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Micro-Penetrator for Canadian Planetary Exploration

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Abstract**—**Space exploration is a highly visible endeavour of humankind to seek profound answers to questions about the origins of our solar system, whether life exists beyond Earth, and how we could live on other worlds. Different platforms have been utilized in planetary exploration missions, such as orbiters, landers, rovers, and penetrators.

Having low mass, good mechanical contact with the surface, ability to acquire high quality scientific subsurface data, and ability to be deployed in areas that may not be conducive to landers or rovers, Penetrators provide an alternative and complimentary solution that makes possible scientific exploration of hardly accessible sites (icy areas, gully sites, highlands etc.).

The Canadian Space Agency (CSA) has put space exploration as one of the pillars of its space program, and established ExCo program to prepare Canada for future international planetary exploration. ExCo sets surface mobility as its focus and priority, and invests mainly in the development of rovers because of Canada's niche space robotics technology. Meanwhile, CSA is also investigating how micro-penetrators can help Canada to fulfill its scientific objectives for planetary exploration.

This paper presents a review of the micro-penetrator technologies, past missions, and lessons learned. It gives a detailed analysis of the technical challenges of micro-penetrators, such as high impact survivability, high precision guidance navigation and control, thermal protection, communications, and etc. Then, a Canadian perspective of a possible micro-penetrator mission is given, including Canadian scientific objectives and priorities, potential instruments, and flight opportunities.

Keywords**—**micro-penetrator, CSA, planetary exploration

I. Introduction

PEXPERIMENTS (both static and dynamic) can, when designed properly, be a powerful method to determine material strength and layering of sub-surface materials on solid bodies of the Solar System [1]. Penetrators are bullet-shaped vehicles designed to penetrate a surface and emplace experiments at some depth. Vehicle speed varies in the region of 60-300 m s^{-1} to penetrate to the planetary surfaces, depending on factors such as the desired depth, the mass and geometry of the penetrator, the expected surface mechanical properties, the shock resistance of internal components, and constraints imposed by the entry and descent from orbit or interplanetary trajectory [2]. Penetrators may consist of a single unit, or slender forebody and a wider aftbody linked by an umbilical tether, the two parts separating during penetration to leave the aftbody at the surface. Although modularity favors two-body penetrator, it is preferable to use a single body penetrator design for reliability.

Besides being a modest cost solution there are some other advantages that show penetrators as a good solution for *in situ* astrobiological investigation as well as for planetary seismology, heat flux measurements or planetary geochemistry. Probes are placed subsurface in more stable environment with less temperature variation and protected from radiation on the surface. Penetrators offer a number of advantages for space exploration over other platforms. These advantages include:

- low mass
- good mechanical contact with the surface
- ease of deployment

These advantages translate into a number of attractive mission options, including the ability to deploy multiple penetrators on a single mission (due to their low mass), their ability to acquire high quality subsurface data (due to their embedment in the surface), and ability to be deployed in areas that may not be conducive to landers or rovers. Such a place can be [1][2][3]:

- many sites on the Moon including Procellarum region, lunar polar permanently shadowed craters or other farside lunar sites
- areas on Mars that may be difficult to access for landers or rovers (e.g. Tharsis plateau, Elysium Planum, gully sites, Olympus Moons etc.)
- the satellites of the outer planets (Jovian moons Europa and Ganymede), near-Earth objects (asteroids and comets)

Low mass reduces launch cost, increases ability to launch multiple probes on a single mission, and multiple probes provide natural redundancy.

The potential scientific return from each individual site can include geological and chemical characterization of the sub-surface material and the detection of water and other volatiles. In the view of astrobiological missions (e.g. to Mars, Europa and asteroids) a major goal of future is to search for biomarkers - organic molecules that might reveal the presence of extraterrestrial prebiotic and biotic signatures. Penetrators allow such key science to be achieved cost effectively and for landing sites not suitable for soft landers.

