DEVELOPMENT OF KINETIC PENETRATORS FOR EXPLORATION OF AIRLESS SOLAR SYSTEM BODIES

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Abstract

We report on investigation and development of kinetic micro–penetrators for airless solar system bodies. Our goal is to design a technically feasible penetrator of low mass ($\sim\ 2-5$ kg) capable of surviving a high velocity impact and performing useful scientific measurements. We present a rational program of development beginning with generic studies and ground demonstration of impact survivability, through a technical demonstrator mission to high profile scientific missions. We aim to take advantage of existing experience from the UK defense sector, and current advances in high technology (e.g. MEMS, holey optical fibres). Key aspects discussed include science aspects, a comparison of kinetic penetrators and landers as a platform for exploration, penetrator technology (orbiter support, attitude control, de–orbiting, impact survivability, power, communications, mass), scientific instruments (temperature, heat flow, seismic, chemical) and future mission opportunities.

1 Introduction

The current rapid pace of technology advance combined with the expected change of emphasis from orbital to ground truth exploration of the Solar System is seen as an appropriate time to begin development of kinetic penetrators which potentially provide access to key science with pre–cursor missions for a great variety of planetary bodies.

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In fact, it is difficult to envisage any other method which allows widely spaced surface exploration of airless planetary bodies that is not prohibitively expensive.

We consider kinetic micro–penetrators which are small probes around 2 to 12 kg that impact planetary bodies at high speed (around $200 - 300$ m/s, and bury themselves a metre or so into the planetary surface. At such impact speeds it is necessary to employ technology able to withstand high gee forces around 10 kgee or higher. In addition, it will often be necessary to employ de–orbiting devices to slow down the probes to such impact speeds, together with attitude control to provide near vertical alignment in order to ensure both penetration and survival of internal components. The small size of these probes allows many to be deployed, which naturally provides redundancy, so no mission is lost due to the loss of a single probe. Whilst their small size does not allow a full complement of the most capable scientific instruments, they are ideal to perform focused investigations across widely spaced surfaces of a planetary body not currently feasible with soft landers and rovers, for example:

- For the Jovian satellite Europa and Saturnian satellite Titan, seismometers could determine the presence of an under–ice ocean, and the possible existence of a habitat for extraterrestrial life, as well as detection of the associated chemistry.
- For the Moon, a seismic network could provide information on the origin of the Earth–Moon system, and ground truth as to whether water and other volatiles exist in the shaded areas of polar craters.
- For NEOs (Near Earth Objects) this could confirm whether they are rubble piles consisting of rather loose agglomerates of rock and dust, or hard rocky bodies as originally thought.

Whilst historically there has been no successful deployment of a high speed penetrator, and the only deployment, DS2 (Deep Space–2) failed along with its companion lander, there is actually no evidence that these are inherently less reliable than soft landers. The only other mission to launch kinetic penetrators was the Russian Mars'96 mission which failed to leave Earth orbit due to a fault unrelated to the penetrators. Though the technology is challenging, it has to be noted that the above probes, together with the Japanese Lunar–A probe, have already been successfully constructed and space qualified (David, 2003; Lorenz, 2000; Smith, 2006; Tanaka, 2006). This includes demonstration of survival at these impact speeds by ground tests of the full–up DS2 and Japanese Lunar–A probes, and extensive military experience of firing instrumented shells into materials consisting of concrete, steel and ice. Also, with major development costs no longer necessarily required, and the low mass of such probes which substantially reduce launch costs, this provides an excellent basis for future low cost missions.

In addition, it is likely that significant elements of technology developed for airless micro–penetrators will also be of benefit for the exploration of planetary bodies with atmospheres, and for other lander and orbital missions for which robustness and very low mass are always advantageous. The rapid pace of technology is also likely to lead to significant further improvements in microtisation, which – together with the unique driving force of high-gee survivability – may generate associated industrial spin–off.

2 UK Consortium

The U.K. penetrator consortium grew from its beginnings in 2002, to reach a point in 2006 when its recommendations for planetary penetrometry was given a high priority by the UK planetary science community. Members of the consortium also provided key information to a study initiated by the U.K. *Particle Physics and Astronomy Research Council* (PPARC) and SSTL which led to the selection of penetrators as the most practical cost effective means of achieving the highest scientific research goals, in the recently announced (January 2007) U.K. initiative for a lunar mission involving 4 penetrators.

