Exploration of Small Bodies

Donald R, Sevilla, Kevin A, Burke, Greg R. Gillis-Smith, Ali R. Ghavimi, Randel A. Lindemann, Frederick Serricchio

Jet Propulsion Laboratory / California Institute of Technology
Pasadena, California, USA
e-mail: donald.r.sevilla @jpl.nasa.gov
Tel: (818) 354-2136 Fax: (818) 393-1324

ABSTRACT

The Exploration of Small Bodies task is developing technologies required to perform ***in situ*** scientific investigations on small interplanetary objects such as comets and asteroids. Because these objects have nearly zero gravity, some type of attachment system must be implemented if subsurface study is to occur. Landing, attachment, drilling and sampling on comets in particular will be challenging due to the expected extremely rough terrain and the unknown mechanical properties of the surface. This paper presents some of the efforts to date at NASA's Jet Propulsion Laboratory in developing a new landing system intended for use under milligravity conditions, a unique compact drilling and sampling system, and the closed-loop controllers that will autonomously operate these systems.

1. INTRODUCTION

Comets are thought to be the least altered by the processes that formed the solar system, and thus have been a high priority in planetary exploration for the primordial information they may contain, Future exploration of these interplanetary small bodies, and including asteroids and small planetary satellites, requires technology development in a variety of areas. Landing and sampling operations in the low gravity environment of small bodies (ranging from 10-4 to 10-2 meter per second squared) is an extremely challenging problem. NASA's Exploration of Small Bodies (ESB) task is developing some of the enabling technologies to accomplish ***in-situ*** scientific studies of these interplanetary objects. The primary objectives of this task are to develop the mechanisms and control strategies to perform landing, anchoring, surface/subsurface sampling and sample manipulation for representative science instruments.

A key technical challenge for this effort is centered principally around the expected minimal resources available from the proposed spacecraft that will perform these missions, For example, the Apollo lunar drill had a maximum power draw of 430 watts and a 13 kg mass, while the ESB task's goal is to consume no more that 30 watts with a drill mechanism limited to a mass of 2 kg,

1.1 Cometary Environment

Comets are believed to be aggregates of interstellar sub-micro dust grains with coatings of volatiles, ices and organics. Most scientists agree that comets consist of fractal rubble piles of irregular shaped particles, rough at all scales. It has been theorized that the surface of a comet consists of a fragile dust layer over a more solid ice-like material. Table 1 describes the range of predicted cometary material properties.

Table 1 -Range of Comet Substrate Properties

Parameter	Weak	Typ	Strong
Density (g/cm^3) - Subsurface	.2	1.0	2.0
- Mantle	.05	1.0	2.0
Porosity (%)	80%	30%	10%
Thermal conductivity (W/mK)	.05	1.0	3.0
Specific heat (J/kg K)	70	120	2000
Compressive strength (MPa)	10^{-4}	10^{-1}	10^{2}
Dynamic tensile strength (MPa)	10^{-5}	10	10^{2}
Penetrability Index	200	50	20

Photographs returned from Giotto's fly-by of Comet Halley showed that the coma formed as the comet approached the Sun actually originates from collimated jets, presumably from cracks forming in the mantle, rather than an overall outgassing. The surface terrain is predicted to be extremely rough because the very low gravity and past erosion will not have formed the cometscape into anything similar to the surfaces previous landers have attempted to land on.

Based on the data from the Halley encounter, there is a concern that the comet surface may consist of a thin mantle overlarge underlying voids that have been vented from past orbits about the Sun, Reliable landing and anchoring in this wide range of material properties and surface conditions is a formidable task, The sample acquisition process must be as reactionless as possible, since the anchoring of the lander must not be disturbed from high thrust loads during drilling.

Another significant technical challenge involves the fundamental nature of comets. Their icy surface is approximately -150°C and in the vacuum of space does not melt, but sublimates. Therefore, the comet will actually "draw away" from any lander structure or anchor that is too warm, and could actually expel the object by a thrust due to the vaporization, This is a problem that past landers have not had to deal with, in that for comet missions the structure and mechanisms that contact the surface must operate at cryogenic temperatures.

The mass and power resource limitations for asteroid missions are expected to be as challenging as the proposed comet landers. Higher demands may be placed on the landing leg design and on the anchoring systems than for cometary missions. An asteroid's surface environment may include both significantly harder rocks and a dusty regolith.

