A "MICRO" CONCEPT FOR A PLANETARY PENETRATOR & DRILL PACKAGE

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Abstract

It is widely acknowledged that the next significant challenge in planetary exploration is to go deeply into the surface of celestial bodies (2 m seems scientifically most valuable and technologically still reasonable). This helps to obtain scientific data that can only be revealed beneath the surface. For example, astrobiological studies search for biomarkers at a few meters below the surface layer, due to ultraviolet flux exposure of most solar system bodies. Major studies at the lunar south pole region aim to find water ice that is likely to exist within $1 - 2$ m depth. Instruments like penetrators and drills are therefore crucial tools to enable surface penetration, autonomous sample acquisition, and preparation for *in situ* experiments. In this paper, we propose a micro–penetrator & drill package (<10 kg) for an asteroid reference mission. A biomimetic approach is adopted to design the onboard drill subsystem to cope with a stingy mass/volume/power budget. The entire package could provide a generic low–cost platform suitable also for other terrestrial–type planetary bodies with a moderate level of modification. The paper presents the first level system definition, including design rationale, engineering prototype, experimental results and analysis.

1 Introduction

As generally suggested, surface penetrators impose minimal mass overheads compared to other landing platforms, and therefore provide a cost saving solution to planetary exploration. Examples include the Mars 96 penetrator (Russia), the Mars Deep Space 2 microprobes (US), and the Lunar–A penetrators (Japan). In a recent ESA study on space systems design (Ellery et al., 2005; Gao et al., 2005) a penetrator–based approach is suggested for an asteroid mission to search for primitive materials. The system is required to go as deep as about 1.5 m and the design is constrained by 10 kg mass budget. By virtue of the general deployability at perceived low cost a micro–penetrator & drill package is proposed.

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The micro–penetrator is designed to reach 0.5 – 1 m depth through regolith or compacted regolith. The micro–drill subsystem serves the purpose of drilling another 0.5∼1 m into more cohesive and hard substrate and taking samples. Instead of using conventional methods (such as rotary or percussive drilling) which have high mass and power requirements, a bio–inspired approach is novelly applied to design the drill. The bionic solution is potentially more efficient in mass, volume and power as a result of evolutionary constraints imposed on biological systems. Space systems are confined in a similar way. This paper provides a system level definition of a micro–penetrator. Design rationale and results of the drill subsystem are elaborated in detail.

2 Micro–penetrator description

2.1 Configuration

The micro–penetrator is designed as a two–body system: the penetrating part (forebody) and the aftbody as shown in Figure 1. The two bodies are connected by an umbilical cable. An envelope of 15 cm (diameter) × 45 cm (length) is currently envisaged for the entire penetrator to house all necessary subsystems. From this volume 5 cm (diameter) × 20 cm (length) is used for the forebody and 15 cm (diameter) × 35 cm (length) for the aftbody. It is in some ways similar to the Mars DS2 micro–probes, but due to on–board propulsion and control systems it is more complex.

The forebody is cylinder–shaped and hollow to accommodate the principal science instruments and electronics. Starting at the nose, the conical shape has an aspect ratio (i.e. length to diameter) of 2:1 to provide an initial low resistance to penetration. The nose is blunt with half of the original length removed to improve ricochet resistance and prevent the penetrator from bouncing back. The bottom segment includes the 5 cm (diameter) × 7.5 cm (length) drill subsystem which is explained later in the paper. The forward diameter of the forebody shaft is 5 cm to accommodate the four suggested scientific instruments, i.e. biomarker detector, seismometer, accelerometer and thermometer. The biomarker detector may be split between the forebody and aftbody (with sensor array in the forebody and rest of electronics in the aftbody).

The aftbody acts as a terrabrake. It is designed to absorb the impact in surface materials of intermediate to high penetrability. At the rear end of the terrabrake sufficient volume is available to accommodate propulsion, power, thermal, and communication subsystems. The solid rocket motor is largely driving the size of the aftbody, though the AOCS (*Attitude & Orbit Control Subsystem*) stability analysis will determine stable configurations. As the forebody penetrates the surface, the separable aftbody is left behind on the surface for communication purposes.