The consortium currently consists of the following institutes which provide the following key space science and technology expertise:

- MSSL – Consortium lead, payload technologies, payload system design
- Birkbeck College London – Science
- Imperial College London – Seismometers
- Open University – Science and instrumentation
- QinetiQ – Impact technologies, delivery systems technologies
- Southampton University – Optical fibre technology
- Surrey Space Science Centre and SSTL – Platform and delivery system technologies and scientific instrumentation.

The consortium is currently seeking funding for the above lunar penetrator mission mentioned above and supporting a penetrator study for the Europa–Jupiter mission proposed in the frame of the *ESA Cosmic Visions* program.

3 Development program

Because the history of kinetic penetrators lacks a first successful mission, it is considered that a key initial element is to provide a technical demonstrator mission. This is considered as especially important prior to any major scientific missions such as Europa–Jupiter. Thus a rational development (Smith et al., 2006) program is considered to encompass the following components:

(a) **Generic penetrator design**: This is considered an investment to enable fast response to opportunities, and cheaper future missions (tailoring only required). It would provide a generic system design, identify critical issues, and establish a library of penetrator components and capabilities.

(b) Ground demonstration: This would build confidence in the technology, via demonstration of successful survival and operation of system and components after firing of penetrator technology into simulant targets on Earth.

(c) Technical demonstrator Lunar mission: A technical demonstrator mission is seen as a key component to establish a successful space heritage for the future of this technology, not only for impact survival but also to demonstrate the ability to provide effective scientific exploration. Initially it should take at least equal priority to scientific goals. A Lunar target is ideal as a technical demonstration mission as it is close by, requires no long cruise phase, communications are fast, and there are no exceptional environmental conditions. There is also a powerful scientific rationale for the Moon as a target.

(d) Follow–up mission opportunities: Following a successful technical demonstrator mission, a considerable body of technology, including scientific instruments, will have been established, so that development costs for future scientific missions can be considerably cheaper. A gradually increasing prominence of scientific goals over technical demonstration would be sensible. Such follow–up mission opportunities could include Europa, comets, near–Earth objects, asteroids, Mercury and other fascinating Solar System bodies.

This program will provide an incremental build–up of technical readiness, confidence, heritage, and provide a sound basis to enable cheaper and faster development for later missions.

4 Penetrator architecture and development process

We propose a development process based around a penetrator system architecture, as presented below. Because penetrators require a delivery system, which is often likely to involve a de–orbiting thruster and attitude control system, a 'descent probe' containing one or more penetrators is often required. With the addition of the attachment of the probe to the spacecraft, the overall system can be considered to consist of the following 3 major sub–systems (see Figure 1 for a descent probe attached to a penetrator):

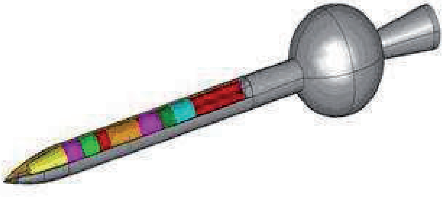

Figure 1: Concept for a descent probe with a penetrator.

(1) Spacecraft attachment: This attaches the descent probe to the spacecraft, and includes spacecraft ejection system and spacecraft interfaces including power and local and remote telecommand facilities.

(2) Descent probe: This consists of a de–orbiting and attitude control system, and possible communications and descent payload such as camera, and the connected penetrator(s). Because of their independent free flying nature, such descent probes can be considered to be small spacecraft in themselves and require appropriate systems engineering.

(3) Penetrator: This is the body which survives impact with the planetary surface and performs the desired investigations. It is composed of two main parts, the platform (structure, power, communications, data handling) and payload (scientific instruments such as seismometers, heat flow and chemical detectors).

