THE DEEPER PROJECT: A TESTBED FOR 20m SCALE DRILLING TECHNOLOGIES

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ABSTRACT

In 2020 the University of Glasgow, British Antarctic Survey, and Apogee Engineering formed a consortium to create the ESA "Drill for Extensive Exploration of Planetary Environments by Robots" (DEEPER) system. The objective was to reach 20m in regoliths, rocks, and ices, using a downhole drill module deployed by an unrolling-tube drillstring architecture. The downhole module clamps to the borehole walls during each drill peck, while spoil is passed up through the module and brought to the surface using a shuttle-bucket or bailer. The system then advances from the surface, repeatedly, until depth is achieved. Currently, the downhole module has demonstrated a complete peck, and it will soon be mated to the surface module. Field tests at a quarry and cold environment will follow in mid-2022.

1. DESIGN PROCESS

The requirements are as set out in ESA Open Invitation to Tender AO9904, with minor agreed modifications regarding the target materials. The design process considered multiple architectures to overcome the essential problems of downhole drilling activities, surface deployment activities, and overall integration.

The downhole activities include: rotation of the cutting face, reaction of the cutting face torque, percussion of the cutting face, elevation of spoil through the downhole module, and extension of the downhole module to deliver each discrete peck, where each peck is a self-contained unit of drilling that is completed before the full system moves down. The most challenging of these tasks, from a power standpoint, are related rock-breaking: the rotation and percussion of the cutting face.

When considering the motive power to deliver these most challenging activities, pneumatic motors were considered to be an attractive option due to their power density and the option of using their exhaust gas to blow spoil to the surface. However, the volume of gas required seemed to suggest that continuous operations would not be possible without an enormous payload on the surface. This meant that an all-electric concept was selected.

The overall system architecture was also evaluated. An interesting concept was to have minimal hardware downhole – essentially just the cutting face attached to the bottom of the tube – and to lower a downhole module that would energise the cutting face and store any spoil internally, before being extracted to the surface and emptied at the end of each peck. However, this would have required acquiring a spline downhole to transmit the torque, which was considered challenging in a blind and dusty environment. Mitigations such as magnetic centring were put forward, but these might have attracted metallic fragments and become unusable.

Therefore the selected concept was a sizeable downhole module permanently coupled to the end of the tube [1]. The downhole module was tipped with a rotating drillface acted upon by a cam-hammer, while the extension was managed using linear actuators governed by a proven semi-autonomous control system [2]. A clamp was proposed to react torque, while spoil was extracted through a central auger and ejected into a toroidal shuttle-bucket for extraction to the surface.

The central auger must be central because it traverses the full height of the downhole module and would otherwise prevent the movement of rotating machinery. This provided a design challenge because all other systems had to be either toroidal in structure, or offset from the axis. Toroidal motors were considered, but could not compete with cylindrical devices on power density. This drove the design towards an eccentric gearbox (Fig. 1).

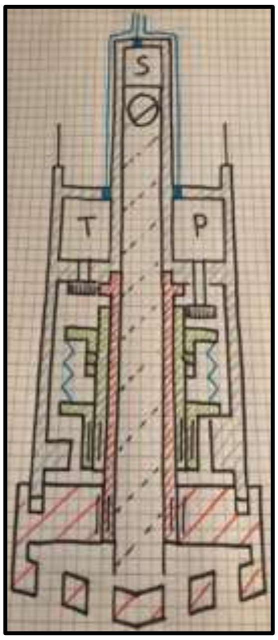

Figure 1. The first sketch of the selected design from the trade-off stage. A torque motor T drives the red cutting face powertrain. A percussive motor P drives the green cam-hammer powertrain, which acts on the cutting face from above. Another motor, S, drives the central auger. The other functions were not yet considered at this stage.

The size of the downhole module is constrained by the sizes of unrollable tube – provided by RolaTube – available off-the-shelf. Surface operations are less constrained from a size perspective, and so a frame was constructed to support the unspooling of the tube, the lowering of the shuttle-bucket, and the delivery of power and communications to the downhole module.

