Drill for Extensive Exploration of Planetary Environments by Robots (DEEPER)

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A	UBAR	All	First issue	28 November 2022
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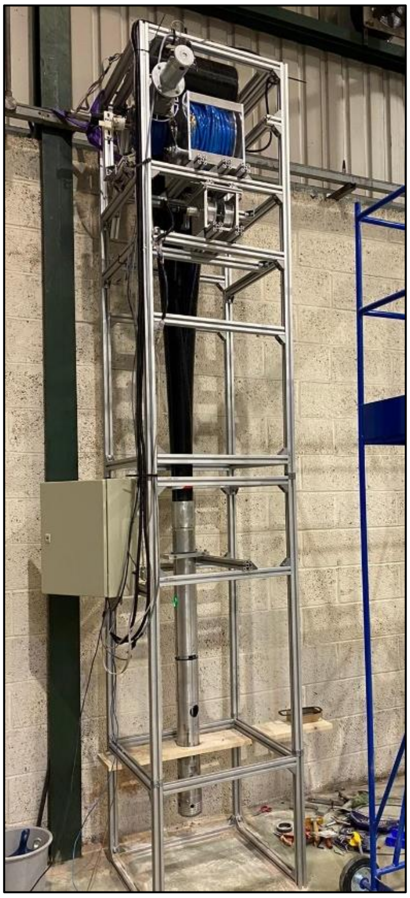
Overview

This is the DEEPER Executive Summary. It summarises the findings of the contract.

Executive Summary



Layout. The DEEPER concept (Fig. 1) seeks to determine if a viable drill system can be deployed to a considerable depth from a RolaTube structure on the surface.

The ground support equipment (GSE) is approximately 3.75m tall. The black RolaTube, which is 20m long, is stored in a spool and deployed by pinch-rollers just below the spool itself. Also below this spool is the blue electromechanical cable spool, which is also 20m long and separately powered, and which provides communications and power to the downhole module. The electrical connections to the downhole module are made via a slipring, which allows the downhole module to descend. Below the electromechanical cable spool is the bucket motor and spool system, which can raise and lower the bucket (which is inside the RolaTube and toroidal around the electromechanical cable). This allows the bucket to shuttle between the top of the downhole module (where it is filled with spoil) and the topside bucket housing (where the spoil is removed by a GSE-mounted auger).

The downhole module (DM) consists of a clamped section, which clamps against the borehole walls (or the launch silo) during each drilling peck; and an actuated section which can be deployed under either manual or autonomous control. The clamped section contains the clamp and the electronics bay, while the actuated section contains the motors and percussion equipment which break the rock. The central auger that elevates the spoil runs though both, from the very bottom to the very top of the DM. At the conclusion of each peck, the DM closes and the RolaTube advances to restart the drilling cycle.

Fig. 1: The final DEEPER unit, as-built in 2022. The launch silo is absent.

Achieving functionality. The device was designed using ideation, trade-offs, and failure analysis, and then manufactured. Subsystem testing was carried out as far as was possible on a block-by-block basis, but given the high degree of interdependency inside the downhole module in particular, it was necessary to proceed to a high degree of integration before the performance could be ascertained.

This integration revealed that the assembled system was operational, but to achieve functionality in actual drilling it was necessary to make some upgrades. These included:

- The addition of a stirrer device to prevent caking of the spoil and facilitate uptake into the central auger.
- The addition of a new spring assembly to improve the recoil performance of the cutting face.
- Instrumentation of the bucket to determine whether it is correctly in place.

At the conclusion of these modifications the performance of the device was tested. A range of materials were used in the laboratory, in the field, and in a cold environment. The key metrics are arguably drilling performance, spoil extraction, and clamping ability.

