Planetary Micro-Penetrator Concept Study with Biomimetic Drill and Sampler Design

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Due to ultraviolet flux to the surface layers of most solar system bodies, future astrobiological research is increasingly seeking to conduct subsurface penetration, drilling and sampling to detect chemical signature of extant or extinct life. To seek a compact solution to this issue, we present a micro-penetrator concept (mass < 10 kg) that is suited for planetary deployment and in situ investigation of chemical and physical properties. To draw inspiration from nature, a biomimetic drill and sampler subsystem is designed as a penetrator instrument based on the working mechanism of a wood wasp ovipositor to sample beneath the sterile layer for biomarker detection. One of the major limitations of sampling in relatively low gravity environments (such as asteroids, Mars, etc) is the need for high axial force when using conventional drills. The ovipositor drill is proposed to address this limitation by applying a novel concept of reciprocating motion that requires no external force. It is lightweight (0.5 kg), driven at low power (3 W), and able to drill deep (1–2 m). Tests have shown that a reciprocating drill is feasible and has the potential of improving drill efficiency without receiving any external force. As part of the European Space Agency (ESA) project on bionics and space system design [1], this study provides a conceptual design of the micro-penetrator targeted for a near Earth asteroid mission. With bionics-enabling technology, the overall penetration/drilling/sampling system provides a small, light and energy efficient solution to in situ astrobiological studies, which is crucial for space exploration. Such a micro-penetrator can be used for exploration of terrestrial-type planets or other small bodies of the solar system with a moderate level of modifications.

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I. INTRODUCTION

A major goal of future astrobiological missions (e.g. to Mars and Jupiter's Moon Europa) is to search for biomarkers—organic molecules that might reveal the presence of extraterrestrial prebiotic and biotic signatures. Looking for prebiotic chemistry is also an objective for missions to asteroids and comets. Although both sample return and in situ analyses can address these goals, the rapid development of microfluidic lab-on-a-chip systems, the complex logistics of sample return compared with in situ missions, and back-contamination issues suggest that in situ analysis is an approach that must be seriously considered. Recent studies show that due to the surface turnover on planetary bodies, the surface layers will not permit survival of organic molecules since they decay on UV/oxidant exposure over aeons. We need to penetrate below the sterile layer to access organic materials, e.g. on Mars this layer is estimated ~ 2 m thick [2], and for much smaller bodies like asteroids the layer is approximately 1 m thick. Planetary penetrators provide a modest cost solution for such in situ astrobiological investigation. They impose minimal mass overheads in comparison with other robotic devices; examples include Mars 96 penetrator (Russia), Deep Space 2 microprobes (US), the Lunar-A penetrators (Japan) planned for launch in 2007, etc.

In this paper, a micro-penetrator/drill package is proposed by virtue of its general deployability at perceived low cost. The micro-penetrator is likely to reach 0.5–1 m depth through regolith/compacted regolith. The biomimetic drill serves the purpose of drilling another ~ 1 m into much cohesive and hard substrate and taking samples. This miniaturised system indicates some enhanced utility that is incorporated into an engineered system inspired from a biological system. Such enhanced utility is critical for space mission designs where a premium is placed on mass, volume, and power. Biological systems are similarly constrained making biomimetic technology uniquely suited as a model of miniaturised systems [3].

This paper aims to provide a conceptual system-level design of the micro-penetrator and a feasibility study of the biomimetic drilling mechanism, which is a continuation and extension of the work from [4]. For a complete system design, a near Earth asteroid mission scenario is assumed. The system is required to reach a total depth of 1.5 m and the design is constrained with an overall mass budget of 10 kg. The rest of the paper is organized as follows. Section II provides the conceptual design of the micro-penetrator—its configuration, scientific instruments, and penetration model. Detailed description of the biomimetic drill and sampler subsystem is provided in Section III. Lab-based tests have demonstrated the feasibility of this novel drill

TABLE I
Scientific Instruments and Experiments

No.	Scientific Instruments	Scientific Experiments	Science Addressed
1	Biomarker detector (above mentioned three options)	To determine existence of organic molecules, e.g. amino acids, in the samples	Chemical signatures that might reveal the presence of extinct or possibly extant extraterrestrial life forms
2	MEMS-based seismometer (by Micro devices Laboratory, JPL)	To measure seismic activity	Internal structure and dynamics
3	Piezoelectric accelerometer (ENDEVCO 2271AM20, used on Huygens)	To determine physical and mechanical properties of the near-surface	Soil formation, deposition and erosion processes
4	Thermometer	To measure the heat flux and thermo-physical soil properties	Internal structure and thermal history

concept and are discussed in Section III. Section IV includes design issues at the system level. Section V concludes the paper.