2. CONCEPT OF OPERATIONS

The concept of operations calls for the downhole module to be launched from a tube, such that the clamping system can obtain purchase even above ground. The clamped downhole module then extends its lower section (with its cutting face) under semi-autonomous control, managing weight-on-bit until a full peck depth of around 100mm is attained. At the conclusion of the peck, the downhole module stops drilling and contracts while the drillstring is extended a corresponding distance. This process helps to feed the spoil into the central auger, for evacuation into the shuttle-bucket. Finally, the shuttle is winched to the surface (through the drillstring) and emptied, before being returned for the process to continue.

This central auger is in some tension with this concept of operations because the module extension must now be delivered by an off-axis powertrain. This could create a bending moment inside the downhole module and risks it becoming bent at the extension section. The design process therefore led to the selection of two parallel linear actuators, as shown in Fig. 2, placed between the T and P motors shown in Fig. 1. Each linear actuator is equipped with its own force transducer to measure the total weight-on-bit.

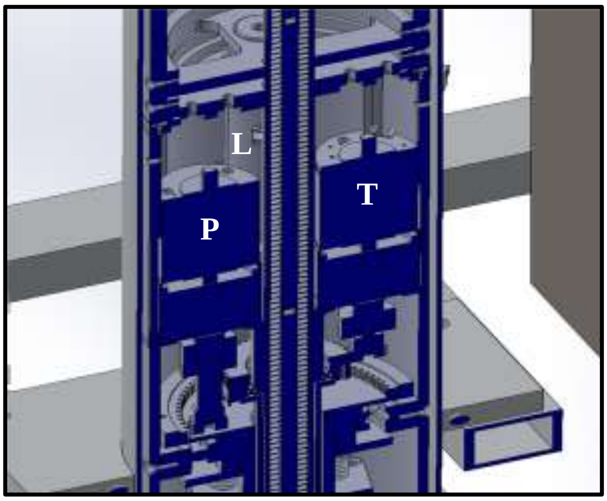

Fig. 2. The linear actuator L (only one is visible) between the T and P motors. Note also the matured eccentric gearbox. The auger design is not representative of the auger as built.

3. TROUBLESHOOTING

After the design process, the hardware was procured, manufactured, and assembled. Some of the design features yielded unwanted and unexpected behaviours, which have been addressed as follows:

Issue 1: the extraction of spoil through the auger. The central auger is 15mm in diameter, of which 12mm is a solid core. This auger operates inside a tube with an internal diameter of 16mm, at a design speed of 330 rpm.

This auger worked well in initial tests using sand, and was installed with some confidence into the hardware. However, when it was used in-service, spoil did not enter the auger (although it would lift when forced in through the bottom), and hence could not be uplifted through the downhole module.

The issue was that fresh spoil ready for extraction, inside the cutting face, did not flow into the auger intakes: rather, the central auger inside the rotating face lay at the centre of a vortex where the spoil was naturally flung away. Meanwhile, the percussion combined with the powdery spoil created a circumferential cake of material that would not flow back towards the centre even when rotation was stopped.

The solution was the addition of a stirrer inside the cutting face. Because the cutting face (and its contents) were spun, the stirrer was actually despun to create relative motion in the spoil.

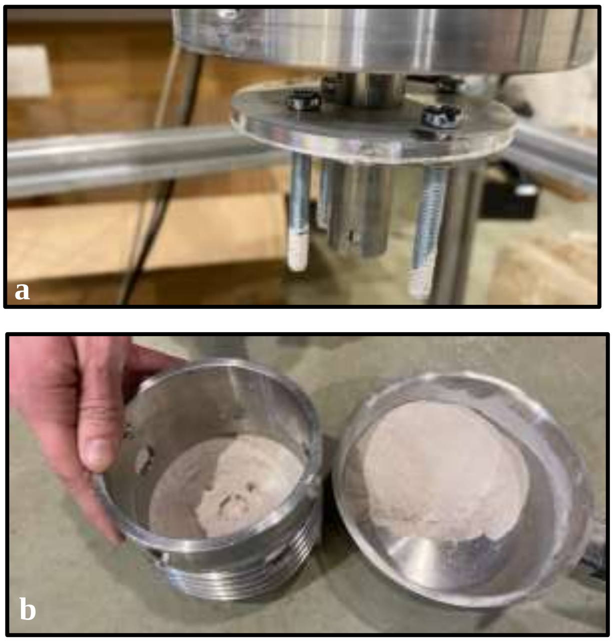

Fig. 3 (a) and (b). The stirrer plate, and its effect on spoil.

