Worrall, K., Timoney, R., Li, X., Harkness, P. and Lucas, M. (2018) UPCD: Field Trial Results and Further Work. In: 16th Biennial ASCE International Conference on Engineering, Science, Construction and Operations in Challenging Environments, Cleveland, Ohio, 09-12 Apr 2018, pp. 297-306. ISBN 9780784481899.

UPCD: Field Trial Results and Further Work

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ABSTRACT

The Ultrasonic Planetary Core Drill (UPCD) project sought to develop and conduct a field trial, in an analogous Martian environment, of a space-compatible regolith-sampling tool. The project implemented a number of key technologies to achieve this aim; a drilling control loop based on ultrasonic power feedback, a bayonet interface system to allow a drillstring to be built up in-situ then disassembled after use, a coring design which captured the cores drilled out, and a mechanism for caching the core samples in sealable containers. The system was demonstrated in the laboratory with results indicating low power, low weight on bit, achievement of the targeted depth, and the retrieval of still-frozen core samples. The routines to allow the system to become fully autonomous were also demonstrated. The drill was deployed to Coal Nunatak on Alexander Island, Antarctica, for analogue trials. The drill was demonstrated to work, as was the caching and drill assembly/disassembly system, but the target depth was not achieved. A review of drill depth is provided along with a laboratory solution to the problems encountered in the field. Further work using the UPCD is also discussed.

INTRODUCTION

Funded by a European FP7 award, the Ultrasonic Planetary Core Drill (UPCD) uses ultrasonic percussive technology to penetrate 30cm into icepack, permafrost, and rock, recovering a sample, of diameter 6-8mm, of the material being drilled. To achieve this the UPCD assembles a drillstring using novel bayonet-style interfaces and maintains an appropriate weight-on-bit by means of a feedback loop. At this time human-in-the-loop command is required for discontinuous functions, such as drillbit selection, however the basic automation of all the discontinuous functions has been demonstrated.

In addition to retrieving and storing the core sample the project sought to achieve, or at least indicate the possibility of achieving, a space-deployable instrument with mass, power, and volume footprints compatible with small lander and rover-based mission concepts as set out in Worrall et al (2017).

This paper presents an overview of the UPCD and results obtained from the field campaign. Follow up tests carried out in the laboratory that address issues observed in the field trial are also shown.

The project was delivered by a consortium consisting of the University of Glasgow (UK), SSF (Finland), Lidax (Spain) and Magna Parva (UK).

ULTRASONIC PLANETARY CORE DRILL OVERVIEW

An image of the UPCD is provided in Figure 1 and each element highlighted is detailed below. Table 1 shows the mass, volume, and power of the field trial model which is representative of the as-tested UPCD specifications.

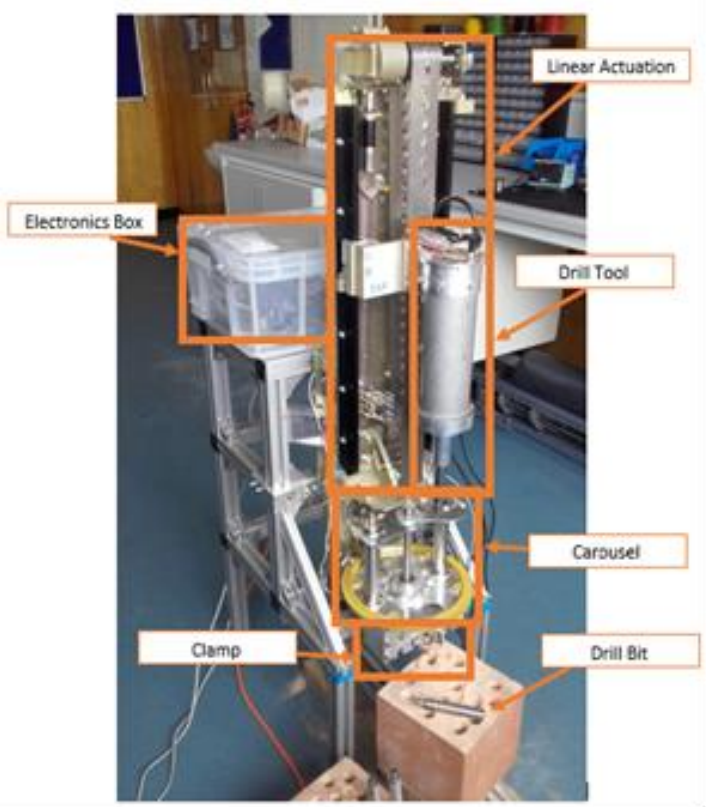


Figure 1. The UPCD. Reproduced from Worrall, et al (2017)

Table 1. UPCD Current Specifications.

