Autonomous Landing and Smart Anchoring for In-Situ Exploration of Small Bodies

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Abstract. Future NASA missions include in-situ scientific explorations of small interplanetary objects like comets and asteroids. Sample acquisition systems are envisioned to operate directly from the landers that are anchored to the surface. Landing and anchoring proves to be challenging in the absence of an attitude control system and in the presence of nearly zero-gravity environments with uncertain surface terrain and unknown mechanical properties. This paper presents recent advancements in developing a novel landing and anchoring control system for the exploration of small bodies.

1. Introduction

Smart Landing systems are essential for in-situ scientific investigation of small interplanetary objects like comets and asteroids. The ability to land on small bodies is a challenging problem mainly due to nearly zero-gravity environments, intrinsic properties of small bodies. The complexity arises as target bodies pose uncertain characteristics in their associated spin axes, rotation rates, geometric orientation, material properties, and surface terrain. In the presence of these limiting constraints and in the absence of an attitude control system, a smart landing strategy is needed that is capable of providing a reasonable impact absorption, a stable landing configuration, and an anchoring system for retaining the lander to the surface of the target body. Science objectives require that

sample acquisition systems and other science instruments operate directly from the lander. Therefore, the anchoring system must be actively controlled to maintain surface retention to facilitate sampling operation and minimize the effects of reaction forces and torques induced by science instruments. The following provides a brief summary of the proposed landing concept, hardware development, and control system design at NASA's Jet Propulsion Laboratory (JPL).

2. Landing System Requirements

The main requirements for the small body landing are based on the earlier version of the Space Technology 4 / Champollion Lander system to be launched in 2003. The target body assumptions are as follows: the gravitational acceleration is nearly zero; the surface terrain has uncertain properties and includes obstacles of up to 0.5 meters in height; the surface has unknown mechanical characteristics whose hardness can range from concrete to fluffy snow.

The lander system does not include an active descent mechanism. The baseline requirements consider impact trajectories with vertical landing velocity of up to 4 meters per second and horizontal landing velocity of up to 1 meter per second, relative to the local surface. Regardless of the large impact velocity and uncertain angle of attack, the rebound velocity must be controlled to less than 1 m/s.

3. Lander Configuration and Design

The proposed architecture for the landing mechanism is a three-legged lander system, where each leg is composed of a tripod of damping struts and an articulated footpad with an integrated anchor and winch mechanism. The damping struts must provide maximum energy absorption to ensure low rebound upon impact at cryogenic temperatures. The articulated footpad conforms to the surface on impact and the pyro fires a tethered anchor. Upon rebound, the winch mechanism brings the footpad back to the surface and maintains surface contact with a prescribed tether tension.
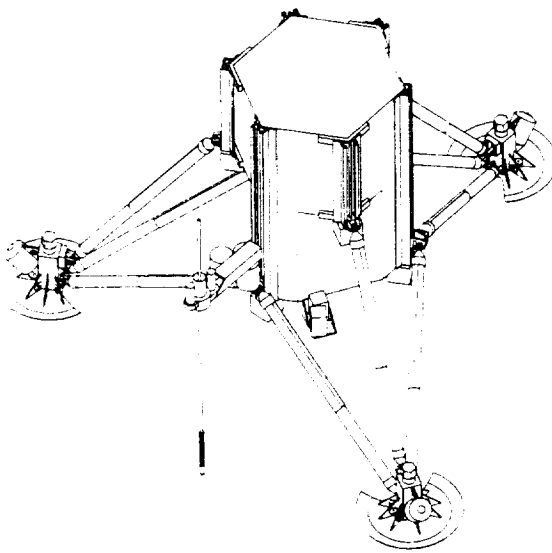

Figure 1.   Lander Configuration

The anchoring system in each foot contains a compact pyro device, a tethered anchor, and a winch mechanism. The compact pyro device launches a tethered anchor into the surface. Each anchor is designed for a tethered high-speed deployment and is accelerated to speeds ranging from 80 to 120 meters per second. The anchor design parameters include mass, shape, material, and impact velocity. These parameters are optimized for minimum momentum transfer

to the lander foot and maximum surface penetration of the anchor. The later capabilities are essential for stability during surface landing, anchoring, rebound, and retention.

The tether in each anchor is connected to a footpad-mounted winch mechanism. The winch motor spools up the tether and provides the necessary means to retain the lander to the surface. The tension in the tether is actively controlled to bring the lander back to the surface upon rebound, maintain surface retention during sampling, and avoid anchor displacement at all times.

The proposed landing concept was implemented in two stages. The first phase of the hardware development involved the implementation and testing of a one-dimensional landing system referred to as *The Sled Mechanism*. The completion of this stage played a key role in the development of the six degree-of-freedom lander design referred to as *The ESB Lander*.