The stirrer (Fig. 3a) was a simple plate with hanging bolts, attached to the despun auger tube. The bolts were placed such that the spoil would see a helical pattern, passing each bolt at a tighter radius than the one before.

The results (Fig. 3b) are clear, in that the cutting face (left) has been emptied almost to the bottom in five minutes, with the contents (transferred to the pan, right) having been uplifted to the shuttle-bucket at the top of the downhole module. Some evidence of spoil caking is still seen inside the cutting face, namely the shape of the central auger and the final position of the stirrers. This is possible because the rotation was stopped and the device was carefully disassembled so that the remaining spoil was able to hold its final shape.

The design of the cutting face itself is presented in Fig. 4. Note that the stirrer is entirely within this piece, which fills with spoil via the circular windows.

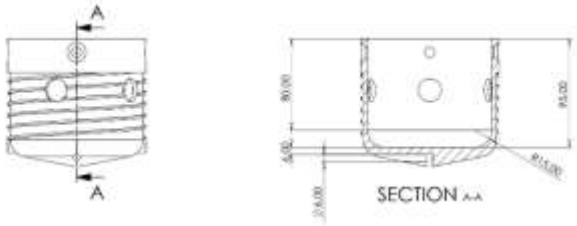

Fig. 4. The cutting face which contains the stirrer plate. A tungsten-carbide tooth (not shown) fits in the slot at the bottom, and is secured by a horizontal set-screw.

Issue 2: torque management of the linear actuators. The two linear actuator units (Maxon EC-22 motors, coupled with a Maxon 363836 spindle drive) need to work together to extend the downhole module correctly.

These linear actuators were difficult to manage because their lead-screw design means that they create a torque, and this torque is transferred through the mechanical interfaces of the force transducers. This caused problems, and it was addressed by creating a further mechanical piece to prevent rotation of the actuators as a separate function to their vertical fixtures.

On reflection, the extension of the downhole module is also a limiting factor on the peck depth, because in the current architecture a deeper peck will ultimately move the cutting face out of reach of the auger. This is not an intractable problem, but it is one that will require some careful design effort as this concept matures. Emerging alternatives to augering [3], [4] may provide more flexibility along the vertical axis in future.

Issue 3: the question of rebound. The hammer is rotated via a ball-spline, such that it can climb a cam and compress the main springs. The hammer then falls onto an anvil, which is connected to the cutting face. Due to the foregoing issues, the entirety of the ball-spline, cam, and hammer was toroidal to permit the passage of the central auger. The layout is presented in Fig. 5

