THE MOLE WITH SAMPLING MECHANISM (MSM) – TECHNOLOGY DEVELOPMENT AND PAYLOAD OF BEAGLE 2 MARS LANDER

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ABSTRACT

The payload of the ‘Beagle 2’ Mars lander of ESA's Mars Express mission included a regolith-penetrating, tethered ‘Mole’ intended for acquisition of several subsurface soil samples from depths between about 10 cm and approximately 1.5 m which would have been analysed by lander-based instruments in a search for chemical evidence of extinct microbial life on Mars. Because of the failure of the lander, this PLanetary Underground TOol (PLUTO) Mole system did not receive the opportunity to operate on the planet.

The actual technology development for PLUTO occurred within the ESA Technology Programme in the ‘Mole with Sampling Mechanism’ (MSM) activity. This was based on a previous ESA-funded development of a soil-penetrating ‘Mobile Penetrometer’ (Mole) which did however not have the capability of sampling and of retrieval to the surface.

1. INTRODUCTION

From 1995 to 1997, a small mechanical ‘Mole’ – or ‘Mobile Penetrometer’ – was developed within the ESA TRP activity ‘Small Sample Acquisition/Distribution Tool’ (SSA/DT) by the team of Tecnospazio S.p.A., DLR and VNIITransmash for applications of soil penetration on small planetary landers (Ref. 1). This compact device of a mass of 400 g consisted of a sliding electro-mechanical hammering mechanism housed within a pointed cylindrical shell of 325 mm length which is tethered to a power supply of an internal motor for compression of a spring supplying the energy for each shock. Soil penetration is accomplished by soil compression and displacement with each hammer strike and, for larger particles, by particle splitting. Essential for the characteristic self-penetration ability of the system – i.e., its non-reliance of reactive forces to be supplied by elements remaining above the surface – is the exploitation of friction with the soil in contact with the housing circumferential area which reduces and generally completely suppresses recoil motion so that a net forward motion is achieved, typically being of the order of a few mm per shock. Penetration depths of up to several m are possible at which the Mole has completely disappeared in the soil with the connecting tether representing the link to the surface.

The Mole developed within SSA/DT did not have the capability to acquire samples or be retrieved (other than manual pull-out on the tether) but served to demonstrate the viability of the concept of subsurface soil access for small landing spacecraft. Its testing included thermal vacuum evaluation of the hammer mechanism down to –166°C in light of possible outer solar system applications. This first small-sized Mole, designated ‘Mobile Penetrometer-1’ or MP-1 for short, was actually based on a significantly larger design prototyped by VNIITransmash in 1988-90 and at the time was considered as one of the payloads of the Russian Marsokhod rover mission and which was field-tested in Kamchatka.

Whilst the MP-1 Mole demonstrated the feasibility of an extremely small and lightweight device for soil penetration down to several m, a meaningful application on planetary landing missions was judged to call for its ability to take (subsurface) samples and to be reliably returned to the surface again. This would then make it a suitable system for repeated subsurface soil sampling on small landers such as ‘Beagle 2’ having been part of the ESA Mars Express mission.

A follow-on Study activity, the ‘Mole with Sampling Mechanism’ (MSM), was then commissioned to develop a Mole system useful for repeated subsurface soil sampling, calling for development of a sampling mechanism integrated with the actual Mole along with a pay-out and retraction mechanism for the tether connecting the Mole to the host spacecraft (lander or rover) (Ref. 2).

In general, the development was to be tailored to the requirements imposed on the subsurface sampling device for the ‘Beagle 2’ application to which MSM was to provide support.

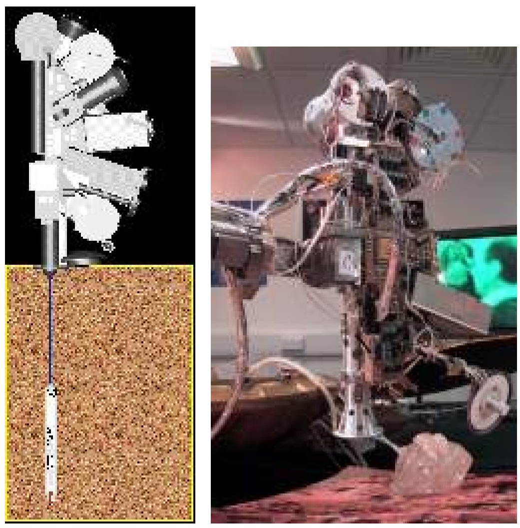

Fig. 1: Schematic (left) and actual mounting of Sampling Mole System on instrument carrier on ‘Beagle 2’ mechanical arm. Left hand view also shows Mole deployment with unreeled tether.