After penetration, the aftbody remains connected to the forebody by a multi–connector umbilical cable of sufficient length. It is paid out from the aft section of the forebody during penetration. A sequence of science experiments is then conducted during the lifetime of the penetrator. The acquired data are stored in onboard memory until they can be transmitted to an orbiting spacecraft for relay to Earth.

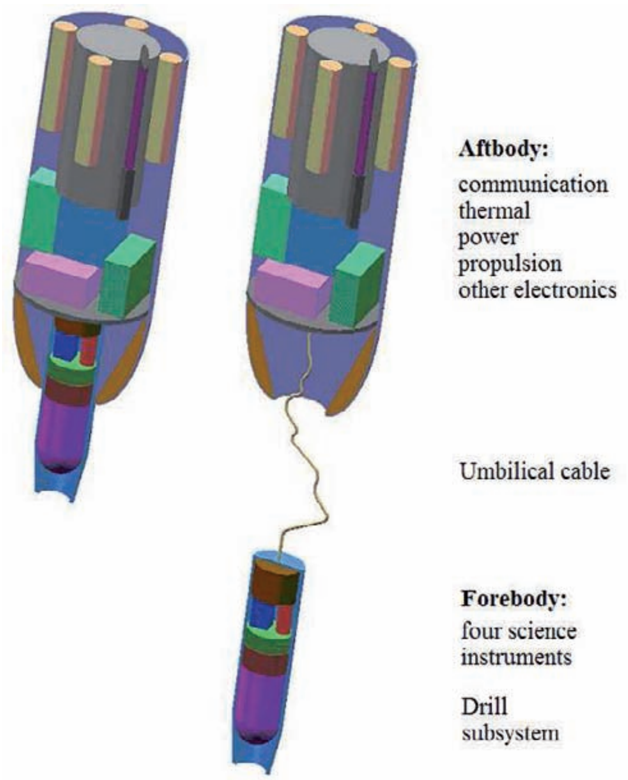

Figure 1: 3D view of the micro–penetrator: before (left) and after separation (right)

2.2 Penetration model

In order to predict the penetration depth for the given design the so–called Sandia formula (Young 1997) is applied. For conditions of $m < 27$ kg and $V > 60$ m/s, the Sandia equation has the following form:

$$D = 4.86 \times 10^{-6} SN \frac{m^{1.1}}{A^{0.7}} (V - 30.5) \quad (1)$$

where D is the penetration depth in [m], S is the penetrability index (typically 1 – 5 for hard targets like frozen soil, and 10 or more for loose soil), N is a nose performance coefficient, m is the mass of the penetrator in [kg], A is the cross–sectional area in [m^2] and V is the impact speed in [m/s]. For a blunted conical nose we have

$$N = 0.125(L_n + L_n^{'})/d + 0.56 \quad (2)$$

where L_n and $L_n^{'}$ are the original and blunted nose length, respectively, and d is the penetrator diameter. The forebody of the micro–penetrator is designed to have $m =$ 3.2 kg, $A = 0.002$ m^2 and $N = 0.935$. For the expected impact velocity V of 150 m/s and for S in the range of 4∼9, the analysis based on Equation (1) indicates that the forebody will be able to penetrate to a depth between 0.6 and 1.3 m, depending on regolith character. This meets the design requirement of 0.5 m minimum penetration depth.

2.3 Structures & materials

The forebody structure is designed to be a shell composed of Titanium, which has the advantage of having high yield strength, and the ability to deform before buckling. Currently a simple tube of 4 mm wall thickness is assumed for the outer structure. For extra impact protection at the nose tip, this could be fanned out to be thicker. A parametric estimate of the structure mass assumes it to be 20% of the overall aftbody mass (refer to Table 1). Extensive use of crushable honeycomb in the aftbody is envisaged to be able to cushion the shocks from the impact. Plates with hardware attached are designed to be thick enough to avoid buckling through critical bending.