Drilling performance. In the laboratory, considerable progress was made in a range of materials, as shown in Fig. 2:

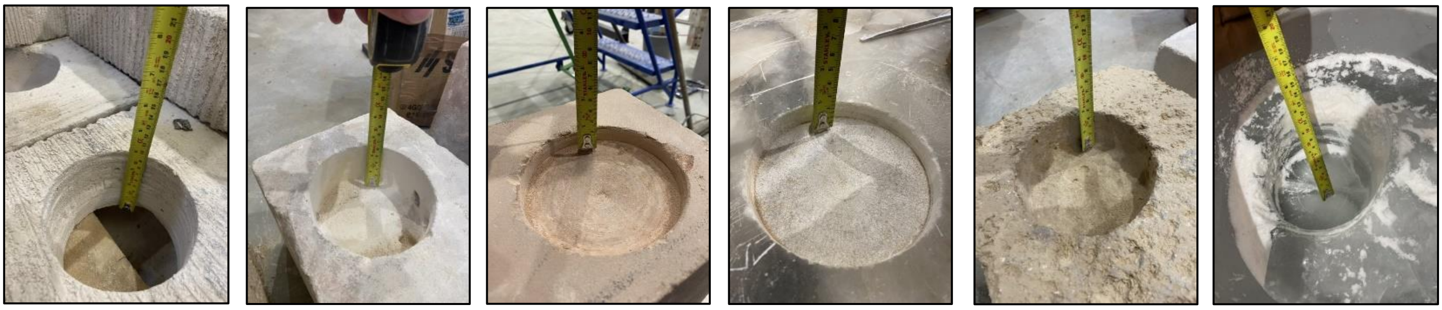


Fig. 2: The results of drill campaigns in aircrete, limestone, sandstone, gypsum, tuff, and ice. A full 'peck' is around 7cm.

The images in Fig. 2 reflect the drill campaigns as set out in Table 1. They are the result of campaigns to achieve a single ‘peck’ of progress in the respective materials, where a peck is around 70mm of extension on the downhole module. It is apparent that pecks can be achieved in ‘easy’ to ‘intermediate’ materials, with these words having broadly the meanings used in [1].

No progress was made in ‘difficult’ materials, but this should be understood in the context of the large volume that needs to be removed if we are to make appreciable progress across the wide front (120mm diameter) of the DEEPER drill.

Table 1

Test Number	**Material**	**Depth, mm**	**Comment**
1	Foam concrete	75	No issues
2	Limestone	75	No issues
3	Sandstone	28	Tooth wear, abandoned at 1h30
4	Gypsum	26	Hammer failure
5	Unconsolidated material	-	Chaotic, no hole to measure after pullout
6	Tuff breccia	5	Plaster remained wet, augering impossible
7	Tuff	69	No issues
8	Marble breccia	-	Progress unrealistic (wet)
9	Marble	-	Progress unrealistic (hard)
10	Basalt	-	Progress unrealistic (hard)

In the field, the system was deployed to a real-world test in a gypsum/mudstone environment. Over 14 hours of consistent drilling, with hammer support, a depth of approximately 100mm was obtained (Fig. 3). 170g of spoil was found inside the drilling face at the conclusion of this experiment (Fig. 4).

To characterise the performance in these materials:

Sandstone (lab). DEEPER achieved 28mm in 90 minutes, which given its 120mm face suggests 3.5 cc per minute.

ExoMars, in sandstone, typically achieves 4mm per minute [1], which given its 25mm diameter face suggests 1.96 cc per minute. DEEPER is therefore cuts sandstone at 178% the speed of ExoMars. This is considered to be an ‘easy’ material.

Gypsum/mudstone (field). DEEPER achieved 100mm in 840 minutes, which suggests 1.35 cc per minute.

ExoMars, averaging between gypsum and claystone, may achieve up to 3mm per minute [1], which suggests 1.47 cc per minute. DEEPER (in the field) therefore cuts gypsum/mudstone at 91% the speed of ExoMars (in the lab). This is considered to be an ‘intermediate’ material.

In both circumstances, DEEPER drew on the order of 150W.

Fig. 3 (above): Drilling gypsum/mudstone in the field.

