Autonomous Sample Acquisition for Planetary and Small Body Explorations

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Abstract. Robotic drilling and autonomous sample acquisition are considered as the key technology requirements in future planetary or small body exploration missions. Core sampling or subsurface drilling operation is envisioned to be off rovers or landers. These supporting platforms are inherently flexible, light, and can withstand only limited amount of reaction forces and torques. This, together with unknown properties of sampled materials, makes the sampling operation a tedious task and quite challenging. This paper highlights the recent advancements in the sample acquisition control system design and development for the in situ scientific exploration of planetary and small interplanetary missions.

1. Introduction

Sample Acquisition systems are envisioned to be an essential part of future NASA plans for both the sample return missions and in situ scientific exploration of planetary and small body objects. Near-term NASA missions requiring autonomous sample acquisition capabilities include Mars Sample Return ('03, '05, '07, '09 missions) and Space Technology 4/Champollion launching in 2003. The sample acquisition operation for these missions is required to be off rover or lander systems. These platforms are expected to be light, to be flexible with low-frequency structural modes, and to have little resistance to sampling induced reaction forces and torques. Furthermore, the environments possess uncertain surface substrate with unknown mechanical properties. The stability of the sampling mechanism and the supporting base platform require that forces and torques must be limited and controlled to certain prescribed threshold, which in turn, impose additional complexity. In light of all these constraints, the sample acquisition operation can be quite challenging and key control system technologies are necessary to ensure stability and performance of the integrated sampling system.

The Jet Propulsion Laboratory (JPL) has developed a rock coring system and a subsurface drilling mechanism that are capable of acquiring samples from flexible and light supporting platforms. A smart sampling control system has also been devised for autonomous and robust operations of these mechanisms. The following highlights a summary of the proposed sampling control system design. Actual test results of the integrated coring and drilling control system design are available demonstrating the autonomous control of the smart sampling control system.

2. Problem statement and Requirements

The minimal requirements for small body exploration are taken from those of the Space Technology 4/Champollion flight project. The basic approach for sample acquisition on small bodies is expected to be lander-mounted drilling platforms. Because of many uncertain characteristics of small bodies, aside from the challenging task of

Proc. Fifth International Symposium on Artificial Intelligence, Robotics and Automation in Space, 1-3 June 1999 (ESA SP-440)

successful landing, landers must be anchored to the surface to avoid detachment from the surface. In this case, anchors can only provide nominal retention force and torque for lander-based drilling. To ascertain the dynamic stability of the lander-drill system, the drill mechanism must be actively controlled to retain reaction forces and torques generated during sampling.

The primary requirements for planetary sample acquisition are derived from those of the Mars Sample Return missions. The general strategy for planetary core sampling is envisioned by means of rover-mounted coring platforms. By design, rovers are expected to have lightweight and flexible modes with little damping. Further, rover system can have excessive suspension deadband and backlash. Moreover, the expected axial drilling force is comparable with the effective weight of the rover. Therefore, the coring system must be actively controlled to limit the effect of reaction forces and torques imposed by uncertain interactions between the coring bit and the sampling surface.

To satisfy performance requirements for in situ scientific studies, applied drill forces must track commanded force profiles to within certain specified accuracy. The telemetry data such as penetration and rotation rates can be used to derive information about material properties of the sampled rock or substrate drilled. This together with other uncertainties and structural dynamics impose challenging constraints on the end-to-end operation of the coring or drilling control system.

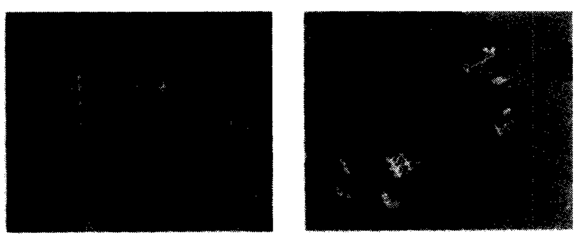
3. Hardware Development

JPL has developed prototypes of two generations of a drill and a coring system. The ESB drill was developed under the Exploration of Small Body Task and is consisted of three modes of operations: 1. Drill Axis for penetration, 2. Rotation Axis for drilling, and 3. Arm Axis for indexing. The ESB drill has been integrated and tested on a rigid platform, a one-dimensional landing leg, a three-legged lander, and a super light rover with variable mass and flexible modes.

(a) (b)

Figure 1. (a) ESB drill on a Lander system.
(b) ESB drill on a flexible rover.

The RDC Mini-Corer was developed under the Robotic Drilling and Containerization Task and is consisted of four axes of operation: 1. Drill Axis for penetration, 2. Rotation Axis for drilling, 3. Break-Off Axis for core breaking, and 4. Push-Rod Axis for core ejection. The RDC Mini-Corer has been integrated and tested on rigid platforms, on a mock rover with variable mass and stiffness, and on the FIDO rover system developed by the Exploration Technology Task. The mounting interface to the platforms is accomplished by a pitch and yaw mechanism that allows motions in two directions.