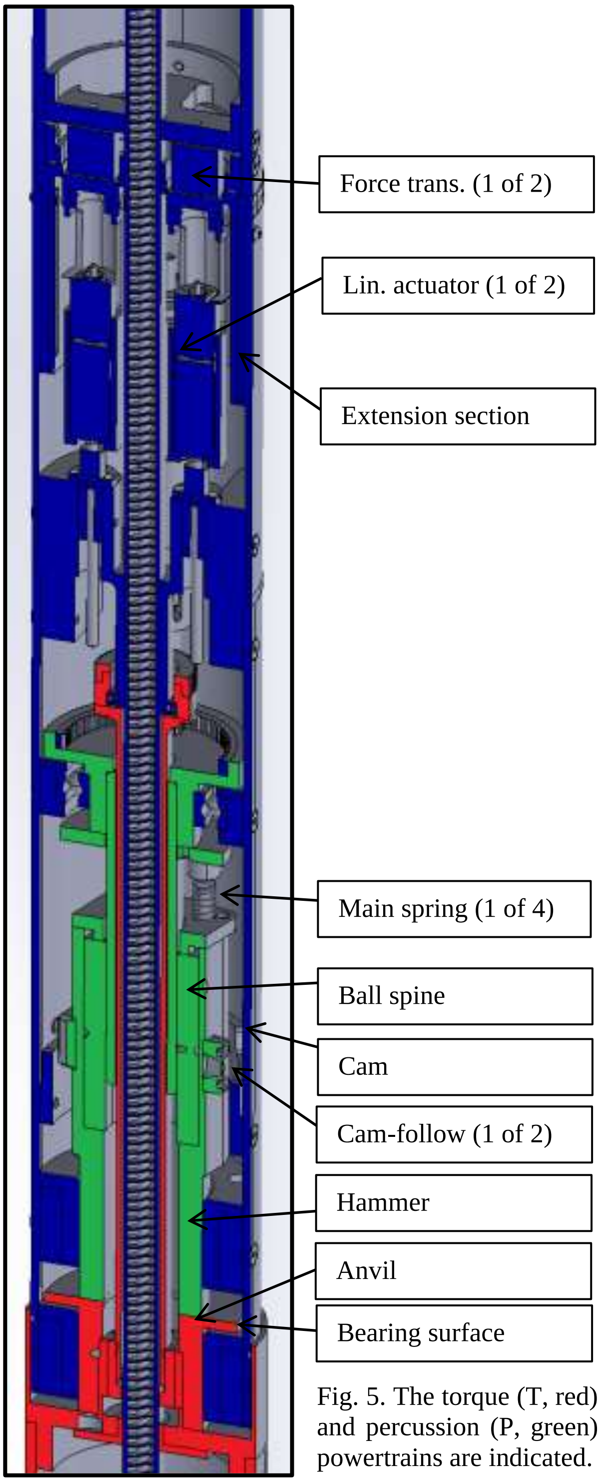

Fig. 5. The torque (T, red) and percussion (P, green) powertrains are indicated.

As is apparent from Fig. 5, the hammer (green percussive power train) acts upon the anvil / cutting face assembly (red torque power train) while the latter is rotating. This separation of powertrains is important because it allows the degree of rotation and the degree of percussion to be varied independently.

However, a problem arose in the first drilling tests. The cutting face did not appear to move in response to the hammer blows, and progress was no faster with or without the application of the hammer. In addition, the torque power demand was higher than expected and the rotation of the cutting face was not smooth, but rather surged fast and slow.

After careful thought, some circular windows were cut into the hull of the downhole module so that the lack of percussion could be better understood. It was determined that the anvil flange was resting on the bearing surface immediately below, such that the impulse was reacted internally. There was also a great deal of friction on the underside of the anvil flange.

The anvil flange, as first realised, was designed to stop the anvil / cutting face assembly from dropping out of the bottom of the downhole module, with the intention that weight-on-bit would maintain separation between the flange and the bearing surface in service. However in practice, as viewed through the new windows, the hammer blows simply drove the anvil to the bottom of its travel, and it stayed there.

Therefore, a new assembly was designed to facilitate rebound and eliminate this unwanted friction. To this end a wavespring was introduced under the anvil flange, seated into a new spun assembly that permitted movement of the anvil. The action of this new assembly is shown in the images in Fig. 6: the hammer falls from top to bottom, and collides with the anvil piece and drives it lower by temporarily compressing the wavespring. This spring is seated in a race that replaces the solid bearing surface previously installed, which means that it does not become twisted in service.

The result of this upgrade is that the cutting face now rebounds approximately 1mm after each blow delivered in free air, which allows the percussion to be delivered to the target without being transmitted into the casing of the downhole module itself.