II. MICRO-PENETRATOR DESCRIPTION

The considered micro-penetrator is a self-sufficient space probe equipped with control systems and other devices to ensure its delivery after separation from the host spacecraft, descent into the atmosphere (if applicable), penetration into the planetary surface, subsequent measurements, and transmission of scientific information to the main spacecraft for relay to Earth.

A. Scientific Instruments and Experiments

Over the last decade, the drive to miniaturize common laboratory techniques has produced systems that are relevant for astrobiological research and solar system exploration. This has enhanced the feasibility and capabilities of in situ biomarker detection on extraterrestrial planets. To reduce the overall mass budget, three existing biomarker detectors based on microelectromechanical systems (MEMS) technology are chosen as potential candidates for the system. They include two biomarker chips and one laser Raman spectrometer: 1) a microfabricated organic analyzer (MOA) [5], 2) the 'SMILE' life marker chip [6], and 3) a Confocal Microscope and Raman Spectrometer (CMaRS) [7]. To maximize the scientific return within the engineering constraints, we have considered a complete sensor suite as shown in Table I to facilitate in situ measurements and experiments.

B. Configuration and Geometry

After careful consideration of design alternatives, the configuration concept is illustrated in Fig. 1 and Fig. 2. The micro-penetrator consists of two main parts: the penetrating part (forebody) and

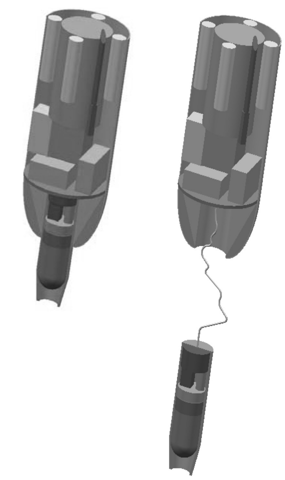

Fig. 1. 3D view of micro-penetrator: before (left) and after ground impact (right).

the afterbody. An umbilical cable connects the two parts. An envelope of 15 cm (diameter) $\times$ 45 cm (length) is currently envisaged for the entire penetrator to house all necessary payloads, where 5 cm (diameter) $\times$ 20 cm (length) for the forebody and 15 cm (diameter) $\times$ 35 cm (length) for the aftbody. It is in some ways similar to the Mars DS2 microprobes, but is more complex due to on-board propulsion and control systems in order to be compatible with airless bodies.

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 [8]. 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) $\times$ 7.5 cm (length) drill and sampler subsystem. The forward diameter of the forebody shaft is 5 cm to accommodate the four major scientific instruments shown in Table I. The biomarker detector is split between the forebody and aftbody (with sensor array

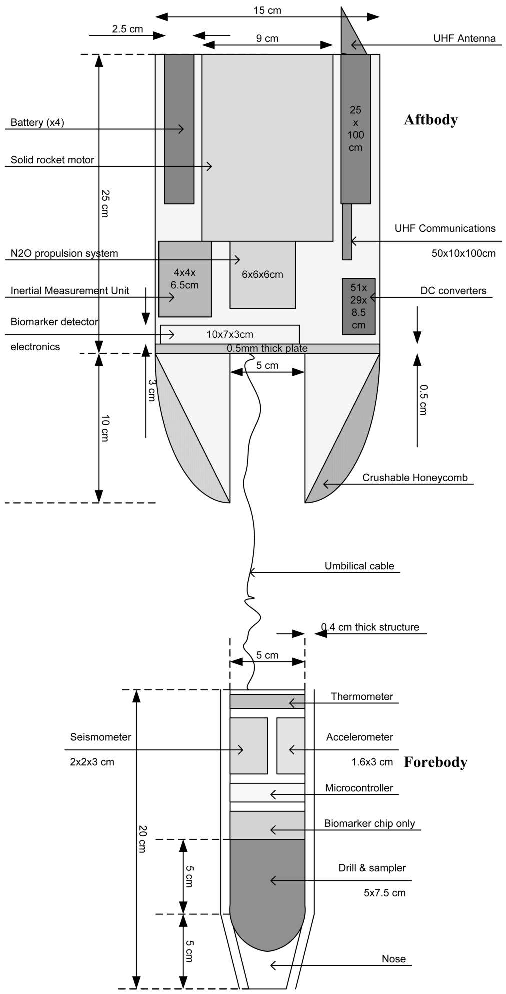

Fig. 2. Schematics of micro-penetrator configuration.

or sensor head in case of Raman in the forebody and rest of electronics in the aftbody).