To date, most penetrator concepts have been developed for specific planetary environments, e.g. Deep Space 2 microprobes [12][13][16], Lunar-A [10][15][18], or Mars 96 [14][17][21]. Although none has yet to be successfully

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deployed, they have a high TRL of 6 in that they are flight-ready as a technology despite the challenges of impact survivability – such survivability has been demonstrated in impact tests undertaken in the UK. [27]

II. PAST MISSIONS OVERVIEW

There were several attempts to reach other planets with the penetrators and deployed them into the surface to investigate interior of the planet. However none of these missions have been successfully completed so far.

The Russian Mars 96 penetrator probes, launched in 1996 to investigate Mars by the Russian Space Forces, had been lost when Mars96 failed to leave Earth orbit. The scientific objectives of the penetrator experiments were to obtain images of the surface, study Martian meteorology, examine the physical, chemical, magnetic, and mechanical properties of the Martian regolith, including its water content, collect data on the magnetic field, and record seismic activity [14].

The NASA's Deep Space 2 (DS2) mission was the only flown mission which successfully reached the Mars orbit. It was designed to validate 10 advanced, high risks, high-payoff technologies, including an ultra-low-temperature lithium battery and a very-low-power micro-processor. Mars Polar Lander (MPL), with the two DS2 probes, was launched 1999. The probes reached Mars apparently without incident, however, no communications from MPL or the probes were received. [13][12] It is still not known what the exact cause of failure was. The JPL Special Board suggests several possible causes for failure [12]:

- the probe radio equipment had a low chance of surviving the impact.
- the probes may simply have hit ground which was too rocky for survival.
- The batteries on the probes, which had been charged prior to launch almost a year earlier, might not have retained sufficient power.

The LUNAR-A mission was planned to provide some important clues by exploration of lunar interior using seismic and heat-flow experiments. In order to achieve the scientific objectives, penetrators were thought to be the most effective method, because they can deploy scientific instruments at several sites in one mission. And also, the LUNAR-A mission would be the first technological demonstration to constitute a geophysical network since the crewed Apollo missions [10]. Programme terminated before launch after extensive development and trials (primarily due to potential thruster faults) in January 2007 [15].

Furthermore several penetrator mission concepts were proposed in the past years, but for different reasons, all of these proposed missions still remain at the concept stage. UK proposed the MoonLITE [29][19] mission, which lead to the creation of UK penetrator consortium. This consortium also proposed other two penetrator missions LunarEX [6] and LunarNET [9] with broader international collaboration based on MoonLITE concept. MoonLITE was a lunar science mission comprising 4 scientific penetrators that will make in-situ measurements at widely separated locations on the Moon. Russian Vesta mission [20] would have consisted of two identical probes to be launched in 1991 into Venusian atmosphere. At Venus, a French satellite dedicated to asteroid flybys would be released. A combination of various factors, the partial failure of the Phobos mission, financial troubles and the disbanding of the Soviet Union, didn't allow for the project to advance beyond the planning phase. CRAF (the Comet Rendezvous Asteroid Flyby) mission [34] was designed to answer the many questions raised by *the* Halley missions by exploring a cometary nucleus in detail, following it around its orbit and studying its changing *activity* as it moves closer to and then away from the Sun. In addition, on its way to rendezvous with the comet, CRAF would fly by a large, primitive class main belt asteroid and would return valuable data for comparison with the comet results. CRAF was cancelled in the early 1990's (1992) in order to free budget up for the Cassini mission to Saturn, which used the same Mariner Mark II bus. Polar Night mission [7] was submitted as a Discovery Mission to NASA in 2000 but it was not selected for flight. The design of 3 penetrators was a variation of the widely used penetrometer family developed by Sandia for Department of Defense aerial delivery of science instrumentation. Russian Luna GLOB mission [23][30] was slated to be launched in 2012 and then postponed for later years (currently for 2015). In the beginning it was an unmanned mission to the Moon planned by Russia including an orbiter with ground penetrating sensors. Later, Luna Glob was supposed to carry Lunar A penetrators**.** Current status of Luna Glob mission does not seems to carry any penetrator. [31]