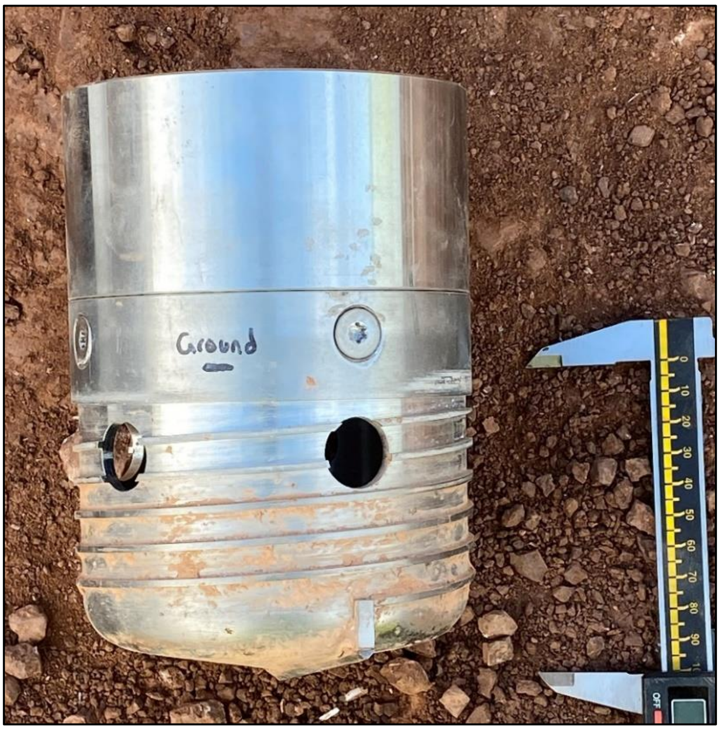


Fig. 4 (below). The drillbit after 14h in the field.

Spoil extraction. A the three-peck campaign was executed in aircrete over the course of approximately two hours. The three-peck protocol was selected because this allows the full action of the device to operate, with the second peck being bracketed end-to-end by the first and third pecks.

The spoil removal system, overall, displayed the performance set out in Table 2:

Table 2		
Body of spoil in question	**mass**	**Explanation of losses**
Estimated mass equivalence of hole drilled	1077g	Total spoil generated
Spoil taken into the cutting face from the hole	301g	Lost material airborne or piled up around the hole
Spoil uplifted by the central auger from the cutting face	97.3g	Lost material remained in cutting face
Spoil delivered to the bucket by the auger	76.9g	Lost material remained in auger
Spoil emptied from the bucket by the GSE auger	33g	Lost material remained in bucket

The drilling and spoil handling system therefore achieved complete process functionality, from downhole rock-breaking to surface spoil-dumping.

Although the losses appear severe, they are mostly the effects of transients: that is, the auger cannot clear the entire face, but only the volume above a certain level. It seems likely, or at least possible, that the throughput percentage would increase to near steady-state levels if the drill campaign were to be continued.

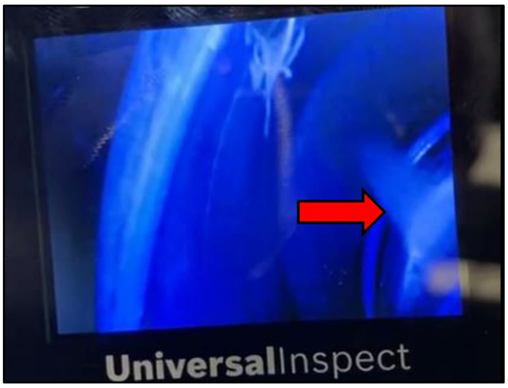


Fig. 5: Using an endoscope, spoil can be seen pouring (arrow) from the top of the 'tower' at the bottom right, and into the circumferential bucket.

Clamping ability. The hard materials were bored out and the clamp was inserted and deployed. Torsion was tested by applying a torque until the clamp turned in the hole, and force (or end-load) was tested by applying a pull-out force. This test was not possible in the loose materials because the material would fall out of the test chamber. The results were as shown in Table 3.

In the case of the marble, it was not possible to bore out a hole to receive the clamp due to the hardness of the test material itself.