The aftbody acts as the terrabrake, which has a length of 35 cm with a base diameter of 15 cm, designed to arrest and absorb the impact in the surface materials of intermediate to high penetrability. At the back end of the terrabrake is sufficient volume to place the propulsion, power, thermal, and communication subsystems. The solid rocket motor is largely driving the size of the aftbody, though the AOCS (attitude and orbit control subsystem) stability analysis will determine stable configurations. As the forebody penetrates below the surface, the separable aftbody is left behind on the surface for communication purposes.

After penetration, the aftbody remains connected to the forebody with a multi-connector umbilical cable of sufficient length that is paid out from the aft section of the forebody during the penetration. A sequence of science experiments is then conducted during the life of the penetrator and the data stored in onboard memory until it can be transmitted to an orbiting spacecraft for relay to Earth.

C. Penetration Model

The penetration model is applied both to predict the penetration depth in a specified target, and to infer the target properties from penetration measurements. A widely used formalism is Young's empirical equations, also known as the Sandia equations. For conditions of $m < 27$ kg and $V > 60$ m/s, the Sandia equation is in the form of [9]:

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

where D is the penetration depth in meters, 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 blunted conic nose, we have

$$N = 0.125(L_n + L'_n)/d + 0.56 \tag{2}$$

where L_n and L'_n is the original and blunted nose length, respectively, and d is the penetrator diameter.

Given its dimension in Fig. 2 and mass in Table VI, the forebody of the micro-penetrator is designed to have $m = 3.2$ kg, $A = 0.002$ m^2, and $N = 0.935$ (using (2)). For the expected impact velocity of 150 m/s and for S in the range of 4–9, the analysis based on (1) indicates that the forebody will be able to penetrate to a depth between 0.6 and 1.3 m, depending on regolith character.

III. BIOMIMETIC DRILL AND SAMPLER SUBSYSTEM

A. Wood Wasp Ovipositor Drill

Wood wasps use their ovipositor to drill holes into trees in order to lay eggs. The ovipositor drill uses reciprocating rather than rotatory or percussive motion and was considered as a basis for the drill and sampler of the micro-penetrator in this study. Vincent and King [10] analysed the working mechanism of the wood wasp ovipositor. The drill bit is composed of two valves that can slide against each other longitudinally as depicted in Fig. 3. Rather than the helical sculpturing of a rotatory drill, the reciprocating drill has backward-pointing teeth that present little resistance to being moved downwards but engage with the surrounding substrate to resist being moved in the opposite direction. Once the teeth are engaged, the tensile force that can be resisted, tending to pull the drill out of the substrate, allows the generation of an equal and opposite force in the other valve tending to push it further into the substrate. The drilling force is generated between the two valves and there is no

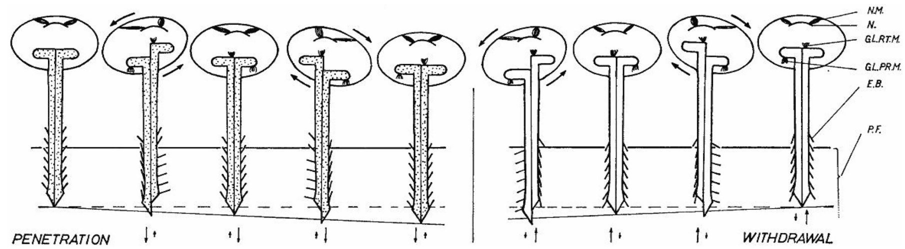

Fig. 3. Wood wasp reciprocating drill. Piercing process during the first phase (perforation of the skin) and second phase (penetration into the pulp). (Diagrammatic; explanations. $C.S.T.$ = compressed stipes; $E.B.$ = erectile barb; $GL.PR.M$ = galea protractor muscle; $GL.RT.M.$ = galea retractor muscle; $GL.P.$ = galea under pressure; $N.$ = neck;$N.M.$ = neck musculature; $P.F.$ = pulp of the fruit; $S.F.$ = skin of the fruit; $O.M.$ = oblique muscle.