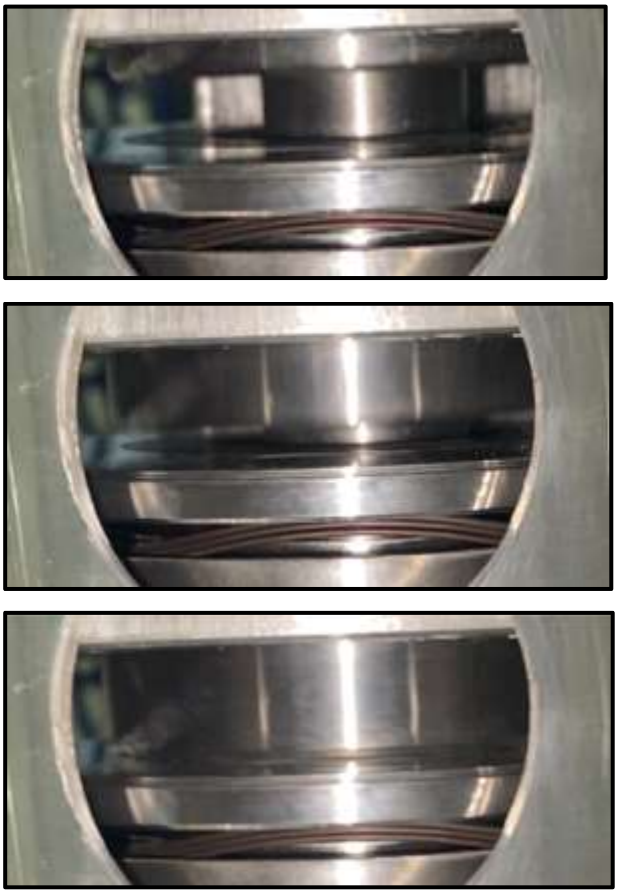

Fig. 6. The hammer falls onto the anvil, and drives it (and the attached cutting face) downwards by compressing the wavespring. The central auger tube is visible inside the toroidal moving parts.

Issue 4: off-axis gearboxes and cam-hammers. The percussive powertrain is the outermost of the three concentric spools present in the DEEPER architecture: the percussion spool, the torque spool, and the central auger (which is surrounded by a despun tube). The P-motor drives this outermost powertrain through a large-diameter internal gear, which takes up the effort required to drive the hammer around (and up) the cam.

However, as the cam-follower rolls off the cam drop, there is a moment of torque reversal due to the radius of the drop locally reversing the direction of the rise of the cam. An examination of Fig. 2 shows that the P-motor has a long drive shaft, which is vulnerable to this reversal of the transverse load and is therefore shock-deflected by around 1mm every time the hammer drops.

This architecture is off-optimal and is likely to have a limited life due to the large deflections of the parts that are not intended to move. However, it is functional and cannot easily be upgraded, so it remains in the testbed as-designed.

4. TEST PERFORMANCE

The DEEPER testbed, at the time of writing, is undergoing full integration. The characterisation of the performance is therefore described at a subsystem and module level, where these are now maturing.

Drill Mechanism. The drill mechanism tests require a drill to a depth of around 0.1m (a single peck) in various test materials. The tests in foam-concrete have already been carried out, and reached the peck depth in around 30 minutes. Drilling is shown in Fig. 7 (a), and the spoil is sucessfully transferred into the cutting bit, as shown in Fig. 7 (b). From here it may be uplifted, as per Fig. 8.

Fig. 7 (a) and (b). The cutting face proceeds into the target material, and the spoil arising is transferred into the cutting face, through the circular windows, for uplift.

Material transfer. The issues surrounding the auger and the need for stirring have been discussed above. After these upgrades, the cutting face may be emptied into the shuttle-bucket in around five minutes (Fig. 8).

Fig. 8. Spoil is uplifted from the cutting face, through the downhole module, and into the shuttle-bucket.

Clamp. The clamp (Fig. 9) is designed to with an over-centre cam function, so it is only energised while changing state. When deployed, the holding torque was measured to be 18.3 Nm against the launch tube.

Fig. 9. The clamp unit. As with all the subsystems, a toroidal architecture was required to allow the central auger to pass through the middle.

Deployment. A number of services need to be spooled from the surface frame, including the unrollable tube (which creates the drillstring), the electromechanical cable (which provides power and an emergency pullout function), and two shuttle-bucket cables (two, because the bucket is toroidal to fit over the spoil-ejection tower that arises from the centre of the downhole module.)

In subsystem test, these all performed within requirements, but those which use spools (such as the cables) were only marginal in terms of repeatability, but those which use pinch-rollers (such as the drillstring tube) were much more accurate. This is because the spooling architecture is affected by the diameter of the spooled content, which varies according to the amount on the spool (which can be compensated for, to a certain extent) and the exact manner in which that amount has been taken up (which is much more chaotic).

5. SUMMARY OF ACHIEVEMENT

Fig. 10 shows the downhole module. The achievement, so far, is a complete peck with a demonstrated unbroken process from rock-breaking to spoil-in-bucket.