2. LANDING SYSTEMS DESIGN

A lander for the milligravity environment of a comet or asteroid would require performance capabilities for rough terrain far in excess of previous landers such as Surveyor, Viking or Apollo. Achieving ***dynamic stability*** after contact requires arresting the overturning moment of the lander due to any residual horizontal velocity relative to the surface. The baseline navigated trajectory assumes landing velocities of 4 m/s vertical and 1 m/s horizontal, relative to the local surface, which is similar to the performance requirements of Viking and Apollo's landing systems. Viking's performance specifications limited the angle of the local landing surface relative to the velocity vector to 19 degrees, while the early Apollo missions were limited to 12 degrees. ESB has assumed a requirement for dynamic stability when landing on a local surface 45 degrees from the velocity vector. This requirement to accommodate significantly higher local horizontal velocities, and the near absence of gravity to return a tipping lander back to the surface, makes the challenge to arrest lander overturning a much more significant problem. Obstacle height in the local terrain is assumed to be limited to.5 meters.

The culmination of a design study was to develop a three legged landing system that at first appears similar to the Surveyor, Viking and Apollo landers (Figure 1), However, there are a number of obvious and subtle differences that result in this approach being the most robust solution. The three legged configuration was selected for the wide footprint, which helps to maintain landing stability. More significantly, this configuration is also needed to achieve the low operational temperature requirements of the structure that will contact the comet by isolating it from the warm lander body and providing large radiating areas to space, Each footpad must have sufficient surface area to provide buoyancy on a weak landing substrate. In a departure from past landers, each footpad contains an integrated anchoring system consisting of a tethered anchor, a pyrotechnic accelerator and a winch mechanism. In this configuration, redundancy of anchoring may be provided,

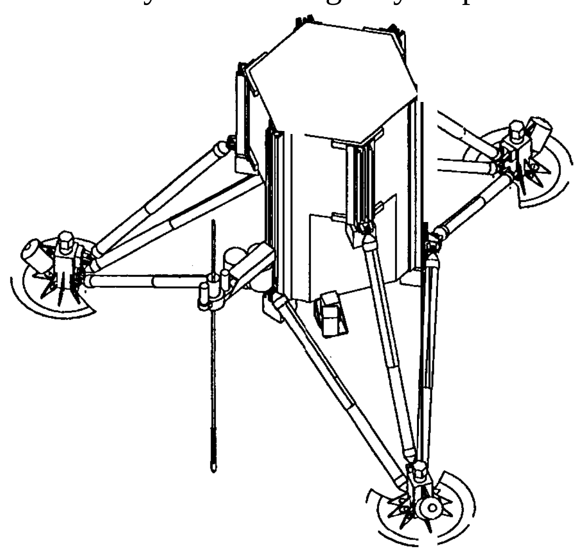

Figure 1- ESB Lander Configuration

Another departure from landers of the past is the capability of each leg to conform to the local surface to direct each anchor to be fired relatively normal to the surface, and to provide a more stable final landing platform. This high-conformance is produced by the large-stroke damping struts that make up each leg assembly and the degrees of freedom of the various end fittings. Also new is the type of damping strut utilized, designed to provide a lower amount of rebound energy, and a "smart landing" control system to individually minimize the force each anchor must impart to the substrate.

2.1 Kinematics Modeling

Extensive modeling using ADAMS (for Automatic Dynamic Analysis of Mechanical Systems) was performed to predict the performance of this landing system, and to allow the engineers to tailor the design of each component prior to fabrication. A model of the lander was created with the inertia, mass, stiffness and damping characteristics of each discreet component. The modeling includes all of the forces internal to the lander, such as mechanism and inertial forces, as well as external forces that result as different parts of the lander interact with the terrain, The terrain is also modeled to represent topography and surface strength. The ADAMS lander model contains 46 rigid bodies connected by interface constraints and forces to yield a system with 141 degrees of freedom. Each leg assembly is comprised of 3 damping struts connected to the basebody and footpads by universal joints. Each of the damping struts are modeled as 4 rigid bodies, Each footpad contains a 3 mass assembly of the structure, a pyrotechnically fired piston and the anchoring **penetrator.** All momentum transfer is correctly modeled, The tethered anchor is lodged into the landing surface and a drag force (generated by the winch) resists the increase in radial distance between the anchor and the footpad,

2,2 Adaptive Landing Controller

The adaptive landing controller in development receives inputs from basebody accelerometers and gyros, as well as input from accelerometers in each footpad and anchor (Figure 2). Landing in the rough terrain is made more robust by the strategy of individual control of each pyre/anchor/winch mechanism. The controller senses when each footpad has conformed normal to the surface, and fires each anchor prior to the foot rebounding off the surface, The controller also tailors the operation of each winch motor. By sensing the angular acceleration of the basebody as well as computing the distance that each foot bounces off the surface, lander tip-over is arrested by powering the winch motors. Since the strength of the comet surface is unknown, it is highly desired to minimize the forces that the anchors must retain, Thus, the controller can minimize each anchor load by calculating the force required to zero out the relative velocity between each footpad and anchor before a critical height is reached, Lander rebound and tip-over are issues when landing on a hard substrate. For landing on soft substrates the majority of the landing energy is absorbed by the surface.