Besides ‘Beagle 2’, a compact Mole system for multiple sampling from depths of up to several m would prove to be highly relevant for planetary missions after Mars Express, such as ExoMars/Pasteur, the NASA Mars Science Laboratory (MSL) and Mars Sample Return (MSR). Furthermore, Moles are considered to represent a new and promising direction in planetary landing missions, especially if also the accommodation of in-situ instrument heads within the Mole is considered as is now subject of a follow-on activity to MSM, the ‘Instrumented Mole System / Mole-Carried Sensor Package’ (IMS/MCSP).

2. MSM DESIGN DESCRIPTION

2.1 Requirements summary

To make to MSM Mole system applicable to the ‘Beagle 2’ application, the overall system had to comply with severe volumetric and mass-related restrictions. In particular, stowed length could not exceed 370 mm and system mass was constrained to 900 g. At the same time, the Mole was called upon to nominally obtain three soil samples of around 50 mg mass each from different depths in the Martian regolith down to a maximum depth of 1.5 m. That this was principally feasible had been recognized as a result of the MP-1 small Mole devlopment as part of the SSA/DT Study, provided that Mole retrievals are supported by a reverse hammering capability in addition to forward hammering for soil penetration. This is because reverse hammering in initial experiments was shown to reduce tenfold the required pull-out forces for retrieval, regardless of whether the borehole had collapsed or not (in turn depending on soil properties), and regardless of any Mole deflection from its original path in the subsurface.

2.2 MSM design

Whereas the device for acquiring samples, preferably located in the tip of the Mole, and the tether pay-out and retraction mechanism as well as Mole support elements would be new developments for MSM, the actual forward hammering mechanism within the MSM Mole is functionally highly similar to that of the MP-1 system (Fig. 2): a DC motor/planetary gear combination – powered through lines within the tether reaching to the surface - drives a roller-template mechanism to convert rotary motion into a longitudinal one for compression of a spring (so-called ‘force spring’) to store energy for each shock. An interruption of the screw-like template surface causes a sudden spring release accelerating two masses the smaller one of which – the ‘hammer’ – impacts inside the tip of the Mole shell whereas the larger one – the ‘suppressor’, consisting largely of the actuator – travels towards the back of the Mole shell to subsequently return to the Mole tip, delivering a second shock, within a fraction of a second after the one from the hammer. Because two masses are moved by the expanding spring into opposing directions, the forces from the forward shocks are significantly larger than the backwards-directed recoil forces being transferred from the suppressor to the Mole shell primarily through friction. This way, appropriate mechanism sizing ensures that recoil is reacted by friction between the Mole and the surrounding soil to result in net forward motion with each shock cycle. One shock occurs about every 4 s which essentially is the duration required for spring compression to initiate a shock event.

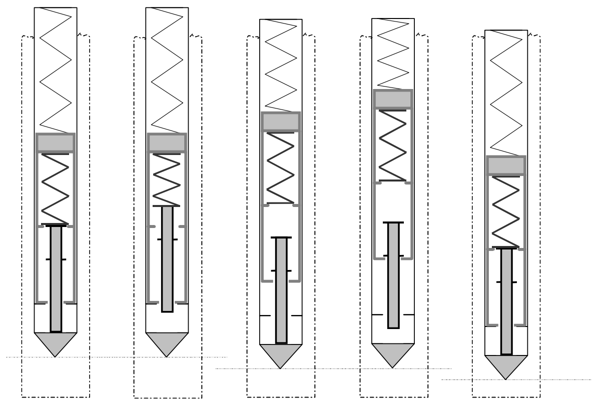

Fig. 2: Principle of Mole forward hammering.