III. TECHNOLOGICAL REVIEW AND CHALLENGES

The penetrator concept is a generic one with possibility to accommodate a wide range of planetary environments. As it was said earlier, penetrators may consist of a single unit, or slender forebody and a wider aftbody linked by an umbilical tether (Fig. 1), the two parts separating during penetration to leave the aftbody at the surface. The forebody design provides low resistance to penetration while aftbody being flared controls the penetration depth from the surface. Aftbody with tapered upper part provide increased resistance to penetration which acts as a conical terrabrake. Typically, most of the electronics, power and communications are housed in the aftbody while scientific instruments are emplaced in the forebody. Single body penetrators are more compact but can suffer from worse communication. It is preferable however to use a single body penetrator (Fig. 2) design rather than a separable forebody/aftbody for reliability. A compromise could be a single body penetrator with flaring upper part serving as a terrabrake similar to CRAF concept (Fig. 3)

Fig. 1 Two body penetrator (DS2) [25]

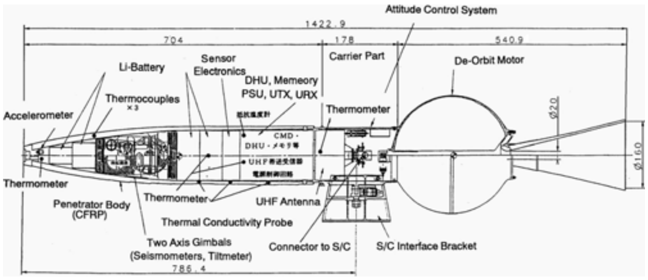

Fig. 2 Single body penetrator (Lunar-A) (cancelled) [10]

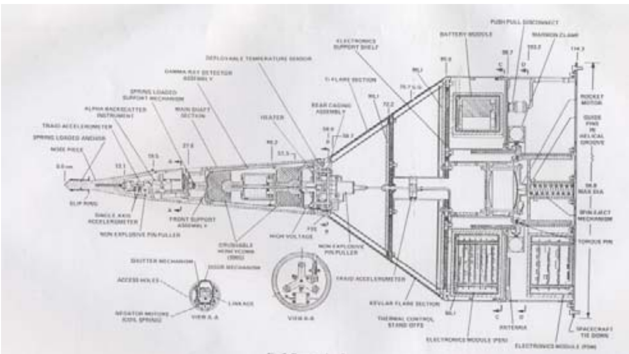

Fig. 3 CRAF (Comet Randevous Asteroid Flyby) mission penetrator (cancelled) [34]

For airless bodies, attitude and trajectory control will be more challenging but on the other hand it provides some degree of targeting capability. For atmosphered bodies such as Mars, Venus, Titan or Jupiter, entry descent and landing systems exploit the atmosphere to decelerate using ablation or parachutes (eg. DS2 microprobes, Mars96 penetrators).