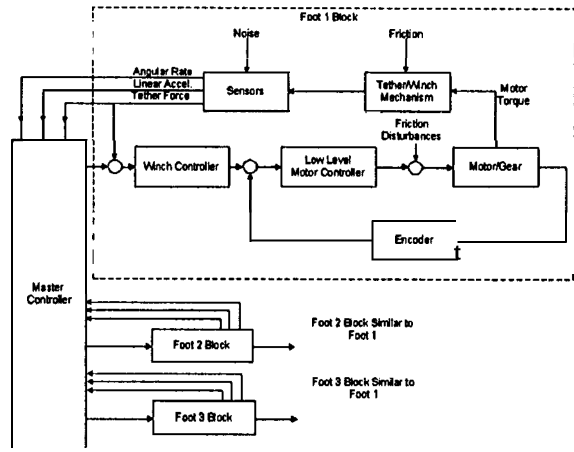

Figure 2- Adaptive Landing Block Diagram

Therefore, the anchoring force requirements are low because there is little horizontal momentum to arrest and the drilling force requirements will be small.

2.3 Lander Hardware Development

New technology damping struts were developed for this lander. Viscous dampers (such as used by Surveyor) could not be used because of the design criteria that all structure of the landing system operate at cryogenic temperatures. Darnping struts using crushable aluminum honeycomb were utilized for Apollo and Viking, but some energy was returned (rebounded) and additional mechanization was required to produce tension and compression struts. To provide the correct landing geometry, the primary damper strut must exhibit approximately twice the collapsing force as each of the two secondary struts, To limit the landing load of a 45 kg body at 5 m/s below 30 Gs, the primary strut must start collapsing at approximately 900 N for a stroke of 30 cm, The secondary struts must have damping in tension as well as compression, and all struts must retain tension loads after compression if the lander is to interact with the surface (such as drilling). The ESB task has developed struts using the shearing action of plunging cutters into vacuum-rated polyurethane foam. (Imagine thrusting a thin knife into a sheet of Styrofoam, and then trying to pull it out). The performance characteristics of the struts can be tailored by utilizing different densities of the foam and varying the crossectional and surface area of the cutter plunger. Prototype struts were fabricated and tested at room temperature and -165°C. This type of damping strut exhibits less than 40% of the rebound of aluminum honeycomb. While the performance of this technology currently is erratic under room temperature conditions, at cryogenic temperatures it performs very well because the foam shears more predictably, A test strut designed to start collapsing at 450 N exhibited a 130 N tension force capability after compression, A full size test lander was fabricated with a functional landing leg system, and was drop tested at 5 m/s with the struts pre-cooled using a liquid nitrogen bath, Acceleration of over 85 Gs was measured at the footpads while the acceleration of the basebody was less that 12 Gs, demonstrating the impact attenuation of the system (Figure 3). A pyrotechnic anchoring mechanism was developed to accelerate 80 g penetrators to 100 m/s exit velocity. Under test conditions of - 165°C the device demonstrated an exit velocity of over 85 m/s.

Figure 3- Lander Drop Testing

A test program was also initiated to study the effectiveness of anchoring in various strength and density materials. Penetration testing involved the acceleration of the anchor using a laboratory compressed air gun. The targets were selected with compressive strengths and porosity similar to the medium and strong ranges of predicted comet properties, It was deemed impractical with the available resources to perform accelerated anchor testing against targets with characteristics near the weak range of comet strength. Adequate anchor retention was demonstrated in all but the strongest materials (sandstone). The porosity of the sandstone was so low that it was deemed a non-relevant analog, and specialized concrete targets are currently in fabrication at this time.