To comply with the ‘Beagle 2’ accommodation requirements, the actual Mole of MSM – dubbed ‘MP-2’ - had to have a shorter length than the MP-1 from the SSA/DT activity. Whereas the Mole external diameter of 20 mm was retained, the length could be reduced from 325 mm to 280 mm by optimizations of the mechanism design.

It was decided that in order to show satisfactory robustness in Mole retrievals from the subsurface, the possibility for reverse hammering was required in a switchable fashion, i.e. the hammering mechanism would have to be capable of being operated in forward as well as in reverse hammering mode, depending on choice of MSM operations phases. Reverse hammering as well as actuation of the sampling device in the tip of the Mole were combined with the design realization of the forward hammering function while using a single actuator for these three functions in order to minimize overall length and mass of the Mole: an internal lead screw being part of the hammer can be extended by actuator reverse rotation (as opposed to the rotational sense for compression of the force spring), during which the roller-template assembly is decoupled by a ratchet mechanism and no hammering occurs. Resumption of hammering (actuator rotation in the designated ‘forward’ sense) then either results in the lead screw impacting onto a piston to push the Mole front tip outwards for exposing the sample chamber (Fig. 3), or in the lead screw offloading the sliding hammer mechanism and resulting in reverse shocks (Fig. 4), depending on amount of lead screw extension. During each reverse shock, the sampling head is secured by a revolving lock phased with the hammering mechanism to prevent loss of the sample.

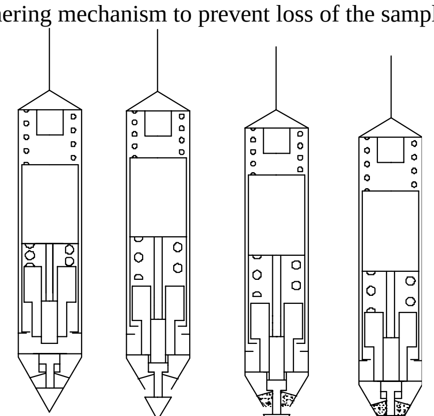

Fig. 3: Schematics of sampling head opening.

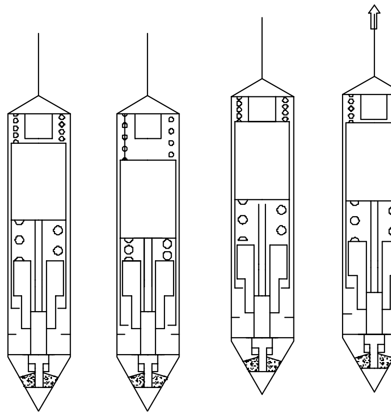

Fig. 4: Schematics of reverse hammering.

The pay-out and retraction mechanism for the tether connecting the Mole to the host spacecraft (lander or rover) is based on a tether reel with slip rings and an actuator which in one sense of rotation can operate a clutch to release the reel and in the opposite sense transmits torque to the reel to retract tether. It also includes a so-called 'launch tube' which surrounds the stowed Mole and supports it laterally during the phase of initial soil penetration which is characterized by an insertion of less than one Mole length. It forms the major structural item of the MSM system and provides a mounting interface to the carrier vehicle. The launch tube carries a lateral locking pin to arrest the Mole relative to the tube until after landing, and it is then pulled out once before the Mole is deployed for the first time. To arrest the Mole internal sliding hammering mechanism with respect to the Mole shell to resist launch vibration and the landing shock, a second locking function is needed and implemented, being an internal launch lock of the hammering mechanism which is released upon first operation of the hammer after landing, i.e. thus not requiring a dedicated actuator for release.

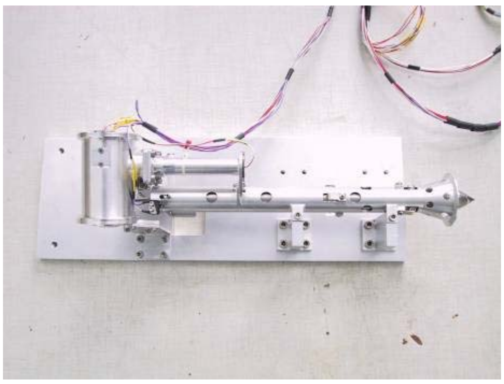

Fig. 5: PLUTO Mole system Qualification Model (with winch mechanism and launch tube); overall length from Mole tip (right) to reel housing is 365 mm.