A. Guidance and Navigation Control

The guidance and navigation control (GNC) system controls the penetrator separation from the main orbiter, the descent of penetrator modules, and surface penetration. Before the penetrator modules are separated from the main orbiter, the penetrator modules are required to spin along their longitudinal axis for stabilization and ejection. After the penetrator modules are released from the main orbiter, the orbit velocity of the penetrator modules is required to be cancelled by the de-orbit motor. In order to descend the penetrators onto the planet's surface, the motion direction of the penetrator modules is required to change 90 degree, and the nutational motion caused by the de-orbit motor during the cancellation of orbit velocity is required to be controlled. To reach the expected landing site with the desired attack angle, the attitude and orbit of penetrators are required to be controlled simultaneously. There exist two sorts of guidance, navigation, and control systems for penetrators, single axis attitude control and three axis attitude and orbit control. These two control methods have their own advantages and features and can be suited for different planetary exploration missions. *The single axis attitude control* requires only a single thruster with features of simple structure, less weight, and low cost. Due to one single thruster used in the single axis control, only attack angle of the penetrators can be controlled. The orbits of penetrators cannot be controlled after the de-orbit motor is separated from penetrator modules. This means the landing site of penetrators cannot be controlled after the de-orbit motor is separated from the penetrator module. Single thruster control has been proposed for Lunar-A mission and MoonLITE mission as well. *For three axis control*, it is required at least three thrusters installed in the penetrator body, and more sun sensors, or IMU etc. Although the three axis control has a more complicated structure, more weight and higher cost compared with single axis attitude control, it can provide three axis attitude and orbit control capability for penetrators and obtain higher accuracy of landing site and surface penetration. Three axis control have been suggested for the penetrator attitude control in Polar Night mission proposal and Luna Glob mission proposal. Mars microprobes had no active control or propulsion systems, but were designed to passively orient themselves during free fall with the forebody front forward.LunarEX penetrator impact error ellipse [6] was determined with a 2º error, a landing ellipse of 28km diameter would be achieved (using single thruster controlling only the penetrator attitude after its separation from spacecraft with effect to attack angle). This conservative estimate can be compared with crater-targets at the Lunar poles. However, for non-crater targets the landing precision is more than adequate. The US Polar Night penetrators [6] were expected to be delivered to a target point on moon surface within accuracy of 2.2km. The Polar Night penetrator modules would be spin up to 60 rpm for stabilization and ejection. It would have two 267N de-orbit motor each to cancel penetrator's orbit velocity, and six 4.5N thrusters for three axis attitude and orbit control of penetrators.

B. High impact survival

The level of impact loads of a micro-penetrator is dependent mainly on three key factors: impact velocity, characteristics of the material being impacted, and orientation. Prior to performing the trial, it is needed to develop a model and simulate the impact, to identify any high stress locations that might lead to failure, and to predict the penetration depth. Based on the mission target body and objectives, impact velocities up to 300 m/s were planned in many penetrator mission proposals. Depending on the assumed target surface material characteristics, sophisticated impact simulation predicted peak impact deceleration between 10,000 g in rubble up to 50,000 g in hard rock. [32][8] In fact, it is entirely possible for an instrument to survive an impact of 300 m/s and resources have been devoted to such conditions within the defense context [9][10]. Penetrator-type devices are common place within the defense sector and instrumentation is available off-the-shelf which will survive impacts higher than 50,000 g. It is interesting to note that a new class of weapons can penetrate 30 m of earth or 6 m of concrete [11]. Weapons in this class use 'Hard Target Smart Fuze' which use accelerometers to 'count floors' to detonate at a specific floor or depth.Several techniques have been developed to prevent failure during such high impact short duration loading, for hardware not expected to survive such environment by themselves. The techniques successfully applied to micro-penetrators will now be briefly reviewed. Except for ruggedizing the sensitive subsystems or payloads, or part of them, these techniques are related to properly packaging the hardware to be protected. Ruggedizing hardware implies modifying the design or manufacture process such that the device will be able to resist much higher shock loading than what is observed in a spacecraft. However, such modifications often are not an option due to the additional cost or schedule implication. Another reason for eliminating such an option could be the associated compromise in the device performance. In such frequently occurring situation, the only other means of ensuring hardware survivability is to implement a proper packaging approach.

The following are some of the packaging techniques that have proven to be effective in the context of penetrators:

- Use of potting compound material that encase sensitive components. [3]
- Use of glass microspheres that encase sensitive components [27], which provides shock dissipation.
- Use of sublimating material: The idea is to encapsulate the shock sensitive part of the device in a strong enough solid material for achieving the shock protection. After the impact, the material is disposed of through the process of sublimation (passing from solid to gas state directly), when such disposition is essential for the device operation. This innovative approach has been successfully demonstrated for protecting the suspension system of a microseismometer developed for the MoonLITE mission. Without such protection, the suspension system could not resist to more than 35 g before being damaged; testing has shown that the same suspension system survived shock levels up to 15,000 g when encapsulated into sublimable naphthalene or paradichlorbenzene (PDB). [28] It is currently not clear if they have the required temperature range for space use (lunar South Pole in particular).