4. The Sled Mechanism

The Sled Mechanism is representative of a special case of one-dimensional landing in a low-gravity environment. The sled platform slides on two nearly frictionless rails. A hanging counterweight and pulley system is used to obtain a realistic simulation of a low-gravity test environment by overcoming the effects of the residual friction. The mass of the sled platform is about 45 Kilograms to closely approximate the actual lander mass as defined by the requirements. The full travel length of the rails is about 3 meters and is sufficient to simulate the one-legged landing scenario over the prescribed range of impact velocities. Further, the amount of travel during rebound is representative of the amount of tip over that is seen by the three-legged lander system. The setup provides an ideal testbed for the evaluation of the control system performance of the sled platform.

Moreover, performance analysis can be conducted based on variation of rebound velocity that is controlled by scaling the impact velocity.
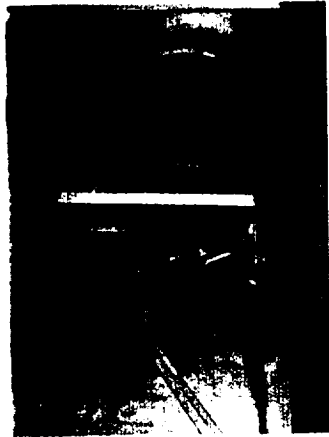

Figure 2. Sled Mechanism

The sled lander setup consists of a winch mechanism, tethered anchor, and compact pyro device. The winch mechanism includes a motor, encoder, tether spool, force sensor, and accelerometer. The sled platform accelerates towards a cylindrical target surface to achieve a prescribed 5 meters per second impact velocity. Upon impact sensed by the accelerometer, the compact pyro device launches the tethered anchor into the target surface. The motor, encoder, tether spool, and force sensor provide the means for the sled control system to bring the sled platform back to the target surface after rebound and maintain surface retention with a prescribed contact force.
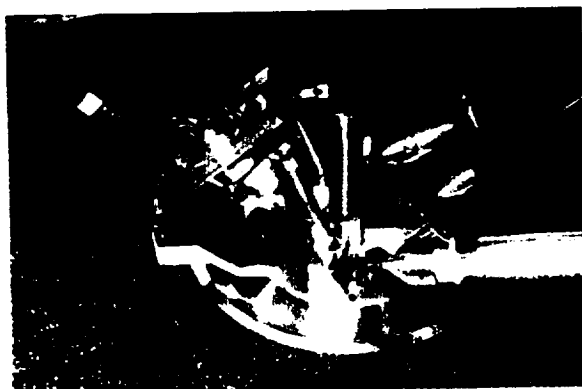

Figure 3. Integrated Foot, Tethered Anchor, Spool, Compact Pyro, and Winch Mechanism

The tethered anchor embedded in the target surface has limited force retention capabilities. Note that independent tests were conducted to measure the force threshold of the anchor in various cometary simulant materials. During rebound, bounce off, surface return, and retention, the control system must control the tether tension to within thresholds imposed by the anchoring force constraint. This means that the motor may pay out the spool before it acts to wind up the tether spool to bring the sled platform back to the surface. This is particularly important during active sampling operation, when drilling forces continuously behave as disturbances to the lander control system

5. The ESB Lander

The ESB Lander is representative of a six degree-of-freedom landing in a low-gravity environment. The system consists of a central body and three landing legs. Each leg includes a tripod of damping struts connected to an integrated footpad described in Figure 3. A sampling system is attached to the central body for drilling purposes as shown in Figure 4.
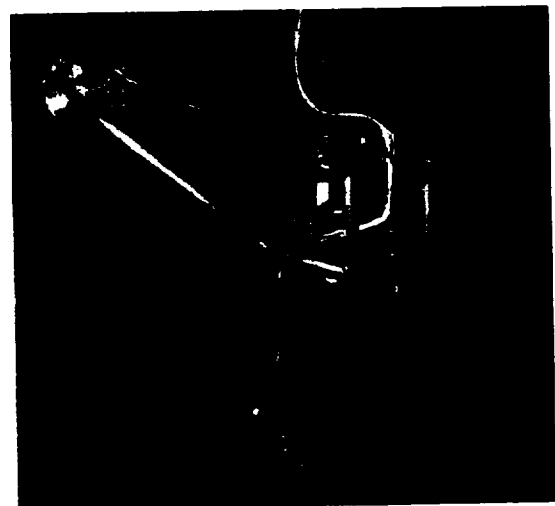

Figure 4. ESB Lander

The lander is hung from a long tether and is released from an off vertical position to accelerate into the target surface. At impact,

damping struts are compressed, the legs are conformed to the surface, and pyros are fired.

JPL has developed a novel damping strut design that utilizes the shearing action of plunging cutters into vacuum-rated polyurethane foam designed to operate at cryogenic temperatures. This strut design is capable of providing passive damping under both tension and compression loads. Another significant property of the damping strut is the capability of retaining tension loads once the struts have been collapsed. This is an essential requirement during any sample drilling operation, as reaction forces tend to apply tension load to the damping struts.