Parameter	*Value*
Mass	25Kg
Volume	88L
Power (Idle)	10W
Power Drilling Peak	120W
Power Drilling Average	60-80W
Power Drilling Minimum	40W

Drill Tool. The Drill Tool (DT) is the ultrasonic assembly with support structures. The drill uses the ultrasonic-percussive technique, where the transducer assembly is free to travel as a sprung mass (via front and back springs) over several mm in order to deliver recurring percussive interactions with a free-mass, which then goes on to hammer against the drill string. This concept is covered further in Li, et al, (2017). The travel range is additionally exploited to permit the relative vertical movement needed to connect and disconnect the drillstring elements.

Linear Actuator. The Linear Actuator provides the vertical motion required by the UPCD. This motion is belt-driven to reduce the overall vertical footprint whilst also providing an increased degree of dust tolerance, as set out in Worrall et al (2017).

Carousel. The Carousel retains the Drill Bits, Silos and Lids. After drilling the Drill Bits are stored, with recovered samples, within the Silos and locked into place using features in the Lids themselves.

Electronics Box. The Electronics Box houses the control and power electronics for the UPCD. The main elements of the Electronics Box are localized power conversion, Ultrasonic control system and UPCD Control system.

Clamp. The Clamp is required to hold the Drillstring in place during the assembly and disassembly sequences.

In addition to these main elements, the following elements are also part of the UPCD:

Drilling Control Loop. The drilling control loop governs progress during drilling, monitoring the ultrasonic power drawn and commanding the Linear Actuator's progress accordingly.

Bayonet. Bayonet connectors, as set out in Timoney et al. (2015), are designed to connect the Drill Bits to the relevant parts of the UPCD. The bayonets are used to hold the Drill Bits during the outbound flight, connecting them to the DT, and to allow the disassembly of the Drillstring for caching the samples.

Drillstring. The Drillstring is made up of three separate Drill Bits: the cutting bit, which has the cutting teeth embedded, and two drill pipes. The drill pipes extend the auger and provide additional length to the Drillstring. Each bit is 100mm long with an internal bore of 10mm.

Core Catchers. Each Drill Bit contains a Core Catcher which is designed to retain the core and snap it during the drill string disassembly.

Silos. The Silos hold the Drill Bits before drilling and then store them (with samples) at the end of the drill cycle.

Lids. The Lids are used to recover the Drill Bits from the ground and seal them (with samples) into the Silos at the end of the cycle.

Operational Concept. This describes how the UPCD carries out a complete drill cycle. The drill cycle starts from when the drill command starts and all parts are at the home positions. The cycle finishes when the third drill bit is stored in the silo and the DT returns to the home position. The full sequence of movements is covered and describes the drilling, assembling, disassembling and caching stages. A full procedure can be found in Timoney et al. (2015).

FIELD TRIAL SITE

The selected field test site was Coal Nunatak on Alexander Island, Antarctica, as shown in Figure 2. Coal Nunatak is located 72°7′S 68°32′ and is 500km south of the BAS base at Rothera. Figure 3 provides a satellite image of the site. The site is described by Engelen et al (2008) as a sandstone and mudstone outcrop, and the location has been compared, by Wynn-Williams and Edwards (2000), to the Dry Valleys in Antarctica in terms of climate, desiccation, temperature, ultraviolet radiation and rock type. This was a significant factor for selecting the site as the Dry Valleys are listed as a Mars analogue site in the 2017 ESA Catalogue of Planetary Analogues.