C. Communication

Signal attenuation is not thought to be significant for dry lunar regolith, or icy regolith at the expected concentrations, but further studies are needed, including the possibility to leave a trailing aerial on the surface. Such an aerial would be deployed from the rear of the penetrator to limit stresses on the wire during deployment; a technique which has extensive heritage in the defense sector. [5] Communication unambiguously favours separable aft- and forebody to guarantee reliable link between micro-penetrator and orbiter as the communication from a few meters beneath the surface could be attenuated by regolith. For missions such as Europa, where the icy surface is not very well known, this will be a deciding factor. Omnidirectional antennas which were widely used are now being superseded by patch antennas which do not require deployment mechanisms. Patch antennas comprise a flat area of almost any shape (though circular or rectangular forms are most commonly used) of metal conductor (such as copper) on the surface of a dielectric insulator substrate, typically glass/ceramic materials.The DS 2 aftbody included the telecommunications subsystem which was supposed to relay data back to Earth via the Mars Global Surveyor (MGS) spacecraft. The receiver and transmitter operated in the Ultra High Frequency (UHF) range and were supposed to transmit data to MGS at a rate of approximately 7 kbit/sec. [16] Lunar-A planned to use UHF (f=400 MHz) hybrid telemetry system for communication between deployed penetrators and relay spacecraft with the data transfer rate of up to 1 kbits/sec. [18] The data rate from the MoonLITE penetrator to the orbiter is assumed to be 30 kbits/day. Because of the infrequent communication contacts with the orbiter (e.g. every 15 days), each penetrator will need to operate autonomously, collecting, compressing, and storing data until each uplink opportunity. However, a detailed study will be made of regolith communication transparency properties, and the possibility of a trailing antenna especially for the case of immersion into regolith containing a significant proportion of ice. The LunarNET communication baseline design is a body antenna mounted at the aft (trailing) end of the penetrator. The antenna would be conformed to the surface of the penetrator, to ensure a smooth, projection free surface. As the body diameter is quite small for a UHF antenna, a helical or similar antenna may be needed; alternatively dielectric loading could be employed at the expense of mass. The dielectric properties of the regolith would need to be taken into account in designing the antenna in order to optimize performance when buried. [29] The UK penetrator consortium is investigating the key design issues and penetrator subsystems including AOCS, material, communication, power, payload operations, etc. The LunarEX and LunarNET proposals outline their progress.

D. Power and Thermal protection

As it was said earlier, power will be one of the major constraints in the mission, and the battery type will affect nominal mission life time. DS2 nominal life time was a few hours while Lunar-A life time was expected to withstand much longer (one year). [3] Power options include solar cells, fuel cells, batteries (currently lithium-chloride batteries) and micro RPS (Radio-isotope Power Supplies). Solar cells needs to remain aftbody on the surface which would not be possible in case of single body penetrator. Mars 96 power supply included 150 W.h batteries + 0.5 W Pu-238 RTG. [17] DS-2 power was supplied by low-temperature Li thionyl chloride primary batteries with conductive fins and expected life time of 1 – 3 days.[3] Lunar-A power [18] is supplied by the same battery type as DS-2 microprobes, Li-$SOCl_2$ with power density of about 430 WH/kg. MoonLITE concept also assumes high energy-density lithium ion batteries (providing 500 W.h) that are capable of operating at low temperatures (-60°C) together with Radioactive Heating Units (RHU). [19]The thermal control system ensures that all components are maintained within their temperature tolerance limits. Thermal control and management will be critical for such a small spacecraft deployed in cold environments but is limited to passive techniques (heaters will reduce the mission lifetime substantially) – aerogel or basotect insulation is currently favoured over multilayer insulation for their greater insulation properties. The purpose of the thermal control system is to balance the heat flow into the spacecraft plus the heat generated internally and the heat flow out regulating the temperature of the penetrator. [33] Batteries are the most sensitive components to temperature excursions. They will require heating sources but the use of local resistance heaters will be crippling in terms of power consumption. For the Mars96 penetrators, active heating radiator and passive heat insulation were used. [17] Lunar regolith is a good insulator but heat generated by impact will be dissipated rapidly (within hours). This represents a challenging thermal environment – high initial temperatures (up to 1000^{o}C) which rapidly fall to ambient temperatures (for Mars the regolith temperature at -120^{o}C is less than air temperature -80^{o}C at night). All electronics and instruments must be designed to withstand the -80^{o}C temperatures in the aftbody and -120^{o}C in the forebody. CMOS technology is relatively robust to a wide range of temperatures. On Mars, the major problems are fatigue, embrittlement and coefficient of thermal expansion mismatches due to day/night thermal cycling. The commonest wire breaks are at the wire ends where they are bonded. Thermal energy may be rapidly redistributed through the penetrator through micro-heat pipes if necessary – variable conductance heat pipes may offer solutions. [33]