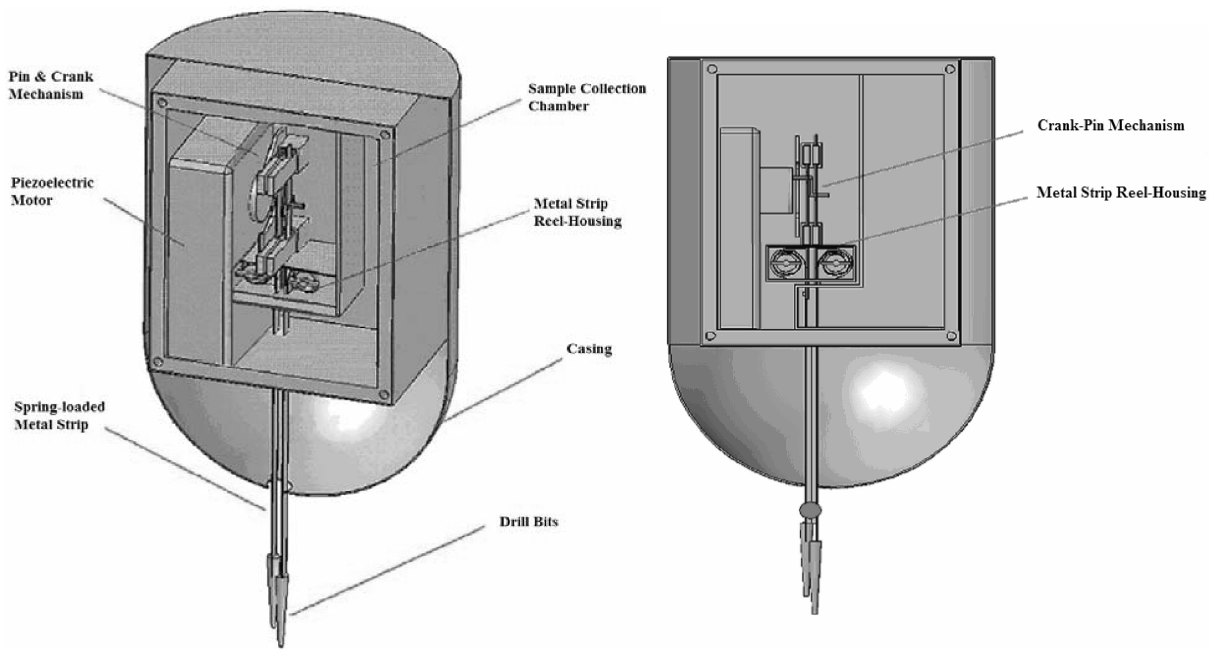

Fig. 4. 2D and 3D views of drill and sampler subsystem.

external force required. The two valves repeat this process in a reciprocating motion.

One of the major limitations of sampling in low gravity environments is the need for high axial force using rotary drills (e.g. Rosetta/SD2), which suffers from high mass, buckling problems, and high power requirements, etc. Drills like the Mole flown on Beagle 2, the JPL ultrasonic/sonic/drilling/coring (USDC) using percussive motion may offer low power consumption and low overhead mass, but result in low drilling rate. The ovipositor drill provides a novel solution by applying reciprocating motion and working on both tension and compression. It requires no reactive external force from the carrier system. The drill can be designed as a self-contained system and deployed independently from any other device.

B. Drill and Sampler Subsystem Design

As mentioned above, the drill and sampler subsystem is housed within the micro-penetrator's forebody in a cylinder-shaped capsule of 5 cm in diameter and 7.5 cm in length. Details of the system are given in the following subsections.

1) *Drill Bit Design*: The drill bit is designed in the way to mimic the cutting teeth of the ovipositor drill. As shown in Fig. 5, the drill bit is constructed from half cones (increasing in diameter) and the edges of the cones carry out the gripping and cutting action. To produce efficient gripping, sharp pins or shims can be attached on the edge as shown in the figure. However, this design can be difficult to manufacture, as the pins have to be firmly fixed on the drill bit. Consecutive drilling may introduce a risk of buckling for the pins. But the risk is not very critical using the reciprocating motion (with little overhead force) and slow planetary drilling speed. Some design factors such as geometry and material of the drill bit can be investigated further to improve the design robustness.

2) *Drill Bit Deployment*: As shown in Fig. 4, drill bits are attached to spring-loaded metal strips (i.e., drill strings), which are reeled into the housing. The design of the spring-loaded metal strips is similar to a tape measure design, whereby the metal

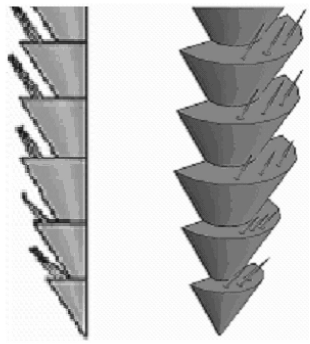

Fig. 5. 2D and 3D view of drill bit.