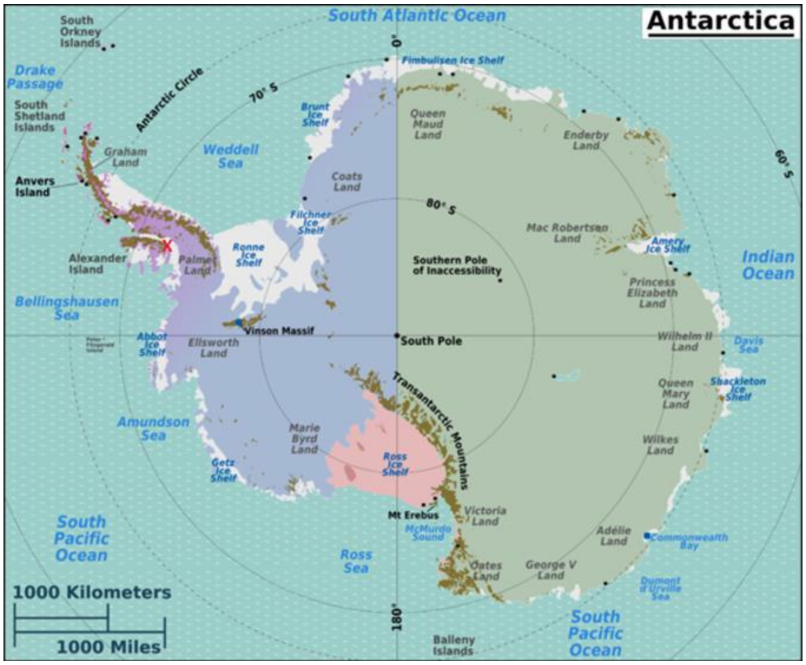


Figure 2. Location of Coal Nunatak (marked with red X), Alexander Island, Antarctica. Image from WikiTravel.

This site was selected for its relative ease of access, the average temperature at the time of year in question (-10°C), and the overall resemblance to Mars. For example, on arrival at the site, features similar to those found on Mars were noted such as lineae and frost polygons, as depicted in Figure 4.

However, the conditions encountered were not as expected. While testing was undertaken it was unseasonably warm, at times -3°C to 0°C, with even higher ground temperatures. This led to extensive soil moisture and even some surface water being present, although ice and frozen surfaces predominated.

Figure 3. Satellite Image of Coal Nunatak. From Google Maps

Figure 4. Frost Polygons at the field site

PRE-FIELD TEST RESULTS

Before deployment to the field the UPCD was tested to ensure that the full operational concept could be carried out with a human in the loop. The drilling part of the operational concept was carried out by an autonomous control loop that maintained a set US power level which results in a controlled Weight-on-Bit. The full operational concept was demonstrated and effective drilling was achieved in sandstone, limestone and permafrost. The results obtained showed low weight on bit and low US power during the drilling, while a target depth of 30cm was achieved in sandstone and a depth of 12cm (the maximum depth of the permafrost samples available) was achieved in permafrost. Core samples were retrieved, with the permafrost cores retrieved still frozen. All details are set out in Worrall et al (2017).

At this stage there was confidence in the full UCPD.

FIELD TEST RESULTS

After transit, a full system shake down was carried out at Rothera to ensure that the UPCD was in working order, and a further set of tests were conducted in the field to validate all operations. These tests showed that all elements of the UPCD worked and that the full operational concept could be tested.

During the drill tests it was quickly discovered that the drilling was not operating as expected. Though the system had carried out the initial steps of the operational cycle, when drilling began the rate of progress slowed to near zero. An example of this is shown in Figure 5.