E. Instruments

Micro-penetrator scientific payload is limited by weight of approximately 2 kg, which means that instruments selection has to be particular with respect to required scientific return. Two-body penetrators offer the advantage in providing data on the atmosphere, surface and sub-surface simultaneously within the same small package. Universally-adopted instruments include miniaturized accelerometers, seismometers and temperature sensors on forebody or a small optical camera mounted on the aftbody (TABLE). Most of these instruments have space heritage and high RTL.

TABLE I
EXAMPLES OF UNIVERSALLY ADOPTED INSTRUMENTS PROPOSED FOR DIFFERENT PENETRATOR MISSIONS

Instrument	Mission
Accelerometer	Lunar-A [15], MoonLITE [22], LunarEX [6], Mars96 [21], DS2 [16]
Seismometer	Lunar-A [15], MoonLITE [22], LunarEX [6], Mars96 [21], Luna GLOB [23]
Tiltmeter	Lunar-A [15]MoonLITE [22], LunarEX [6]
Temperature sensors	Lunar-A [15] MoonLITE [22], LunarEX [6], Mars96 [21]
Camera	Vesta [20], Mars96 [21]

Additional possibilities include a micro-drill similar to the DS2 micro-drill, meteo station similar to Mars 96 meteo set or any spectrometers such as Angstrem X-ray spectrometer on Mars96 or NIR spectrometer planned for VESTA. Proposed instruments should require minimal or no sample processing, have to be of a small volume and weight and well ruggedized. Beside the above mentioned requirements there are other several important points for the scientific instrument suite:

- scientific relevance and value
- remote calibration
- survival of space and planetary environment regimes
- low power requirements
- limited data rate capabilities
- limited internal data storage
- high reliability

Many spectrometric instruments such as X-ray spectrometers for elemental analysis require miniaturization and ruggedisation though potentially suitable instruments do exist. Miniaturized fibre-optic based sensors offer much promise for multi-source scientific measurements (eg. confocal microscope, strain/pressure/temperature, etc). Scientific instruments of several missions are shown in TABLE

TABLE II
SCIENTIFIC INSTRUMENTS ON SOME PASSED FLOWN PROPOSED PENETRATOR MISSIONS

Mission	Instruments
VESTA [20]	The following scientific instruments supposed to be included: A wide angle camera (~6.5° field of view, 512x512 pixel CCD) A narrow angle camera (~0.5° field of view, 512x512 pixel CCD - 3.9 arcsec/pixel) A near-infrared spectrometer (measuring between 0.5-5 micrometers with lambda/delta lambda = 50, 5 arcminutes per pixel) Possible further instrumentation: UV spectrometer Radar altimeter/radiometer A dust detector (ion or neutral gas detector)
Mars96 [21]	TVS TV-camera MECOM METEO SET Gamma spectrometer X-ray spectrometer Alpha-Proton spectrometer Neutron-Proton spectrometer Accelerometer Thermoprobe Seismometer Magnetometer
DS2 [16]	The evolved water experiment The soil conductivity experiment The impact accelerometer The Atmospheric Descent Accelerometers (ADA)
Lunar-A [15]	Two-component seismometer Heat-flow probe Tiltmeter Accelerometer

