover motion using force control.

VI. CORING TEST

A coring tool was attached to an 85kg rover and coring tests were performed. The coring test setup is shown in Figure 6. The coring bit and resulting hole and core are shown in Figure 7. The LSAS coring tool [1] was attached to the Pluto rover in the JPL Planetary Robotics laboratory for the tests. The LSAS tool is a rotary percussive coring tool and weighed 400 grams and required 15 N average weight on bit. Maximum impact forces felt by the arm were about 60 N. A 2 cm core was acquired at a rate of about 2 cm/hour in limestone. A longer core could have been acquired. Cuttings were removed by a vacuum (an alternative approach would be needed for a Mars application). Coring started easily without a centering bit. An intact core was acquired. This test was significant in that it demonstrated that coring from a low mass rover is feasible.

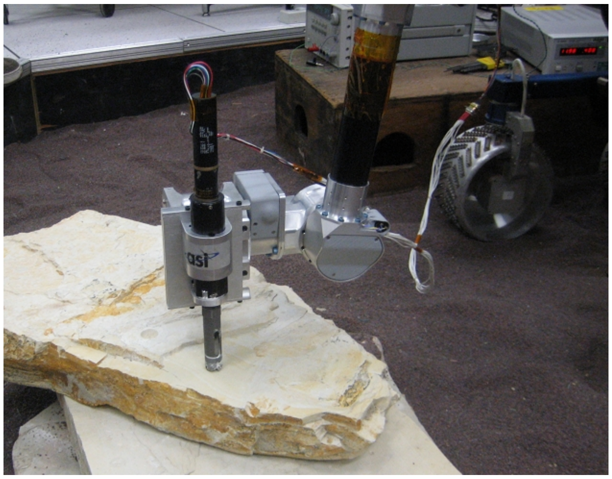

Figure 6: Coring Test using LSAS Coring Tool

VII. SIMULATION RESULTS

The use of a high fidelity simulation environment allows for reduction in the cost of experimentation associated with hardware and software rover design. SAI [4] (Simulation and Active Interface) is the simulation tool developed at Stanford University. It is used within the framework of this project to assist the design of the physical rover. It is also a valuable tool to analyze the behavior of a low mass rover coring rocks on slopes. The controller design stage can also benefit from such a simulation tool since it provides a low cost means to validate controllers developed for the rover.

Figure 7: Coring Bit and Resulting Hole and Core

SAI is unique in that it is a real-time interactive environment that allows the user to apply and sense forces within the virtual world via haptic devices. SAI features multi-contact resolution for multi-body systems, efficient algorithms for articulated body dynamics, and simulated friction and ground reaction forces.

SAI is based upon a general framework [5] for the resolution of multi-contact between articulated multi-body systems in the context of operational space control for robots [6]. Using this framework, the dynamic relationships between all existing contact points can be described. These relationships are characterized by the masses as perceived at the contact points. A force exerted at a contact point, whether from a collision with another object or from interaction with a user, can be translated into forces at all related contact points. The necessary computations can be performed with an efficient recursive algorithm.

The contact space representation allows interaction between groups of dynamic systems to be described easily without having to examine the complex equations of motion of each individual system. A collision model can be developed with the same ease as if one were considering interaction only between simple bodies. Impact and contact forces between interacting bodies can then be solved efficiently.

SAI was used to simulate the slippage occurring while coring on a terrain with slope (pitch: 16.2°, roll: 6.2°). A model of the forces induced by the coring tool operation was input to SAI and simulations were run where the manipulator configuration was held fixed using a stiff joint controller. The resulting slippage of the wheeled platform as well as the wheels' orientation were shown to be similar to empirical results obtains with the Rocky 8 rover. This simulation however required an adaptation of the friction model in SAI. SAI utilizes rigid-body dynamics and cannot utilize friction models that include wheel sinkage and deformable terrain. To model this behavior, SAI represents friction as a combination of static and Coulomb friction where the friction coefficients change as the rover slips. Although this is a general model, for initial testing we use a linear relationship relating the friction coefficients to distance, to represent wheels digging in.

We also use SAI to develop an algorithm that computes the optimal coring configuration given the coring conditions: terrain slope, coring point location, ground type. This requires the definition of the criterion use to characterize the optimality of a given configuration. We used different manipulability measures [7] so that the force capabilities of the robot along the coring tool axis are maximized and the overall manipulability is maximized in all operational direction. We are still working on incorporating a third requirement associated to the fact that the effects of disturbance forces at the end-effector should be minimized in terms of slippage.

Finally, SAI is used to test different control strategies for the coring task. In order to provide the system with a model that is generic enough for force analysis purposes, we chose to use the free-floating representation of the system. This representation does not assume the contact of the wheels on the ground as a granted fact. The system is rather represented as a floating system subjected to gravity and ground reaction forces. This is a very general description framework which is an interesting characteristic for analysis. However this induces the necessity to describe which constraints have to be enforced for the wheel/ground contact to be maintained. This constraint can for example be expressed as: “null acceleration for the wheel/ground contact point in the contact normal direction”. Given this virtual task, any other task assigned to the rover has to be realized without violating this highest priority task, i.e. has to be realized in the null space of the wheel/ ground contact task. Within this framework, a controller for the coring task is being integrated and tested in SAI.

VIII. CONCLUSIONS

Technology to enable coring from a slow-mass rover is being developed. Absolute motion visual odometry (AMVO) was tested to show that small slip motion of a rover can be measured. A coring test was performed that demonstrates the feasibility of coring from a low-mass rover. The SAI simulation environment is being used to simulate the coring system. Coring control is being further developed with results anticipated during the summer of 2007 that will show that coring with modest rover slippage will be feasible.

IX. ACKNOWLEDGEMENTS

The research described in this publication was carried out at the Jet Propulsion Laboratory, California Institute of Technology, and at Stanford University under contract from the National Aeronautics and Space Administration (NASA), with funding from the Mars Technology Program, NASA Science Mission Directorate.

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