Prior to a Mole operation, the MSM system is placed on the soil surface in the desired orientation by e.g. a mechanical arm as on 'Beagle 2' or by a more simple mechanism, and the tether winch actuator is then decoupled by the winch mechanism, allowing tether to be unreeled by Mole forward shocks. Hammering may be interrupted or stopped as a function of deployed tether length or number of shocks delivered, followed by operation of the sampling device to capture a local soil sample. The Mole can then be retrieved to fully return into the launch tube. To deliver the acquired sample to instruments on the host spacecraft, the MSM assembly may be maneuvered accordingly by a supporting mechanism such as the 'Beagle 2' arm.

Overall mass of the MSM system, essentially identical to the PLUTO Mole system flown on 'Beagle 2', is 860 g, with a maximum length of 365 mm, of which the Mole itself contributes 350 g and 280 mm in length, respectively.

2.3 Sensors & control

Operation of the MSM system consists of operating the two mechanisms motors with time-tagged commands and little sensory feedback. In some operating modes, the current uptake of the Mole hammering mechanism motor has to be measured and monitored by host spacecraft software to allow appropriate real-time control of the MSM. This is needed primarily during extensions of the internal lead screw (i.e., in motor 'reverse' rotation) in order to count the number of screw rotations to within ~30° to not only maintain knowledge of the amount of lead screw extension but also to keep track of the phasing of the revolving sampling device lock with the hammering function.

In the implementation on 'Beagle 2', current measurement for this purpose was accomplished by the lander electronics at 50 Hz with real-time filtering through settable S/W parameters. The obtained signature is indicative of number of rotations due to discrete load and thus current pulses from the ratchet which is operated during Mole motor reverse rotation. Alternatively, it would have been conceivable to implement a shaft rotation encoder but this option was discarded due to wiring accommodation issues within the tight confines of the Mole core mechanism.

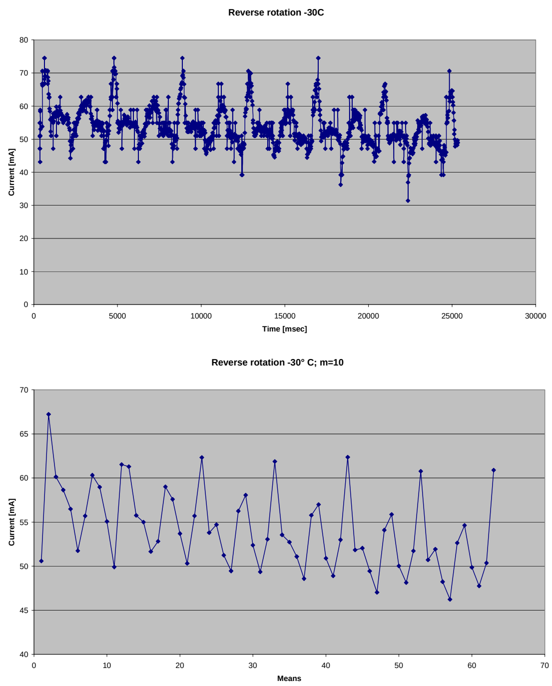

Fig. 6: Recorded PLUTO Flight Model Mole motor current at –30°C during reverse rotation (i.e., lead screw extension) acquired at 50 Hz (top) and filtered data (bottom) as required for real-time control.

Dedicated sensors as part of the MSM H/W are a discrete winch count sensor on the tether reel to indicate length of tether extracted, a microswitch to identify Mole full retraction into the launch tube, and a temperature sensor inside the Mole near its back end.

The reel rotation sensor is needed to

- enable autonomous control of soil penetration down to a specified depth
- enable autonomous detection of stalled penetration (due to excessively dense soil or buried rocks)
- allow soil penetration profiles to be reconstructed from stored sensor data for off-line determination of soil strength profiles with depth, thus representing science data.

