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High velocity penetrators used a potential means for attaining core sample for airless solar system objects

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ABSTRACT

Sample return missions offer a greater science yield when compared to missions that only employ in situ or remote sensing observations. Such missions have high ΔV requirements, and the return yields to date have been typically only of a few grams for robotic missions. Planetary penetrators offer an alternative that significantly reduce a mission's ΔV, increase sample yields, and allow for the collection of subsurface materials. The following details the design, development, and testing of penetrator/sampler technology capable of surviving supersonic impact velocities that would enable the collection of a solid core of geologic materials, without the need for any drilling equipment,,thereby reducing the overall mass and propellant budget. It is shown through both modeling and field testing that penetrators at speeds between 300 and 600 m/s (~Mach 1–2) can penetrate into the ground to depths of 1–2 m with overall structural integrity maintained. The first flight tests demonstrated the potential for survivability at these speeds. The second flight series demonstrated core sample collection with partial ejection of the sample return canister. The 3rd flight series demonstrated self-ejection of the sample return system fully intact and with the core retaining the full stratigraphy of the rock bed. The recovered sample also shows the survivability of macro-organic structures. Possible mechanisms for the recovery of the ejected core sample are also discussed.

1. Introduction

The National Research Council [1] advised that Discovery and New Frontier class missions should play a critical role over the next decade in the study of primitive bodies given their relatively low cost and applicability for destinations both in the inner solar system, and beyond the asteroid belt. These missions will provide vital contributions in understanding the basic building blocks that created our world, as well as assessing potential hazards impacting bodies represent to our biosphere. Sample return missions from primitive bodies are excellent candidates for NASA's Discovery and New Frontier Programs given their potential for a high science yield while requiring only a fraction of the investment typical of a Flagship mission, and could supply materials long demanded by the science community for furthering our study of the solar system. To date more than 150,000 asteroids have been identified in the main belt alone [2], but difficulties in collecting samples has resulted in returning limited material.

Scott Sandford [3], a team member of the OSIRIS-REx mission speaking at an Exploration Science Forum, highlighted some of the advantages sample return missions have over in-situ and remote sensing methods, including: an increase in the quality of the data produced through the application of technology that was not available during the spacecraft's development; returned samples become research resources for both present and future scientists; sample analysis is not limited by design constraints of the spacecraft. He [3] also spoke to their potential to reduce research limitations that result from poor assumptions saying, “...if you decide to measure *A*, and you go there with your *A* measuring machine... it is possible that the main thing that you will learn... is maybe you should have measured *B*, and now you need new spacecraft and another mission”.

The Apollo program, most noted for being the first exploration series to land humans on another rocky body, has provided the largest quantity of returned sample to date. Between the summer of 1969 and winter of 1972, Apollo astronauts gathered and returned more than 300 kg of lunar material. While NASA employed human beings to collect material from the Moon, the Soviet's Luna program became the first automated system to return samples collected from a minor body, albeit in much smaller quantities. The manned Apollo missions were able to bring back a few tens of kg each missions while the robotic Luna programs only brought back a fraction of a kilogram each [4]. However,

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Nomenclature

A	penetrator cross-sectional area in m^2
ANSYS	Analysis System computer modeling software
D	depth of penetration in meters,
K_s	scaling factor dependent on mass
N	penetrator nose coefficient
S	empirical target constant
SRC	sample Return Container
TAGSAM	touch-And-Go Sample Acquisition Mechanism
V_s	impact velocity in m/s
α	an empirical constant equal to 1.75×10^{-5}
ΔV	Change in velocity

manned missions are vastly more expensive, and no humans have traveled beyond the orbit of the Moon so that the issue of making significant sample returns in cost effective manner still remains an important issue.

The Apollo and Luna programs both employed soft-landing techniques, requiring the expenditure of considerable amounts of fuel to safely arrive on the Moon's surface, and additional propellant to ascend once collection efforts were completed. These maneuvers significantly increase a mission's ΔV budget, and require flawless execution to ensure the survival of sensitive instrumentation.

NASA's first sample return efforts after Apollo 17 was the Genesis mission [5], designed to characterize and sample the solar wind using a halo orbit around Lagrange point 1. The spacecraft gathered samples using collector arrays from late 2001 to spring of 2004, but the failure of its parachutes to deploy during Earth re-entry in September 2004 caused the Sample Return Capsule (SRC) [6] to impact the landing zone at more than 86 m/s, resulting in the possible contamination of the sample. Despite this non-ideal landing Genesis was able to successfully capture noble gases and isolate important isotopes.