2.4 Propulsion & avionics

An on–board cold gas propulsion system could first separate the micro–penetrator from the host spacecraft, place it – in the reference mission – into a controlled orbit around a 1.5 km diameter asteroid at 3 km altitude (1996 FG3 is the target Near Earth asteroid), and assist further trajectory control. The orbital velocity is only about 0.2 m/s in this case, which requires additional propellant to increase the micro–penetrator velocity to about 150 m/s and achieve the desired penetration depth. As a relatively high acceleration is required due to the short distance to travel, a small solid motor is envisaged, i.e. a derivative of the *Marc 36A1* by *Atlantic Research*. Attitude determination and descent guidance has assumed an *EADS Inertial Measurement Unit* with a simple processor (the same as the one on the *CAN–X2* Canadian picosatellite), and a cold gas (N_2O) reaction control system. The very fast descent rate means that there is no time for ground control to monitor the micro–penetrator and navigate or adjust the landing point.

2.5 Power

Based on the preliminary design, the power and energy budget of the penetrator is shown in Table 2. The drill power is set to 3 W and a 100% safety margin is given. The total energy requirement of the system is about 145 Wh for a 9.2 hours mission. The penetrator has a configuration that is not well suited to solar power generation, because it is relatively long and thin with limited solar capture area. Therefore, for simplicity and cost reasons, a primary $LiSOCl_2$ battery pack has been selected as the baseline power system for simplicity and cost. This is composed of 8 *Tadiran TL–6526* cells in each of the four vertical stacks around the central solid motor (see Figure 1).

2.6 Communication

Due to the short ranges involved, communications between the micro–penetrator and the orbiter can be done by a low power, omni–directional link. Several miniature communication transceivers have been put together by the micro-satellite community by modifying commercial off-the-shelf systems, including systems for the *SSDL Saphire*, the *USU ION–F*, and SSTL's *SNAP–1* satellites. A similar approach would be expected to be effective for the penetrator. The link between the orbiter and the micro–penetrator is a simple, low power UHF system. A 0.6 m medium gain antenna on the orbiter is assumed. The combination of low data transmission rate and short link distance means that there is a very large signal to noise ratio for the received signal.

2.7 Total mass budget

The mass budget is shown in Table 1. The system is less than 10 kg including a 20% margin.

Table 1: System mass budget

Forebody	**2.7**
Drill	0.5
Biomarker	1
Seismometer	0.2
Accelerometer	0.03
Thermometer	0.3
Microcontroller	0.07
Structure	0.6
Aftbody	**5.6**
Propulsion(wet)	2.4
Power	1.3
Communication	0.19
Avionics	0.2
Thermal	0.01
Other electronics	0.3
Structure	1.2
Margin(20%)	1.66
Total Mass	9.96

Table 2: System power budget

	Pre–impact	Drilling	Measuring
Total Power [W]	16	16	14
Avionics	2.7	0.3	0.3
Communication	0.3	0.3	0.3
Power	3.0	3.0	3.0
Propulsion	10.0	0.0	0.0
Thermal Heaters	0.0	5.3	5.3
Biomarker chip	0	0	5.0
Seismometer	0	0.1	0.1
Accelerometer	0	0	0
Thermometer	0	0.8	0.8
Drill Subsystem	0	6.0 (50% margin)	0.0
Operation Time (hr)	1	7.2	1

3 Micro–drill subsystem

3.1 Design rationale

The micro–drill is designed as a low mass (0.5 kg), low volume (5cm × 7.5cm) and low power (3 W) subsystem. Two basic or conventional methods commonly applied to planetary missions are rotary and percussive drilling (e.g. Rosetta SD2, Deep Space 2 probe drill, Beagle 2 Mole, etc). Using rotary drills in a low gravity environment (as for the asteroid) generally requires high axial force which results in very large overhead mass and high power consumption. This limitation makes the rotary mechanism not qualified to meet the low–cost design requirements. Percussive drilling on the other hand can operate at relatively low mass and low power budget, but it cannot easily deal with rocky materials. Since most asteroids are largely formed of silicates and metal, a percussive mechanism seems to face a genuine problem too. The question therefore is: *Can we find a digging mechanism that requires little overhead load while still works on hard materials?* We believe this is a situation where learning from the nature could reveal an answer.