(a) (b)

Figure 2. (a) RDC Mini-Corer on a mock rover.
(b) RDC Mini-Corer on FIDO Rover.

The selection of hardware components, e.g., motors, gears, encoders, drivers, electronics, sensors, and other mechanical properties, was accomplished by extensive trade studies between the mechanical design specification options and the control system objectives. The hardware setup in each case played an important role in the development of the key control system technologies.

4. Control System Architecture

The main objectives of the sampling control system are to ensure stability, performance, and efficiency throughout the sampling operation. The following highlights important constraints that must be accounted for by the sampling control system. Rovers and landers can withstand limited reaction forces and torques. Sampling operations can excite structural modes of the associated rover or lander platform. Sampling objects have uncertain mechanical properties, e.g., hardness cohesiveness, porosity, or texture, and can induce fast transient responses. Live rocks and surfaces are inherently unstable and impose additional uncertainty in the sampling process. Thus, a viable drilling initiation strategy, together with a stable and robust drilling control algorithms, becomes a crucial part of the sampling control system.

The control system architecture is composed of three levels of decentralized controller design, where an executive controller commands each individual local servo and accordingly an associated low-level servo in each axis of operation. The executive controller is event-based driven and ensures dynamic stability during the sampling operation and provides fault detection and hazard avoidance. The local servo in each axis is unique and operates independently of other axes. The local servos accept commands from the executive controller and provide closed-loop control of position, rate, force, or torque. The operating plant in each local servo is an independent low-level motor/encoder servo loop. The controller in each local servo utilizes commanded data, position, rate, force, or torque, to zero out the tracking error between the commanded data and the actual motion profile. The controller associated with each low-level servo loop is designed so that the servo is stable, meets tracking performance, and has a proper and fast reaction response. The overall control system design is fully autonomous and incorporates a hybrid of appropriate controller design methodologies. The low-level and local servos perform continuous control of the sampling dynamics and employ highly optimized loop shaping methods. The executive controller responds to event-based scenarios, fault protection, and fault recovery.

5. Servo Loop Shaping Design

The stringent stability and performance requirements in each axis of the sampling operation demand a highly optimized loop-shape design for each servo subsystem. In general, the control system loop design is function of the sampling frequency, the structural resonance of the system, and sensor noise. The expected sampling frequency provided by the real-time operating system is expected to be between 50 to 100 Hz. Therefore, the control bandwidth is limited to be less than 5 to 10 Hz, respectively. Moreover, the control loop gain must be gain stabilized as the Nyquist frequency is of the same order of the structural modes or lower. The strategy in this case is to design the control loop bandwidth as wide as possible for maximum performance and disturbance rejection. Because of the presence of low-frequency structural modes, the high-frequency portion of the loop shape must have a fast roll-off to ascertain sufficient gain margin at the structural resonance frequency. This however reduces phase margin at the crossover frequency violating stability requirements. This limits the loop bandwidth further as sufficient gain margins and phase margins are required in the vicinity of the crossover frequency. Under the above constraints, the application of Bode-Step loop-shaping method [1] is quite applicable for the optimal loop shaping of the sampling control system. Figure 3 illustrates the proposed loop design, where f_b denotes the feedback bandwidth frequency and f_{st} is the lowest structural mode frequency. The slope of the low-frequency asymptote is about 10 dB per octave and the that of the high-frequency asymptote is about 18 dB per octave. The Bode step gain extends over one octave providing sufficient separation between the low-frequency and high-frequency rolloffs. This stability margin specifications are about 10 dB gain margin and 30 degrees phase margin. In this respect, once the frequency of the structural resonance is determined for each axis of the operation, the associated loop bandwidth and consequently, a rational transfer function realization can easily be computed in each case.

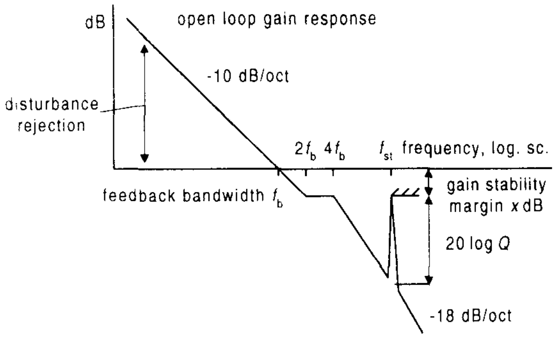


Figure 3. Bode-Step method for servo loop design

Once specific loop shape is designed for each servo subsystem, an appropriate controller can be designed by compensating for the effect of each plant transfer function. The net result is a highly optimal linear controller for each axis of the sampling operation. However, the actual system is nonlinear and is subject to great deal of uncertainties. Best results can be achieved when a nonlinear dynamic compensation is used together with the resulting linear controller in each case. The actual details of the nonlinear controller design are beyond the scope of this paper and will not be presented any further.