IV. Canadian perspective

In December 2008, a large group of Canadian scientists came together with representatives from universities, industry, and government to consider the potential Canadian science activities beyond the vicinity of Earth. From discussions at that meeting – the 6th Canadian Space Exploration Workshop (CSEW6) - and many discussions following that workshop, a number of extremely promising directions have been identified as the scientific objectives for Canadian space exploration programs [4]. To fulfill scientific objectives, which are defined by Canadian scientists and are also included in the framework of the Global Exploration Strategy, several platforms, such as orbiters or landers including micro-penetrator could be utilized.

Scientific objectives with regard to the CSEW6 Report and outgoing Scientific Tasks that would be completed by using Canadian Micro-Penetrator are summarized for Moon in TABLE , for Mars in TABLE and for small bodies and outer planet moons in TABLE .

TABLE III
Lunar Scientific Objectives regarding CSEW6 Workshop and potential Canadian Micro-Penetrator Scientific Tasks

Objectives regarding the CSEW6	Scientific Tasks
− Map the distribution and age of lunar bedrock − Characterize the physical, chemical and mineral properties of surface rock, soil and dust − Estimate the rates, processes and effects of impact cratering − Improve geophysical data on the properties and structure of the lunar interior	− Deployment of a global or distributed network of seismometers and heat flow probes. Such a network would provide with unprecedented details on the interior structure of the Moon. − Seismic network *in-situ* measurements would enable to investigate moonquakes − Ground truth measurements to the existence of water and other volatiles in permanently shaded areas in polar craters.

TABLE IV
Mars Scientific Objectives regarding CSEW6 Workshop and potential Canadian Micro-Penetrator Scientific Tasks

Objectives regarding the CSEW6	Scientific Tasks
− Improve geophysical measurements on the interior structure of Mars − Characterize the mineralogy and geochemistry of the Martian crust − Understand the hydrology and hydrogeology of present and ancient Mars − Search for direct evidence of extinct or extant life through biosignatures by developing methodologies and instruments for in situ investigation of planetary environments, and to validate their operational performance in operational contexts at Canadian analogue sites	− Investigation of heat transfer in the mantle and the core that could explain the origin of the Tharsis volcanic province, mountainous terrain in the southern half of the planet and flat plains in the north. − Determining the detailed structure and composition of the Martian crust at local scales for rover's landing site selection. − Detecting the presence of mineral sources using penetrators *in-situ* measurements and combining them with the data collected from remote sensing/observations − Subsurface exploration of bedrock − Direct subsurface detection of water in form of water ice/chemically bounded water in minerals/perhaps even transiently existing liquid water using geochemical instruments − Access Martian subsurface environments to search for buried biosignatures such as deposits protected from exposure to damage on the surface

TABLE V
Small bodies and outer planet moons scientific objectives regarding CSEW6 workshop and potential Canadian micro-penetrator scientific tasks

Objectives regarding the CSEW6	Scientific Tasks
− Detailed investigation of the geology, mineralogy and chemistry, gravity and magnetism of asteroids and comets − Describe and model the water ice dynamics of Ganymede, Europa and Enceladus − Exploit Canada's diverse planetary analogue environments to develop an understanding of the formation and preservation of biosignatures and to develop life detection instruments for flight	− *In-situ* subsurface geophysical and geochemical investigation of NEO's using penetrators − Deployment of penetrometers on Jovian moons Europa and Ganymede and Saturnine moons Enceladus and Titan to investigate the internal structure of the moons − Different environments and geological settings can provide information on different biosignatures; by detecting and analyzing these traces, some of the properties of that biological activity can be determined – mineralogical signatures such as microfossils, biominerals and sedimentary biosignatures

For Canadian scientific society, astrobiology is one of the highlighted fields. Our up-to-date knowledge and available information about other planets and their moons in our solar system evidence that life, as we know it, cannot exist on the surface due to harsh environments and strong UV radiation. E.g. Martian surface is sterile up to 2.5 m and if one wants to look for extinct or extant life on Mars, he definitely has to go into the Martian subsurface. [35] Then a doubtless advantage of proposing Canadian micro-penetrator comparing to rovers is its subsurface functioning in temperature stable environment protected from surface radiation. Our proposed two-body Canadian micro-penetrator mission concept is focused on planetary astrobiological investigation.