3.2 Biological prototype

We know there are digging organisms in nature among insects, such as the female wood wasps and female locusts who use their ovipositor valves to dig into trees or soil to lay eggs. Early studies suggested that the wasp ovipositor digging mechanism is quite distinctive not being rotary or percussive. The ovipositor utilizes the longitudinal reciprocating motion of a pair of 'valves' – each one a long half–cylinder – which slide freely against each other but are held firmly together like the two parts of the 'Ziplock' closure on a polyethene bag (Vincent and King 1995). Figure 2 shows a picture of the ovipositor and its digging model. The backwards facing teeth on one valve snag on the substrate and resist pulling

(Figure 2 right: tension cutting valve). Because the two valves are inseparably connected by the sliding joint, the other valve can then be pushed into the substrate by an equal force (Figure 2 right: compression cutting valve): so long as the net external force is below the Euler buckling load of the entire ovipositor, the compressive force is limited only by the magnitude of the tensile force which balances it. This means that there is no limit to the length of the ovipositor – or of a digging machine using the same mechanism. The digging model illustrated here was used to investigate the 'push–pull' mechanism and its rate of working. A cyclical repetition of this process allows the ovipositor to dig into the substrate without the need for an external reaction force. In addition, the teeth are spaced to allow the forces to be evenly distributed throughout the valves.

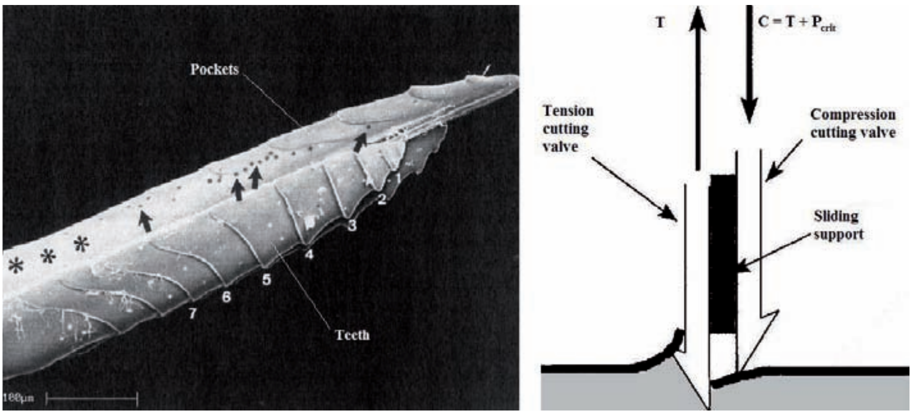

Figure 2: Biological prototype: wood wasp ovipositor (left); model of digging motion (right)

3.3 Engineering prototype

Based on this working principle, the ovipositor–type drill mechanism reduces overhead load and should not require much power to operate. However, it requires cohesive substrates to work on which allow sufficient gripping of the teeth and interaction between the two valves. Generally, this biological solution corresponds well to our problem and is thus used to design the drill. The drilling capability is determined by the force required to penetrate through the substrate, the force able to be exerted by the teeth, and the bending strength of the teeth when engaged with the substrate.

The engineering model mimics the biological prototype. As shown in Figure 3, its teeth have a half–coned shape and the sharp edges are used for gripping and cutting. To allow initial engagement into the substrate, the teeth can have strong pins attached at the tip portion. To duplicate the ovipositor digging motion, a cam (pin & crank) mechanism is proposed to drive two valves. This provides a simple way to transform the reciprocal motion. An extendable support module using reeled housing can deploy drill strings as the bits go deeper.

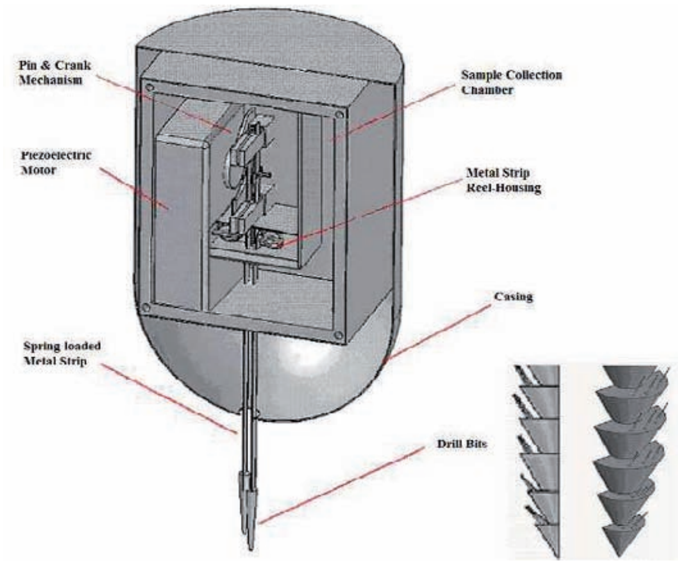

Figure 3: Engineering prototype: micro–drill (left); drill bits (right)