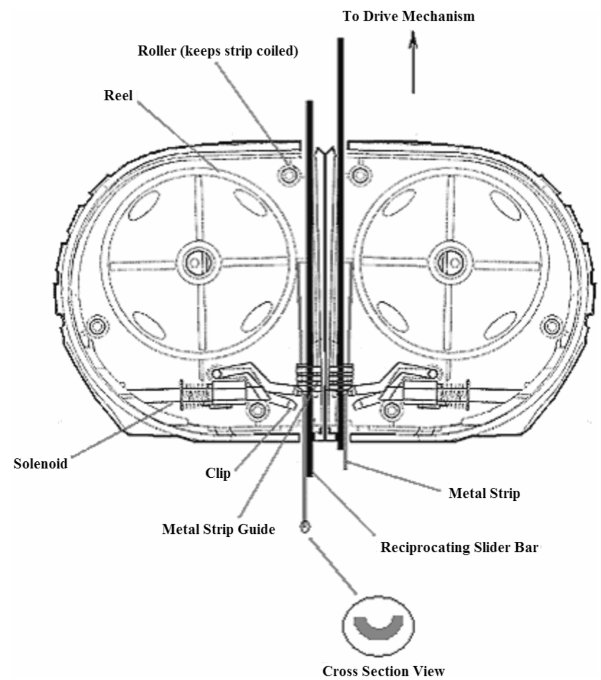

Fig. 6. Metal strip reel housing.

strip is wound into a reel as shown in Fig. 6. Upon reciprocation of the slider bars, the metal strip slides out of the reel housing. As seen from the cross-section view of the metal strips, both sides are curved in order to create a hole as they deploy. A guide way ensures that the metal strip is curved while the joint to the slider bar ensures the strip remains curved. The metal strip is free to slide against the slider bar to extend. The cross-section design helps to stabilize the drill strings. However, the metal strips may still suffer from buckling while drilling depth increases. Small travelling distance of the drill string at each reciprocation and good autonomous control system would be able to reduce the risk of buckling. Other design factors that might further improve the problem include the material and geometry of the drill strings. This issue is not as serious as using rotary motion because the reciprocating drill does not just reply on compression and has little overhead force.

3) *Sample Extraction*: In the case of using optical sensors to study the sample (such as Raman), the drill bits carry the sensor head into the hole and do in situ experiments. But there are cases when the samples need to be extracted from the hole and transported to the sample chamber for experiments. There are many ways to extract the sample. One way proposed in this design is to apply angled bristles between the metal strips as illustrated in Fig. 7. Once a particle is trapped between the bristles at the bottom of the plates, the bristle at one side lifts it and transports it to the opposite plate. Consequently the particles can be collected in between the bristles and transported to a collection chamber placed on top of the plates. This method works in reciprocating motion, which is ideal for this biomimetic drill bit mechanism. As the drill digs into the substrate, sample particles will move up to the sample collection chamber and a hole will be created. Similarly to the drill bit pins design, the bristle design may encounter problems of fragility and buckling under consecutive drilling. But slow planetary drilling speed and little overhead torque help to reduce the risk of buckling. Robust layout and design of the bristles should help to prevent them from being fractured.

4) *Drive Mechanism and Actuation*: In order to meet the major design requirement in terms of size, weight, and power, the choice of drive mechanism and actuation source is restricted. A pin and crank mechanism is chosen to drive the drill, which offers the simplest and most compact way to transform motions. Normal electromagnetic motors tend to incorporate heavy metal components and have slow response times. One reasonable choice of actuation source is a piezoelectric motor. It is generally agreed that the piezoelectric motor has superior torque and response time relative to existing magnetic motors.

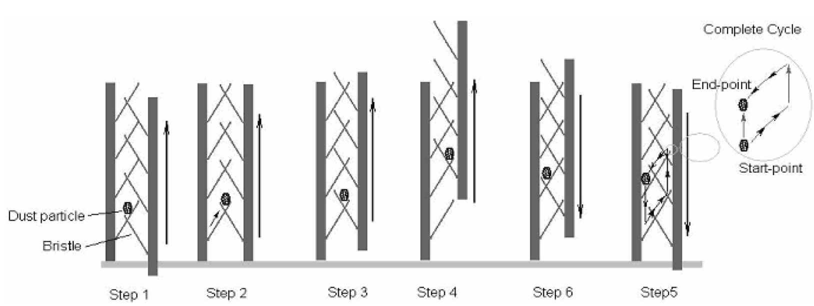

Fig. 7. Sample extraction mechanism [11].