Table 3			
Material	**Force (N)**	**Torque (Nm)**	**Comment**
Unconsolidated material	-	7.5	Force test impossible
Tuff	300	30	
Marble	-	-	Preparation impossible
Limestone	540	84	
Sandstone	780	90	
Tuff breccia	-	18	Force test impossible
Marble breccia	-	-	Not attempted
Gypsum	-	14	Force test impossible
Foam concrete	-	13.0	Force test impossible
Aluminium launch silo	-	18.3	Force test impossible

Likely next steps and anticipated performance of the next iteration. Analysis of the performance of the DEEPER downhole module has indicated that the drive train design should be reconsidered and that the power density should be increased. These upgrades should be combined with the elimination of the central auger, because this feature has had the effect of creating constraints on many aspects of the overall system design. Furthermore, the cam-hammer mechanism has been found to create inefficiencies due to 'hammer drag', which is where the hammer rotating at cam-speed falls upon an anvil rotating at face-speed, and several upgrades (such as the stirrer and additional springs) need to be formalised.

In the ground support equipment, it has been found that the bucket requires careful management on the downward journey, because it is almost weightless and it needs to seat securely onto the downhole module to receive spoil. This may be addressed by adjusting the winch system so that it can provide affirmative forces both upwards and down.

Overall, a new concept architecture for the next iteration may be based around moving the central auger off-centre. This could be achieved if it was held central where it needs to be (for example, where it passes through rotating machinery), but moved off-axis elsewhere. This might be possible with the use of either:

> **Pulse-elevator.** This concept was published during the lifetime of the DEEPER project [2]. The concept allows uplift of material without any form of rotation, and is instead actuated by vibration. In so doing, it obviates the need for gearboxes to transfer energy from one section to the next, because a simple mechanical connection will transfer the motion required.
>
> **Olds elevator.** This is an inverted auger concept in which the auger is stationary while the casing rotates outside. From a gearbox perspective, it is obviously simpler for one external auger casing to turn the next external auger casing, instead of having to transfer the drive from auger-axis to auger-axis through a series of stationary casings. In addition, the casings can act as stirrers, or even scoops, which will facilitate the uplift of the material.

Such an achievement would permit a single linear actuator to be brought onto the centreline, which would prevent a failure mode whereby the parallel actuators came into conflict. It would also allow the replacement of the two off-axis EC-40 motors currently used to drive the rotation and percussion powertrains by a single EC-60 motor, if the additional motivation for two separate powertrains can be addressed.

This motivation is the design requirement that the percussive blow does not land at the same clock-angle of the cutting face on a recurring basis, which could lead to tooth imprintation. This is easily achieved by running the two powertrains at different rpms, but an alternative layout has now been proposed by Andrew Ball (ESA):

> **The golden angle.** If the powertrain was divided and geared such that one shaft turns at a speed which is a golden ratio factor of the other, this type of superposition should not happen. A simple implementation could be that the single motor drives the cutting face directly, but also branches to drive the cam at the factored speed. Percussion could be applied or disapplied by traversing the cam vertically, and the entire implementation would reduce gearbox losses as well.

If these changes were implemented, the diameter of the current device (2 x 40mm motor + 1 x 20mm central auger + 1x 20mm casings = 120 mm diameter) could be reduced by around 30% (1x 60mm motor + 1x 20mm off-axis elevator + 1x 20mm casings = 100mm diameter).

Assuming that, with some refinement, 2 cc per minute was consistently possible (currently we achieve 2 cc per minute in 'easy' materials and 1.4 cc per minute in 'intermediate' materials, then the smaller DEEPER with its 100mm face might be expected to progress at a rate of around 0.25mm per minute, or 15mm per hour. The design depth of 20m in easy to medium materials would be achieved in 1333 hours or 56 earth-days of continuous drilling operation.

[1] https://robotics.estec.esa.int/ASTRA/Astra2011/Papers/05A/FCXNL-11A06-2134323-1-2134323magnani.pdf

[2] https://www.sciencedirect.com/science/article/pii/S0094576522003988