The force sensors trigger the pyros at impact and the landing control system brings the feet back to the surface. The dynamic response of each individual foot in the ESB Lander is similar to that in the case of the Sled Mechanism. A smart control system must be devised, however, to initiate firing pyros in a proper sequential manner after the first foot has made contact with the surface. In other words, the second and third foot should fire their associated pyros based on actual surface impact as opposed to false triggering on the dynamic responses of the first foot. This is, of course, true for the third foot once the first and second feet have made contact with the surface.

5. Control System Design

The primary objective of the landing control system is to enable safe landing and secure anchoring to the surface. A successful landing is defined as: landing within the envelope of specified initial conditions, having all three feet on the surface, and maintaining the desired contact force. This means that the lander control system must provide autonomous actions to firing individual pyros in a proper sequential

manner, preventing the lander from tipping over, minimizing the tether tension, and keeping the anchor embedded in the surface. A robust implementation of a successful landing scenario requires full knowledge of the lander attitude. However, detailed analyses and simulation results show that the proposed three-legged lander design is able to meet the successful landing requirements within the envelope of initial conditions in the absence of a full attitude control system.

The overall control system design is fully autonomous and incorporates a hybrid of appropriate controller design methodologies. The control system is composed of three levels of decentralized controller design, where an executive controller commands the individual local servo and accordingly an associated low-level servo in each foot. The executive controller responds to event-based scenarios: impact, surface contact identification, and enabling surface retention. The local and low-level servos perform continuous control of the lander dynamics: tether tension control and surface retention.

Figure 5. Control System Block Diagram
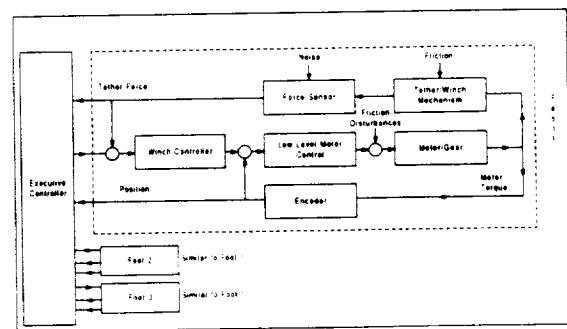
The first function of the executive controller is to ensure landing stability upon impact. A smart controller scheme is designed to determine when true surface contact is made at each foot by exploiting the dynamic coupling of the legs and processing the force sensor and accelerometer data. The

identification of the actual surface contact of each foot is crucial for proper sequential firing of the pyros. The second function of the executive controller is to enable the tether tension control servo to bring the feet back to the surface after surface contact of all three feet are made and the anchors have penetrated into the surface. This action of the landing scenario is performed to avoid pulling the anchors from the surface. Another function of the executive controller is to maintain surface retention in the presence of disturbances from science instruments

The local servos initiate motion on impact, absorb bounce off energy, bring the feet back to the surface, and retain them to the surface all under tether tension control. The operating plant in each local servo is an independent low-level motor/encoder servo loop. The controller in each local servo tracks the force input commanded by the executive controller. This is accomplished by issuing appropriate position input to the associated low-level servo subsystem.

The low-level servos initiate the physical motions of the tether spools. The active elements in the low-level servo plant are a motor and an encoder. The low-level servo controllers are highly optimized for tracking the input commands while minimizing the transient effects and providing fast reaction responses.

6. Simulation Models

A detailed simulation model of the ESB Lander is developed using ADAMS (Automatic Dynamic Analysis of Mechanical Systems). The model includes the inertia, mass, stiffness and damping characteristics of each component. The model incorporates internal dynamic coupling of the lander states, as well as, dynamic interactions with the external surface 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. A complete sensitivity analysis of the ADAMS lander model is performed by variation of important simulation parameters such as impact velocity, angle-of-attack, surface properties, anchor penetration depth, and anchor retention force. The results provide a baseline for choosing a mechanical design approach, as well as, a controller design strategy.

7. Test Results and Demonstrations

The end-to-end operation of both the Sled Mechanism and the ESB Lander was demonstrated under numerous operating conditions. The landing systems were tested for a wide range of impact velocities to assess the control system performance. The ESB Lander was tested for various angles of attack to evaluate the capability of the landing and anchoring system. The anchoring system was tested in various comet simulant materials including foam, plaster, limestone, bishop tuff, and sandstone. The penetration depth and anchor retention force were determined in each case to classify the strength of the anchoring system.

Sample drilling operations were performed from both the Sled Mechanism and the ESB Lander. The lander control systems successfully maintained the surface retention force and limited the tether tension during the drilling operation. The overall landing control system design and implementation met the objectives to demonstrate landing, anchoring, and sampling.

8. Conclusions

JPL has developed a unique landing concept, together with the proposed landing control strategy, that has potential for

meeting requirements for autonomous in-situ scientific exploration of small interplanetary objects.

9. Acknowledgements

10. References

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