V. Canadian micro-penetrator concept

A number of mission scenarios are of particular interest which are suited to penetrator deployment but which require tailored decelerators: Apophos Near Earth asteroid, the South Pole Aitken Basin of the Moon, Europa, the South Pole of Enceladus and otherwise-inaccessible Mars targets. A Canadian micro-penetrator will offer to enrich the scientific data return beyond that achievable from an orbiter mission alone. Detailed mission concept is currently under development and in this paper we describe preliminary suggestions that come out from our previous penetrator study and analysis.The deployment of the proposed two body Canadian micro-penetrator will be from an orbiter – this will require a dedicated spin-up and eject mechanism. This deployment strategy will necessitate autonomous guidance navigation and control function to maneuver the spacecraft for orbit reduction and orientation. For airless bodies, attitude and trajectory control for landing will be non-trivial but provide some degree of targeting capability. Impact mitigation and survival will be a significant technological challenge. The impact dynamics will need to ascertain impacts into different materials whilst ensuring above surface communications availability with the orbiter during its overhead pass. The impact velocity will determine the structural requirements of the micro-penetrator . Ensuring hardware survivability also means to implement a proper packaging approach. Power is another issue to be considered since it influences micro-penetrator lifetime. Two-body penetrator could utilize solar power since aftbody is supposed to remain on the surface. Thermal generation within a micro-penetrator should be implemented through RHUs generating 2.5 W of heat without the use of electrical power.The communications architecture will need to be designed to a robust reconfigurable link budget to accommodate different orbital altitudes for the orbiter relay (nominally UHF). This is a challenge as most spacecraft missions accommodate only single operational communications architecture. A structure-integrated patch antenna is favoured over a whip antenna mounted onto the aftbody without the need for deploymentAlthough Canadian micro-penetrator as aimed at astrobiology will carry mainly astrobiological instrument/instruments, we do not exclude other "non astrobiological" (e.g. geological/geophysical) instruments which serve as complimentary instruments to confirm detected values. Sufficiently miniaturized and ruggedized laser Raman spectrometer could be utilized as one of the candidates for Canadian micro-penetrator. Raman spectrometer using one particular laser wavelength for detection and identification of both geo- and biomarkers would be a good solution giving us information on composition and internal structure of the studied subsurface material at once. Raman spectrometer suitable for the planetary rover [24] is currently being developed for ExoMars 2018 mission. Miniaturized immunoglobin-based protein chips may be possible for astrobiological measurements but the sample handling (micro drill is needed) and microfluidics is likely to be challenging. Micro-penetrator aftbody may accommodate meteo package consisting from the sensors measuring temperature, wind velocity and atmospheric pressure. As a complementary scientific return e.g. seismometers and heat flow probes could be included.

VI. CONCLUSION

There is actually no evidence that penetrators are inherently less reliable than soft landers. Though the technology is challenging, it has to be noted that the penetrator probes have already been successfully constructed and space qualified (including extensive impact trials). Lack of success of penetrator missions to date is not due to penetrator system/subsystems itself, most of the penetrator concepts (MoonLITE, Lunar-A and etc.) were temporarily stopped/cancelled due shortage of financial support. Deep space 2 failed along with its companion lander due to several plausible scenarios named in the first part of this paper and the only other mission, the Russian Mars 96 mission, failed to leave Earth orbit.

Successful micro-penetrator deployment would thus enable world-wide scientific community to extend knowledge about planetary subsurface and even further to discover traces of extant or extinct life.

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