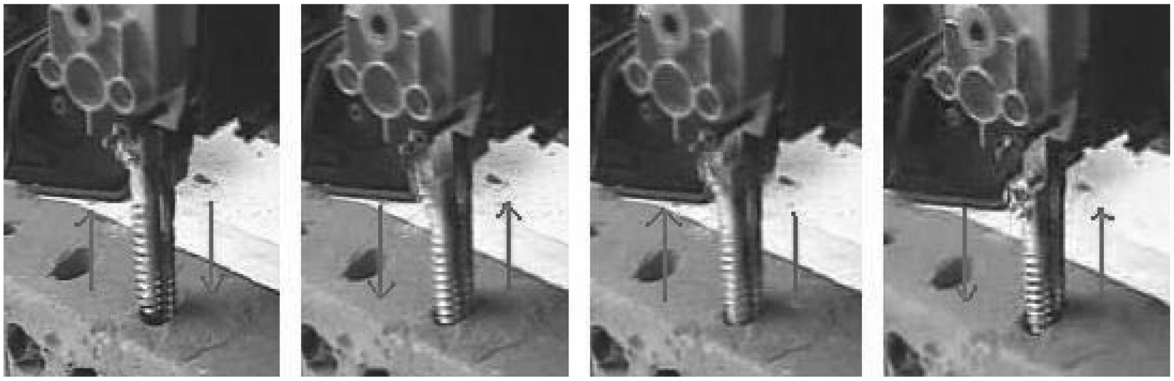

Fig. 8. Lab-based test model.

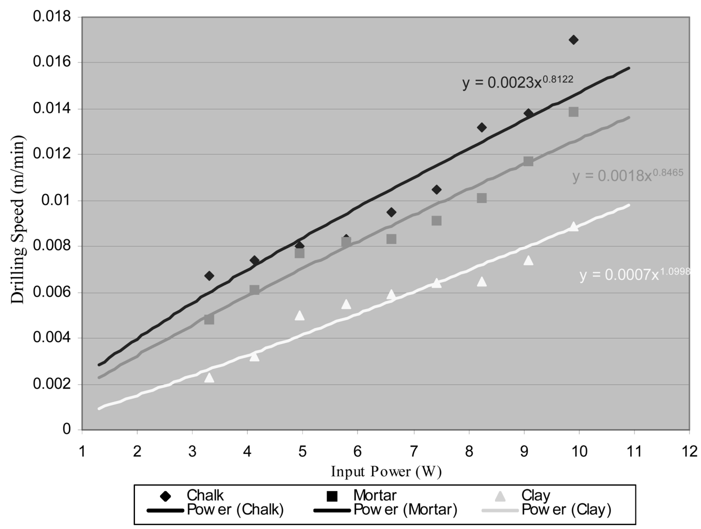

Fig. 9. Approximated drilling speed versus input power.

TABLE II
Physical Properties of Tested Substrates

Substrates	Density (kg/m^3)	Compressive Strength (MPa)
Condensed chalk	1500	0.65
Lime mortar	1560	0.95
Non-fired clay	1769	4.8

C. Lab-Based Test Model and Results

Experiments were designed to test the drilling efficiency of the proposed method in substrates of different hardness. A simplified drill prototype was built based on the previous designs, containing only the drill bit, drive mechanism, and a jigsaw type actuator (as shown in Fig. 8). The metal drill bit (1.8 cm in diameter) was tested on three different substrates varying from high to intermediate penetrability: condensed chalk, lime mortar, and nonfired clay (see Table II for their physical properties). For each test, a range of input power from 0 to 10 W was applied to the drill (9 sampling points were taken). The time taken to drill into different depth was recorded to get an average value for drilling speed at each input power.

Fig. 9 shows the relationship between drilling speed and input power in terms of power functions for the three test substrates. Given an input power budget of 3 W, drilling speed was measured as 0.0056 m/min (chalk), 0.0046 m/min (mortar), and 0.0023 m/min (clay). Drilling speed with respect to the substrate compressive strength can be broadly predicted for 3 W input power (shown in Fig. 10). The drill at 3 W will thus take approximately 3 to 7.2 h to drill 1 m into substrate of high to intermediate penetrability.

The ratio of power to material removal rate in term of J/m^3 provides a useful measure of the drilling efficiency. The smaller the ratio the better the drill efficiency. Table III compares the bio-inspired drill with two percussive drills. The reciprocating drill provided comparable performance with the existing systems and has the potential for further improvement especially for handling harder substrates. For conventional rotary drills, a similar performance would require a high axial force of $\sim 10^2$ N.