The "smart landing" controller development is currently in-process, as is the development of the integrated tethered anchor and winch mechanism. Single axis testing using a lander "sled" on linear bearings is planned to be completed by this September to validate and optimize the control algorithms. Full-up three axis testing will be performed during 1998 by hanging the Lander testbed sideways through its center of gravity and swinging it against a vertically-oriented simulated landing surface,

3. DRILLING & SAMPLING SYSTEMS

The ESB task is developing a unique drilling and sampling system for a cometary mission, with applicability for other missions as well, For missions to small bodies with low gravity, drilling thrust loads must be controlled, or coordinated with the anchoring systems, to prevent ejecting the lander off the surface. Further challenges for a comet mission are the large range of material properties of the substrate to be sampled and the cryogenic operating environment. The Compact Drill Mechanism was designed to meet these challenges and the low resource requirements of current and future small spacecraft, where mass and power must be minimized. The baseline performance requirements are to drill to a 20 cm depth (100 cm goal), acquire a 1 cm3 sample without heating it more that 5°C, prevent vertical mixing of the material, extract the sample and provide it to a mass spectrometer, The goals were to accomplish this against the range of comet materials with a mechanism requiring less that 30 watts, less than 2 kg mass, and without applying more than 45 N thrust.

3.1 Drilling and Sampling Mechanism

The Compact Drill Mechanism (Figure 4) eliminates the drill tower normally required for automated drilling, and concentrates most of the mass in a non-moving housing. The drill has independent control of the thrust and rotation of a drilling stem, with percussion also incorporated in the mechanism. The drill stem passes through the housing and the thrust and rotation forces are applied anywhere along the length of the shaft, This is accomplished by cutting two opposing slots along the length of a modified acme screw, and using one motor to only rotate the screw.

Another motor rotates the acme nut, which provides translation (thrust) of the screw. Thus, the motion of the screw is dependently coupled to the motion of both of the motors (Figure 6). By coordinating the rotation of

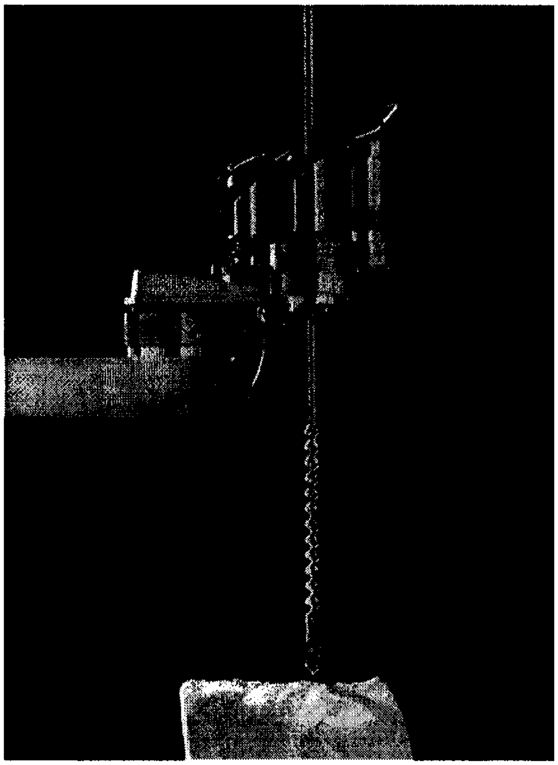

Figure 4- Drilling/Sampling System

each motor, the translation and rotation of the screw can each be varied between zero and a limit set by the gear ratios and the maximum speed of the motors, Percussion is accomplished by the use of a spring loaded mass and cam driven by the rotation motor through the slots in the screw. A 20 cm length of flight auger with a drilling head/sampling chamber is fastened to the end of the drill screw.

Figure 5- Drilling Head/ Sampling Chamber

The sampling chamber is within the custom drill head, and is opened and closed without the need for additional actuators by the technique of thrusting the bit against the substrate, counter rotating the bit to open the chamber and collect drill tailings at the desired depth, and then foı vard rotating the bit to close the chamber (F gure 5), This technique

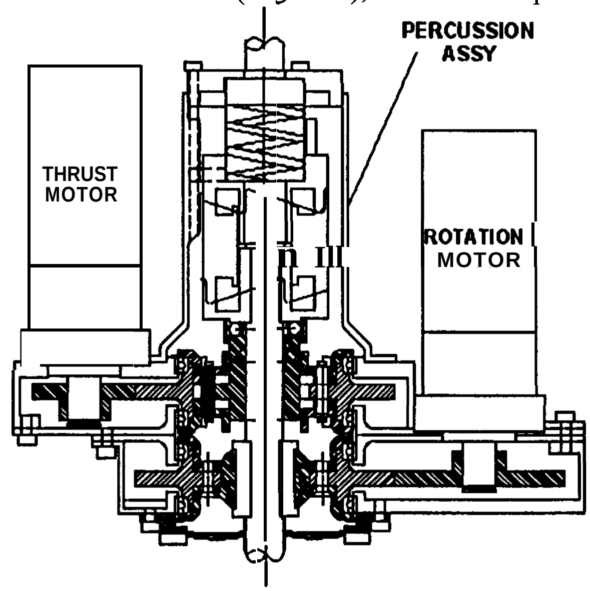

Figure 6- Compact Drill Cross Section

has been tested against extremely low strength materials (such as fine olivine dust) and has proven to be simple and reliable. The drilling head/sampling chamber is removable by docking into a passive station, and using the drill motors to facilitate the removal and replacement of the head. The entire drill head would be placed in the oven of a mass spectrometer and would act as the sample crucible during analysis.