3.4 Experiments & results

Some lab–based experiments were set up to verify and demonstrate feasibility of the micro–drill concept. A simplified test model with metal teeth (9 mm in radius) was used in the experiments (as shown in Figure 4). Earlier studies on asteroids (Lupishko et al., 1998) suggested that the density level of C–type asteroids is around 1500 kg/m^{-3} (C–type asteroids are most likely to preserve primitive materials). In the tests, we used three silicate–type model materials with the same density level of 1500 kg/m^3 but different hardness (measured in compression strength). The metal teeth were operated under three power levels, i.e. 3, 6 and 9 W. The teeth were operated to drill into the simulant to depths of 2.5 cm and 5 cm and the time needed to reach these depths was recorded. The drilling speed was estimated by taking the average value of the two. These tests were repeated for each of the three input power levels and each of the three materials. The test results are summarized in Figure 5. There are three lines for three input power levels. Each line indicates the estimated digging speed versus compression strength of the medium. It is clear that the digging speed reduces as the medium gets harder. Increasing the power input will also increase the digging speed. The figure provides some quantitative measure to predict the performance of the drill at different power levels and material strengths.

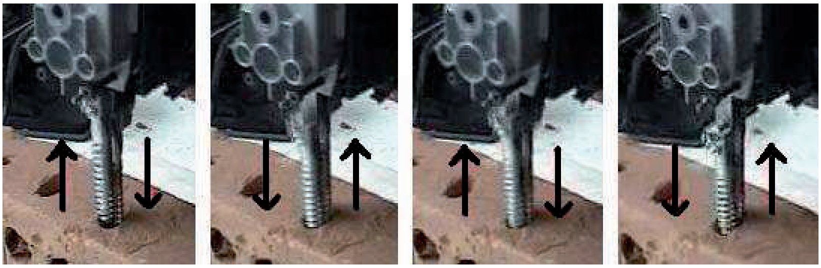

Figure 4: Lab-based test model

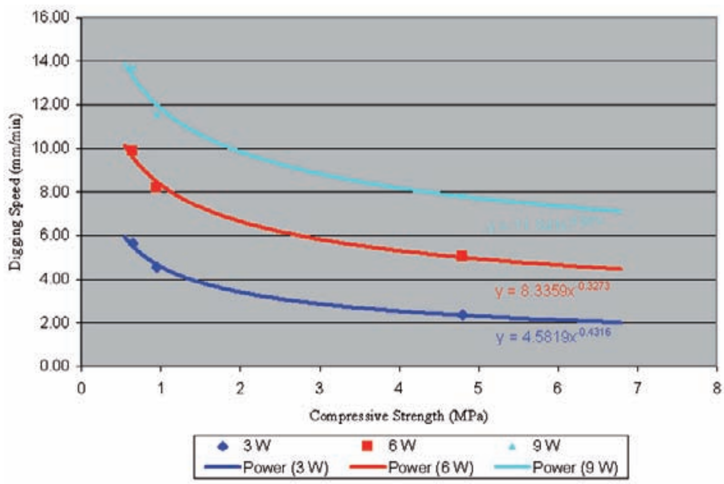

Figure 5: Approximated drilling speed versus compressive strength

4 Conclusions

This paper outlines a micro–penetrator/drill system of less than 10 kg weight that is suitable for planetary deployment and *in situ* subsurface investigation. The drill subsystem implements a novel digging mechanism inspired from insects. Experimental results show the feasibility and the potential of the method to improve drilling performance as compared to conventional methods. For example, we are currently working on a theoretical model to better describe the bio–inspired drilling mechanism. In addition we will examine more closely the drill deployment mechanism, the sample extraction and transfer method. One long–term objective is to design the drill as a self–contained instrument deployable from any platform.

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