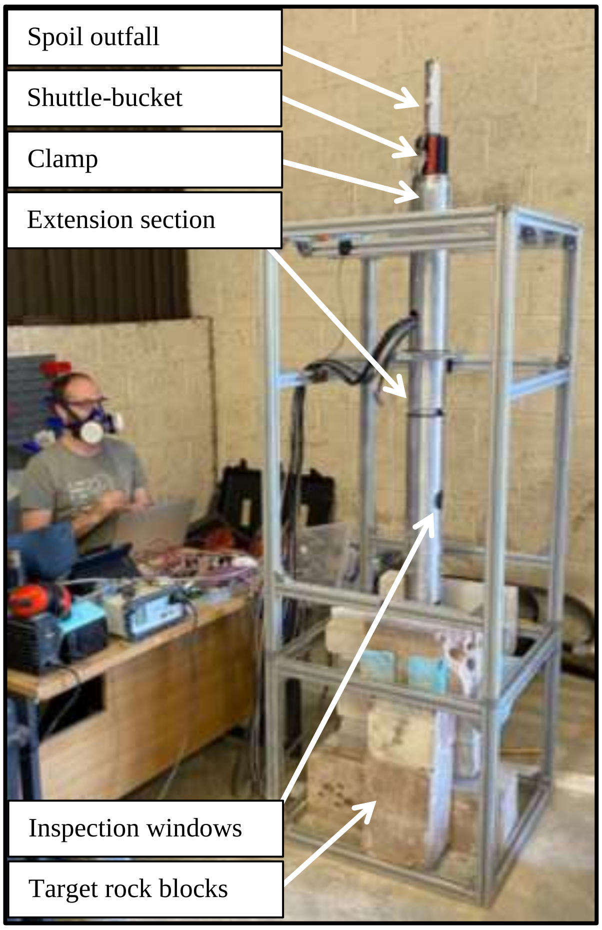

Fig. 10. The downhole module in operation. The wiring will enter from the top of the module after integration with the RolaTube drillstring.

Because the rig holds the downhole module such that it can only execute one peck by moving its lower section downwards, multiple pecks can only be simulated by stacking the blocks upwards as they are penetrated.

Therefore, in Fig. 10, the downhole module is drilling a block of foam-concrete under a pre-drilled first block, simulating a second peck at a depth of around 0.15cm. The peck took around 30 minutes to complete, with combined rotation and percussion. The lower section of the module was then retracted, which successfully transferred spoil up to the shuttle-bucket at the top of the module via the central auger. Around 30g was transferred, corresponding to around 1cm of progress, but the remainder can be accounted for as remaining in the cutting face and auger, and as having escaped between the blocks used to simulate the target.

An interesting finding was that the spoil was more easily ejected into the shuttle-bucket if the hammer was kept on even after the drilling had finished. Each impact resulted in a surge of material.

6. THE NEXT STEPS

The downhole module must demonstrate three pecks in succession, before moving on to deeper drilling. This will require integration with the surface equipment, or GSE. This integration will include electromechanical attachment of the unrolling-tube drillstring to the downhole module, followed by full system tests in both a real-world and a refrigerated environment.

7. CONCLUSION

The DEEPER project has an ambitious target, to demonstrate that deep drilling is achievable using an unrolling-tube drillstring. Thus far, the key functionalities of the downhole module have been demonstrated, and characterisation is underway. In the months ahead, these activities will be expanded to encompass the complete architecture of the device.

8. REFERENCES

[1] Harkness, P., et al. (2011) ‘Architectures for ultrasonic planetary sample retrieval tools.’ Ultrasonics, 51. p. 1026 [2] Timoney, R., et al. (2020) ‘A low resource subglacial bedrock sampler: the percussive rapid access isotope drill (P-RAID).’ Cold regions science and technology, 177. p. 103113 [3] Pitcher, C. et al. (2020) ‘Development of the Third Generation of the Dual-Reciprocating Drill.’ Biomimetics, 5(3). p. 38 [4] United Kingdom (GB) Patent Application No: 2205885.3.

9. ACKNOWLEDGEMENT

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