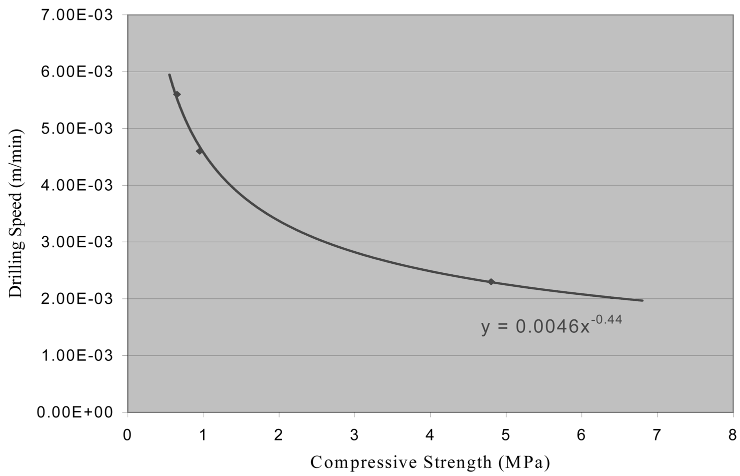

Fig. 10. Predicted drilling speed versus compressive strength at 3 W input power (based on data in Fig. 9).

TABLE III
Comparison of Three Drills

	Bio-Inspired Drill	Beagle 2/Mole [12]	USDC [13]
Diameter (m)	0.018	0.02	0.003
Power (W)	3	5 (peak)	10
Drilling speed (m/s)	$\sim 10^{-4}$ (soil) $\sim 3\times10^{-5}$ (soft rock)	$\sim 2\times10^{-4}$ (soil)	$\sim 5\times10^{-5}$ (soft rock)
Q (m^3/s)	$\pi\times0.009^2\times10^{-4}$ (soil) $\pi\times0.009^2\times3\times10^{-5}$ (soft rock)	$\pi\times0.01^2\times2\times10^{-4}$ (soil)	$\pi\times0.0015^2\times5\times10^{-5}$ (soft rock)
Power/Q (J/m^3)	11.7×10^7 (soil) 3.9×10^8 (soft rock)	6.4×10^7 (soil)	2.8×10^9 (soft rock)

IV. SYSTEM DESIGN

There are a number of drivers for the system-level design of the penetrator, in particular instrument and subsystem accommodation, structural integrity, propulsion capability, penetrator guidance and stabilisation, power requirement, and communication. Section II has provided a preliminary design of instrument and subsystem accommodation (refer to Fig. 2). The rest of the design issues are addressed in the following subsections.

A. Structures and 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 VI). 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.

B. Propulsion and Avionics

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 ~ 0.2 m/s in this case, which requires additional propellant to increase the micro-penetrator velocity to ~ 150 m/s and achieve the desired penetration depth (refer to Section IIC). 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 control 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 not time for ground control to monitor the micro-penetrator, navigate or adjust the landing point.

C. Power and Energy

Based on the preliminary design, the power and energy budget of the penetrator is shown in

TABLE IV
Micro-Penetrator Power and Energy Budget

	Power Modes 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 Conditioning	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
Drilling and Sampling subsystem	0	6.0 (with 100% margin)	0.0
Operation Time (h)	1	7.2	1
Total Energy (Wh)	16	115.2	14

TABLE V
Link Budget

	Inter-Spacecraft Link	Units
Frequency	0.45	GHz
Transmitter power	0.1	watt
Max Transmission data rate	2×10^4	bps
Antenna gain	0	dB
Line loss	0.5	dB
EIRP	−10.5	dBW
Maximum path length	3.35	km
Free Space Path loss	96.02	dB
Pr/Pol loss	0.5	dB
Receiver gain	6.43	dB
System noise temperature	1783	K
Receiver G/T	−26.1	dB/K
Eb/No	52.49	dB
C/N Ratio	95.5	dB
Bit Error Rate	1×10^{-5}	
Required Eb/No	13.3	dB
Coding	FSK	
Implementation loss	1.26	dB
Margin	37.93	dB

Table IV. With a 100% safety margin to the drill power consumption, the total energy requirement of the system correspondingly is about 145 Wh for a 9.2 h 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 a primary LiSOCl2 battery has been selected as the baseline power system for simplicity and cost. This is composed of 8 Tadiran TL-6526 cells in each of four vertical stacks around the central solid motor (see Fig. 2).

D. 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 communications transceivers have been put together by the micro-satellite community by modifying commercial off-the-shelf systems, including systems for the SSDL Sapphire, 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 (see link budget in Table V). A 0.6 m medium gain antenna on the host spacecraft is designed. 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.