In contrast, the Stardust spacecraft [7] sent to collect samples from Comet 81 P/Wild 2 enjoyed a much better success. Launched in early 1999, the Stardust mission first collected samples of interstellar dust in 2000, and again in 2002 following an Earth gravity assist trajectory. The mission's flight team performed a close flyby of asteroid 5535 Anne Frank, using the opportunity as an engineering test of ground and spacecraft operations prior to intercepting Comet 81 P/Wild 2 in 2004, where it flew through the halo of gases and dust at the head of the comet. The spacecraft used an Aerogel filled grid to collect materials thought to pre-date the birth of the Sun, and their successful return to Earth in 2006 has provided new insights into our solar system [8]. There was also some contamination of the sample but signatures of returned cometary organics could be distinguished from the terrestrial contamination though there were concerns that the hypervelocity collection may have modified some of the organics.

Robotic sampling for the actual surface of an asteroid was achieved by JAXA's Hayabusa [9] using a touch-and-go approach on asteroid 25143 Itokawa in 2005. In this scenario, sample retrieval is conducted as the spacecraft briefly contacts the surface of the sampling target, collecting a few grams of surface regolith before moving on. The touch-and-go method avoids the problems of attaching a spacecraft to an asteroid and helps to reduce a mission's ΔV budget. In the case of Hayabusa, a tantalum pellet is fired at 300 m/s to produce ejecta which is then collected inside its sampling mechanism. Hayabusa demonstrated that touch-and-go sampling is possible, despite having hard-landed on Itokawa during a sampling attempt and collecting less than 1 mg of material.

NASA's OSIRIS-REx spacecraft [10] will employ a similar touch-and-go approach in 2019 to gather materials from asteroid 101955 Bennu using its Touch-And-Go Sample Acquisition Mechanism (TAGSAM). During contact with the surface, the TAGSAM will use a burst of nitrogen to blow regolith through a collecting sieve, and lab testing indicates that the method is capable of gathering more than 60 g of material.

These two approaches are only able to attain surface samples which have the potential to be strongly modified compared to subsurface material due to its interaction with the solar wind. An attempt for a subsurface sample will be undertaken by Hayabusa 2 [11] which was launched in 2014 and will arrive at asteroid 162173 Ryugu in 2018. Hayabusa 2 will deploy a 2.5 kg kinetic impactor propelled by a 4.5 kg shape charge to impact the surface of asteroid 1999 JU3 at hypervelocity speed of 2 km/s in 2019, creating an artificial crater and collecting samples from greater depths than its predecessor.

Hypervelocity penetrators has been used in two experiments to eject subsurface material into space where it is then examined using a remote spacecraft. The first was Deep Impact which in 2005 used a 370 kg impactor with an incident speed of 10.5 km/s to generate ejecta comet Tempel 1 [12]. A large increase in organic material as well as carbon dioxide was measured in the ejecta [12]. The Lunar Crater Observation and Sensing Satellite (LCROSS) in 2009 used the upper stage booster to impact a crater in permanent shadow at a speed of about 2.5 km/s. LCROSS was then able to successfully detect water in the ejecta plume [13].

Low velocity penetrators at speeds less than about 30 m/s have been used in variety of applications [14]. These include the dropping of instrument in remote areas to bunker busters. Sample return from icy objects has been proposed using penetrators with impact speeds of about ~30 m/s [15].

In this paper we examined an intermediary system for sample return which utilizes high velocity (200–800 m/s) impactors or penetrators to generate a core sample of subsurface material that is self-ejected from the impact region. The concept for operations is described in Section 2 with the design parameters of the penetrator given in Section 3. The principle is very similar to the ice penetrator of Lorenz et al. [15] but the hardness of the rock is much higher that the ice in their studies, so that much higher impact velocities are required, and the material response to the impact is very different. Because of these differences the design and testing of the system is significantly modifiedfrom that of an ice penetrator. The data from the first few flights are given in Section 4 and show results for impacts at angles away from perpendicular impacts. Behavior of the penetrator and sample collected from a Mach 2 impact into sandstone is given in Section 5. Section 6 shows the results for a self-ejected core sample from a near-final version of the system. It is shown that the sample attained retains the overall stratigraphy of the rock, and macro-organisms retain intact in the recovered sample. A summary of results is given in Section 7.

2. High velocity penetrators for core rock sampling

The concept of sample return by a high velocity penetrator is based on the fact that there is typically a high velocity difference (ΔV) between the target and the approaching spacecraft. A penetrator system can thereby use this kinetic energy for the impact without requiring any propellant. The mission concept for the release of the penetrator is shown in Fig. 1. The term high-speed refers to the impact velocity range of between 0.3–0.9 km/s. This velocity range is below hypervelocity speeds where chemical alterations can be produced but is sufficiently high energy to cause the breakup of most rock types. Depending on the diameter and speed of the penetrator and the hardness of the rock, the penetrator is expected to punch into the asteroid to a depth of 1–2 m. The sample return canister (SRC) lies within the penetrator which has feed ports on its tip to allow material