3.2 Drill Adaptive Controller

The operation of the drill mechanism is controlled actively by a "smart" hardware/software system. This controller performs the closed-loop commanding of the drill for position and thrust as well as providing the autonomous sequencing. In addition, the on-board sensors already required for the control of the drill are also used to provide scientific data about the substrate drilled, The embedded sensors for the drill are individual position encoders on each motor shaft and a single six axis force/torque sensor coupled between the drill and the mounting structure.

The controller system architecture is shown in Figure 7. The system can operate in a direct teleoperated mode or in an autonomous mode, The autonomous procedures are a set of C routines that generate the desired commands to activate the drill to position itself at a specified location to acquire samples at a certain depth. These autonomous tasks generate commands that merely involve the initial and final state of the task. Since the surface properties are not known in advance, a closed-loop control system is required to actively control the commanded rotational and translational force, The elements of this closed-loop system are the low-level translational and rotational servos, the force/torque sensor and the force and torque controllers, The low-level servos themselves constitute a set of closed-loop systems whose driving inputs are the translational and the rotational rates. The sensors measure the net force and torque applied to the surface during drilling, and the controllers use these raw

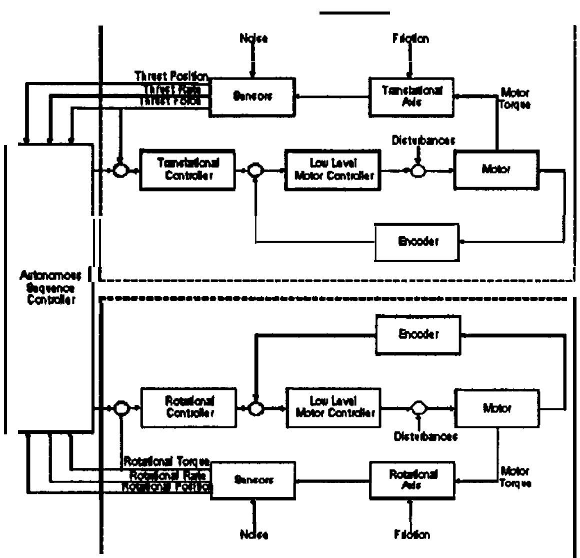

Figure 6- Drill Controller Block Diagram

measurements to derive and command the appropriate translational and rotational rates. The low-level servo system for each axis consists of a motor, gears, encoder and a motor controller, The input to the servos are the controlled rates provided by the higher-level control hierarchy. The motor controller uses the input rate and the encoder measurements to ensure that the actual motor rate tracks the commanded rate effectively.

The mechanism developed meets the performance goals of drilling a 1.5 cm diameter hole in volcanic rock (Bishop Tuff) while limiting the thrust force to less than 45 N. The rate of drilling is 30 cm a hour, while the power consumption is less than 20 watts. The motor/gearbox has been tested at -165°C in a nitrogen atmosphere, and thermal-vacuum testing is currently in-process. Full up drilling testing at cryogenic-vacuum conditions is planned for later this year.

Scientific information regarding the substrate being drilled is available from the embedded sensors within the mechanism. Currently, methods are being developed to perform this data extraction by calibrating the drill against known terrestrial materials. Discriminating information about the mechanical properties of the substrate being drilled appears to be attainable from four different data sets archived by the drill controller:

1) Initial force versus initial translation (substrate stiffness and hardness).
2) Penetration rate versus thrust force (drilling effectiveness).
3) Force declination versus time, while reducing thrust (substrate fracture and friction).
4) Thrust deviation versus time (homogeneity of substrate).

4. CONCLUSION

One of the primary challenges in this task is to verify the effectiveness of the landing system against extremely rough terrain. While the ADAMS modeling assists in the design of the systems, only full-up validation testing will be truly convincing. The 3 axis lander pendulum testing to be performed next year will be initiated against angled, simulated surfaces incorporating obstacles. The single axis tests performed this year will verify the control algorithms using a less complex test, and will provide a test bed for verifying the design of the tethered anchor and winch mechanism,

The technologies developed under the Exploration of Small Bodies task will enable the long-desired scientific study of comets by allowing a lander to perform ***in situ*** remote investigations.

5. ACKNOWLEDGMENTS

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