Because the penetrator system can be considered to be essentially a small spacecraft mission in itself, a development approach is adopted which mimics a normal spacecraft development as follows:

1. Define science requirements
2. Define mission concept
3. Define mission requirements & constraints (elaborate above items)
4. Define penetrator system:
    (a) Spacecraft attachment
    (b) Descent probe (platform and payload)
    (c) Penetrator (platform and payload)

Because of the extremely high gee forces a much closer than normal relationship between instrument and penetrator structure development is required. A significant parallel development is envisaged whereby the platform studies define basic parameters for the internal instruments, such as accommodation, power and high gee environment. However, successful instrument development will be additionally supported by early and continuing close relationships with platform providers through impact experience supplemented by active modelling and controlled experiments to identify key sensitive areas in their development. At the end of this process, a complete penetrator will be constructed and tested.

5 Penetrator technology

Technology for penetrators can be considered for each of the 3 major components as follows:

(a) **Spacecraft Support Technology** includes accommodation on spacecraft; ejection mechanism; and spacecraft interfaces (communications, power, telecommand). The telecommand interface can be used to determine the health status of penetrator prior to ejection which is important for technical demonstration, and the power interface to confirm internal batteries charge status, and if possible to top up power levels just prior to ejection. Electrical interfaces can also be used to initiate a post ejection computer which will be used for descent control and data handling

(b) **Descent Probe Technology** will normally include a micro de–orbiting thruster and attitude control system; communications system; onboard controller; and perhaps payload elements such as a camera. The de–orbiting and attitude control system will provide deceleration and orientation of the penetrator for survivable impact. There may also be a late stage device which separates the penetrator from the descent probe. As the primary purpose of the descent probe is to deliver the penetrator, there is generally no requirement for the descent probe to survive impact.

A descent communications system can provide key technical demonstration information by enabling status reports from the probe as it descends for the periods where communication is possible, and may include the following information:

(i) That post ejection communication system is functioning correctly immediately after ejection.

(ii) Confirmation of descent probe initial thruster firing.

(iii) Confirmation of descent probe correct deceleration and attitude control operations in early descent phase.

(iv) Confirmation of descent probe penetrator separation.

(v) Confirmation of final penetrator attitude control orientation or re–orientation operations.

(vi) Confirmation of final descent profile operations to impact.

In addition to the above specific descent milestones and operation phases, continual probe health monitoring would also be useful (e.g. temperature, currents, voltages, system operation). Such technical monitoring could provide vital information in the case of a failure, as for example occurred with the DS2 (Deep Space–2) probes where there was no probe monitoring from launch onwards.

Descent phase communications could also allow collection of scientific data from any payload instruments such as a camera, or atmospheric instruments (where there is an atmosphere), thus ensuring a partial scientific return should the penetrator not survive impact.

An onboard controller would be responsible for sequencing the descent including the key thruster and attitude control operations; collecting, processing, storing and controlling the transmission of status and payload data. Where descent telemetry bandwidth is limited, data may be directed to be stored within the penetrator for post impact transmission. This is likely for high data rate instruments such as a descent camera where the images might take days, weeks or months to be transmitted after impact.

Penetrator Technology (platform and payload) is the only system component which has to survive impact and perform post impact scientific investigation, and will normally comprise:

(a) Penetrator Platform: This comprises the penetrator body including impact survival internal packaging; communication system; power and heating system; and data handling

(b) Penetrator Payload: This will vary according to the mission, but common factors include very low mass and power requirements. As we are specifically aiming at total penetrator mass < 5 kg, this would tend to imply a total payload to be ≤ 3 kg. Such low mass tends to drive development toward micro–technology such as MEMS (Micro–Electronic Mechanical Systems), as exampled by the micro–seismometer shown in Figure 2.

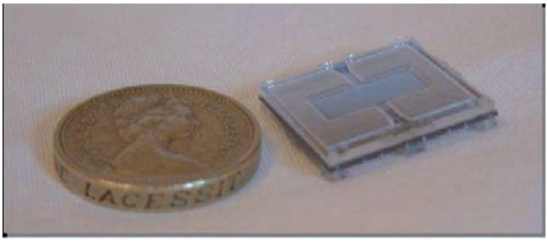

Figure 2: Micro–seismometer — manufactured from a single silicon wafer a few cm across (W.T. Pike, Imperial College, London).

Other payload possible technologies include holey optical fibres (electronic noses) and SAW (Surface Acoustic Wave) sensors. Together, with simple thermometers (e.g. thermocouples) this can give the capability to perform key investigations of seismometry: planetary heat flow and chemical species detection including water and other volatiles potentially including those associated with astrobiology. The payload can also include e.g. detectors for radiation and magnetism, microscope, camera, and a drill for sample collections and probing local areas not modified by the entry process.