TABLE VI
Micro-Penetrator Mass Budget

	Mass (kg)	Mass with Margin (kg)
Forebody	2.7	3.24
Drill and sampler subsystem	0.5	0.6
Biomarker chip	1	1.2
Seismometer	0.2	0.24
Accelerometer	0.03	0.036
Thermometer	0.3	0.36
Microcontroller	0.07	0.084
Structure (22% of total forebody)	0.6	0.72
Aftbody	5.6	6.72
Propulsion (wet)	2.4	2.88
Power	1.3	1.56
Communication	0.19	0.228
Avionics	0.2	0.24
Thermal Heaters	0.01	0.012
Structure (22% of total aftbody)	1.2	1.44
Other electronics	0.3	0.36
Total Mass	8.3	9.96

E. Overall Mass Budget

Given the above-mentioned design, an overall mass budget sheet is provided in Table VI. The system is estimated to have an all-up mass of less than 10 kg including a 20% system-level mass margin.

V. CONCLUSION

This paper outlines a micro-penetrator concept (less than 10 kg) that is suited for planetary deployment and in situ astrobiological investigation. On-board instrumentation in this concept includes a biomimetic drill based on the working mechanism of the wood wasp ovipositor for sampling beneath the surface layer. The ovipositor drill represents a novel approach of reciprocating drilling that requires no axial force. Tests have shown its feasibility and potential of improving drilling performance over conventional drills. The preliminary envisaged micro-penetrator package of less than 10 kg is able to reach about 1.5 m underneath an asteroid surface and provide a series of studies on its chemical and physical properties.

Further design justifications requiring critical design and field-testing are out of the scope of this study but will be looked into in the future study. In particular, we need to further investigate the remaining issues of the drill subsystem design, such as drill deployment mechanism, optimal geometry and material of the drill bits, and the sample extraction and transfer method. We are also interested in deriving the theoretical drilling model and eventually build the drill as a self-contained instrument deployable from any machinery.

REFERENCES

[1] Ellery, A., et al.
Bionics & space systems design case study 2—Asteroid micro-penetrator with biomimetic drill.
ESA Contract Report AO/1-4469/03/NL/SFe, 2005, 1–131.

[2] Ellery, A., et al.
Astrobiological instrumentation for Mars—The only way is down.
International Journal of Astrobiology, **1**, 4 (2003), 365–380.

[3] Ellery, A., et al.
Bionics & space systems design technical note 1.
ESA Contract Report AO/1-4469/03/NL/Sfe, 2005, 1–341.

[4] Gao, Y., Ellery, A., Jaddou, M., Vincent, J., and Eckersley, S.
A novel penetration system for in situ astrobiological studies.
International Journal of Advanced Robotic Systems, **2**, 4 (2005), 281–286.

[5] Skelley, A. M., et al.
Development and evaluation of a microdevice for amino acid biomarker detection and analysis on Mars.
PNAS, **102**, 4 (2005), 1041–1046.

[6] Sims, M. R., Cullen, D. C., Bannister, N. P., Grant, W. D., and Jones, R.
A life marker chip for the specific molecular identification of life experiment.
In *Proceedings of the III European Workshop on Exo-Astrobiology*, 2003, 293–294.

[7] Dickinsheets, D., et al.
J Raman Spectros, **31** (2000), 633–635.

[8] Steltzner, A. D., and Nasif, A. K.
Anchoring technology for in situ exploration of small bodies.
In *Proceedings of the IEEE Aerospace Conference*, 2000, 507–518.

[9] Young, C. W.
Penetration equations.
Sandia Laboratories Report SA-ND-97-2426, 1997.

[10] Vincent, J. F. V., and King, M. J.
The mechanism of drilling by wood wasp ovipositors.
Biomimetics, **3**, 4 (1995), 187–201.

[11] Zacny, K., Quayle, M., McFadden, M., Neugebauer, A., Huang, K., and Cooper, G.
A novel method for cuttings removal from holes during percussive drilling on Mars.
In *Proceedings of Revolutionary Aerospace Systems Concepts-Academic Linkage* (RASC-AL), Cocoa Beach, FL, 2002.

[12] Richter, L., Coste, P., Gromov, V. V., Kochan, H., Nadalini, R., Ng, T. C., Pinna, S., Richter, H.-E., and Yung, K. L.
Development and testing of subsurface sampling devices for the Beagle 2 lander.
Planetary and Space Science, **50** (2002), 903–913.

[13] Bar-Cohen, Y., et al.
Ultrasonic/sonic sampler and sensor platform for in-situ planetary exploration.
In *Proceedings of the IEEE International Conference on MEMS, NANO and Smart Systems*, 2003, 4327–4355.

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