6. Control Software Implementation

The sampling control system software is integrated in the VxWorks real-time operating system running on a dedicated processor. A graphical user interface is designed on an NT or Unix host for command processing, development, data archiving, and post-data analysis. The interface between the target processor and the host is established via an Ethernet or a wireless Ethernet connection. All control algorithms, codes, and device drivers are implemented in C/C++ running on the target processor. Figure 4 shows the high-level schematic of the sampling control system for the ESB drill system. Figure 5 illustrates a block diagram representation of the RDC Mini-Corer control system.

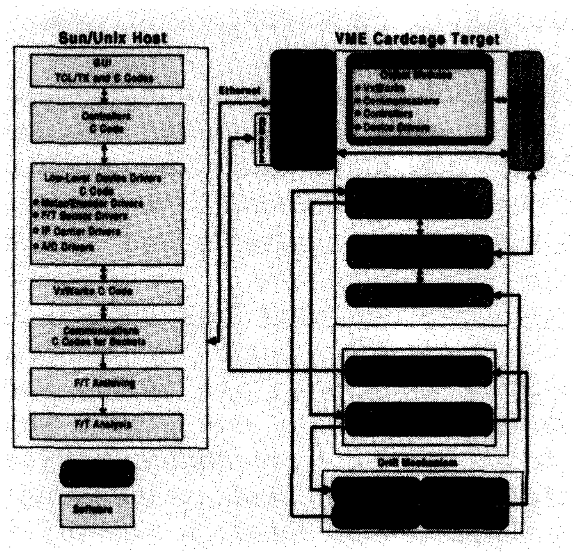


Figure 4. Schematic representation of the real-time sampling control system for the ESB drill.

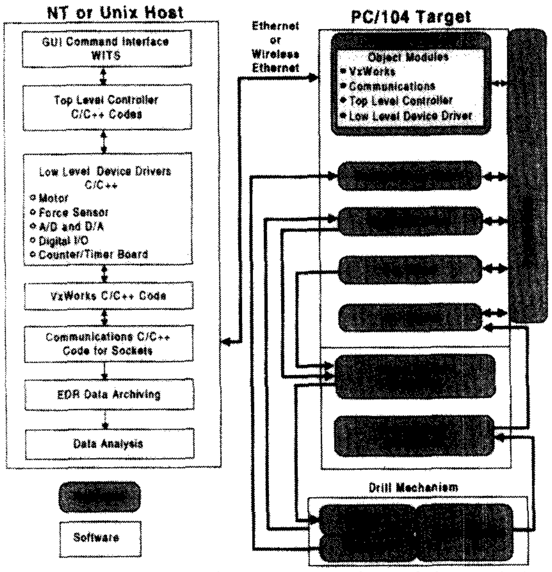


Figure 5. Schematic representation of the real-time sampling control system for the RDC Mini-Corer

7. Test Results

The ESB drill and the RDC Mini-Corer have been tested extensively on various platforms. Numerous test materials have been considered under various operating conditions. The sampling control system strategy proves quite efficient and satisfies system stability specifications, as well as, science performance requirements.

The ESB drill system was used to drill a set of cometary test samples. Real data was archived in each case and was used to generate a material characterization baseline for these test samples. The analyses of the data revealed a great deal of information on the drilling performance, as well as, the sampling material. The results can be classified into an archive to deduce optimal drilling parameters, e.g., thrust force or rotation rate, when drilling unknown materials. Figure 6 demonstrates the results.

The complete analysis of the results is beyond the scope of this paper and will not be presented. The end-to-end sampling operations of these two coring and drilling systems and will be presented in videotapes.

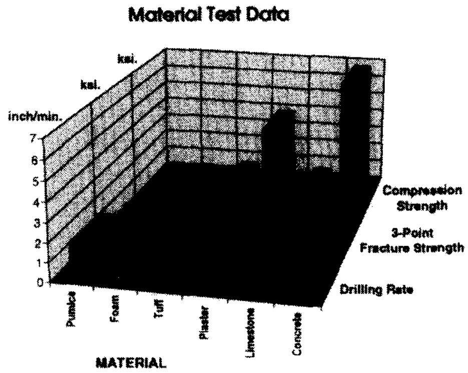


Figure 6. Material characterization for comet simulant materials.

8. Conclusions

The sampling control system design provides the enabling technologies necessary to accomplish autonomous in-situ scientific exploration of planetary and small interplanetary objects. Two generations of sampling mechanisms are developed to perform rock coring and subsurface drilling. Future design efforts for a next generation drill mechanism involve automating a process to add segments to the top of a drill stem for an automated deep drilling.

9. Acknowledgements

This work was performed at Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

10. References

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