Obviously, the launch tube microswitch is instrumental for Mole retrievals in order to provide the winch motor switch-off command to the spacecraft S/W. In case the microswitch functionality were lost during the mission, winch motor current threshold settings can be varied by telecommand to enable autonomous switch-off to take place upon motor stall, combined with S/W real-time processing of winch count sensor data to estimate retrieval progress relative to the end stop.

PLUTO on 'Beagle 2' had six different operating modes in the lander S/W that could be activated for selectable durations and with different commandable values of parameters. During the surface mission, the various operating modes could be combined into Activity Sequences (AS's) against the lander Master Events Timeline that would result in e.g. a sample acquisition and Mole retrieval from a specified depth. Several of those AS's were already stored in lander memory before landing.

3. TESTING

During MSM and PLUTO development and preparation of the PLUTO Flight H/W for 'Beagle 2', different types of tests have been conducted as follows:

- soil penetration & retrieval in 1 g: at ambient (homogeneous soil; layered soil; deflections on buried rocks) as well as at low temperature and at Martian pressure
- soil sampling characterization
- life test at ambient
- life test at low temperature and at Martian pressure
- standard qualification & acceptance test programs
- characterizations in all operating modes, using Flight Spare H/W and mission-realistic data acquisition & control.

Of particular relevance for Mole testings at Earth gravity is the need to scale penetration test results to Mars gravity (or to other gravity levels depending on application), due to a strong dependency of Mole penetration resistance on gravitational acceleration. This is because overall resistance is a function of overburden pressure. Correspondingly, if the test soil had the same physical properties as Mars soil to be assessed relative to Mole penetration performance, then test depths at 1 g of 60…70 cm would suffice to demonstrate representative Mole operations for a depth requirement of 1.5 m on Mars.

Alternative test approaches were implemented as well, in which the test soil has scaled physical properties with respect to the Mars soil to be simulated so that test depth at 1 g would be equal to their equivalent depths on Mars.

For the reference Mars regolith model assumed for MSM & PLUTO development and assuming Mars gravity, the Sampling Mole would require about 2 h to reach a depth of 1.5 m on Mars, based on predictions using a Mole-soil interaction theory developed during the MSM activity.

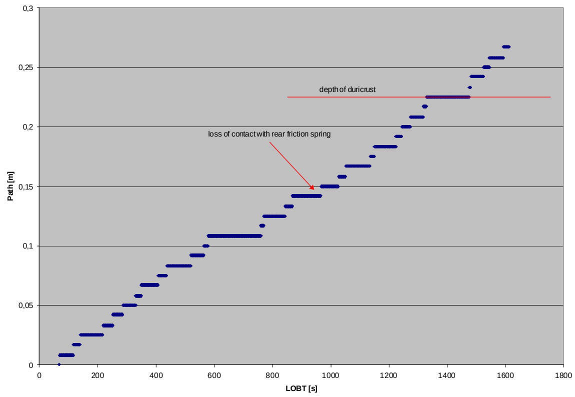

Fig. 7: PLUTO winch count data as function of time as acquired by 'Beagle 2' Ground Test Model electronics and S/W during Mole penetration experiment with layer of simulated duricrust.

4. SUMMARY

The PLUTO subsurface soil sampling system flown on 'Beagle 2' and its parallel technology development in the Mole with Sampling Mechanism (MSM) Study activity represent a novel technique for accessing the upper few meters of planetary surfaces with a lightweight and compact system. This is not only relevant to sampling activities but also to in-situ measurements as future Mole systems can be equipped with a suite of instrument heads.

5. REFERENCES

1. V.V. Gromov, A.V. Miskevich, E.N. Yudkin, H. Kochan, P. Coste & E. Re (1997). The Mobile Penetrometer - A "Mole" for Sub-Surface Soil Investigation. Proceedings of the *7th European Space Mechanisms & Tribology Symposium*, ESTEC, Noordwijk, The Netherlands. ESA SP-410.

2. L. Richter, H. Kochan, V. Gromov, P. Coste (2000). The Development of the "Mole with Sampling Mechanism" Subsurface Sampler. Proceedings, *6th ESA Workshop on Advanced Space Technologies for Robotics and Automation (ASTRA 2000)*, Noordwijk, The Netherlands, December 5-7.