6 Lunar demonstrator mission

Development plans and costings are currently being prepared for the U.K. Lunar Mission Initiative for a 4 penetrator payload targeted at a 2010 launch. The research goals for this mission that the micro–penetrator payload would address include the following key science:

(a) **Lunar seismology**
A network of micro–seismometers could detect the presence and measure the size of a lunar iron core; determine crustal and basalt fill thickness; the deep structure of lunar mantle; the origin and location of the enigmatic shallow moonquakes. These would benefit understanding of the source of the Moon's remanent magnetism; evolution of planetary magnetic fields, and origin of Earth–Moon system.

(b **Lunar thermal gradients**
Passive thermometers would be capable of determining heat flow from the Lunar interior and information on internal near–side/far–side inhomogeneity of crustal heat producing elements (U,K,Th). This is relevant to understanding the Moon's early history.

(c) **Lunar water and other volatiles sensing**
Water sensors capable of detecting the presence, extent, and concentration of water and other volatiles (organic) would provide information on Lunar evolution and future Lunar resources, and could also be relevant to astrobiology. If possible, an isotope discrimination capability could also provide information on the origin of the water.

(d) **Geochemical analysis**
Provide ground truth for remote sensing XFA and multi–spectral imaging.

(e) **Far side**
There has not yet been a far side landing and there is evidence that the near and far sides of the Moon may be quite different internally. It is especially important to make direct measurements of the far side crustal thickness, which to date has not been constrained seismically, and to measure the far side heat flow, which has implications for the distribution radioactive heat–producing elements in the lunar mantle.

To achieve these science goals the major key elements of this mission would consist of:

(a) **Mission**

- Delivery and communications spacecraft (Orbiter).
- Orbiter payload: 4 Penetrator Descent Probes (Maximum 13 kg penetrator + 20 kg propulsion each).
- Landing sites: To be widely spaced across Lunar surface to support seismic and heat flow network; with at least one site on far side; and one at polar region (probably South Pole Aiken basin) for water/volatiles detection.

- Duration: Surface mission to last ≥ 1 year (several years desirable) for seismic network. Other science do not require so long (perhaps a few Lunar cycles for heat flow and volatiles much less).
- Penetrator support: Orbiter to provide power, pre–ejection health status, and relay communications.

(b) Descent phase

- Deploy descent probes from orbit, using a breaking solid rocket motor to reduce orbital velocity to provide target impact velocity ~ 200 m/s.
- Attitude control to achieve penetration closely perpendicular into Lunar regolith to depth of a few metres.
- Camera to be used for descent to characterize landing site. Most images likely to be stored for transmission after impact.
- Telemetry transmission during descent for health status (technology demonstration).
- Impact accelerometer (to determine penetration depth & regolith mechanical properties).

(c) Landed phase

- Single body penetrator for simplicity & risk avoidance. (To avoid extra high–gee forces of an aft component, uncertainty associated with ensuring remains on surface; risks associated with umbilical power/data connection with forebody).
- Battery powered, with comprehensive power saving techniques, to provide target $\geq$1 year operation. (Solar power not possible in permanently shadowed craters for volatile search; possibility of power shadowing by local rocks or self–made crater in other sites, and reduced power due to dust coverage by potential post impact and other processes).
- Payload seismometers, heat flow thermometers, volatile detectors.

7 Conclusions

We have formed a consortium to develop kinetic penetrators for airless planetary bodies through a logical program from conceptual design, ground demonstration, technical demonstrator missions, to science missions. We have shown that high speed micro–penetrators hold great promise as a feasible and very cost effective means of key pre–cursor exploration of wide areas of Solar System bodies. Soft landers offer a greater scientific capability but at much greater cost and much more restricted in areas acceptable to soft landing.

Within the U.K. penetrators have now been established as a priority for UK planetary future directions, and we are currently engaged in supporting penetrators for the recently announced U.K. Lunar penetrator MoonLITE mission. We are also actively engaged in promoting and studying penetrator components for the ESA Cosmic Visions Europa–Jupiter and Lunar Mission proposals.

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