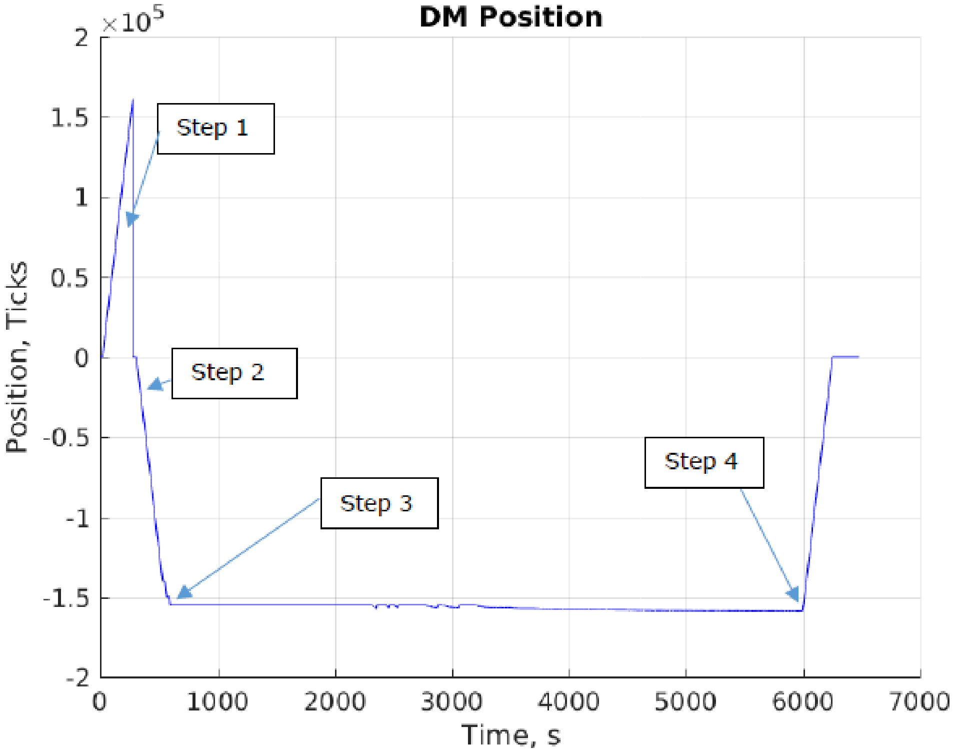


Figure 5. DT position vs Time.

Step 1 on Figure 5 shows the DT returning to a home position. The DT was then lowered to the ground (Step 2). Drilling was then started, Step 3. There is a slight change in position of the depth as the drilling continued. The last step (Step 4) was to return the DM to home when it became clear that there was no progress being made.

To increase the performance of the drilling the control parameters of the drill algorithm were changed. The control parameters for the UPCD are set by an upper and lower limit. The tests carried out in the laboratory indicated that for different rock types different parameters are needed with the as built UPCD. Figure 5 includes the impact of the control parameter changes, indicating that the changing of the control parameters had little impact. During this test no spoil was being removed and the auger started to slow down during the drill cycle as a result of the motor nearing stall condition. Figure 6 shows the increase in current as the drilling progresses.

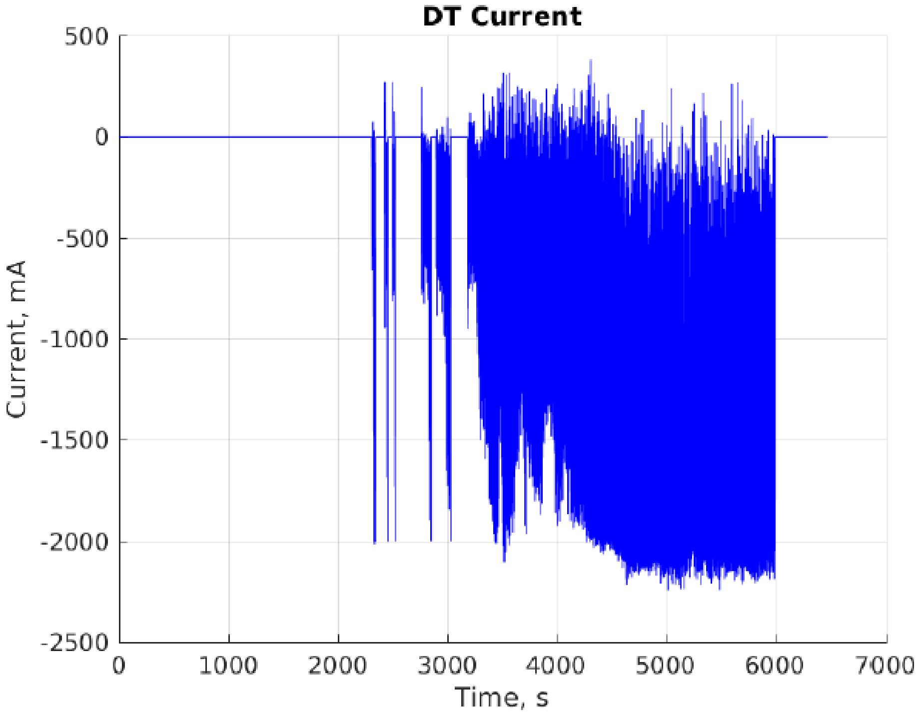


Figure 6. Auger Current.

Unfortunately this pattern of high current demand was repeated throughout all the tests undertaken. In some tests the auger would stall and not recover, in others the auger would start and stop. However the motor driver used had a hardware limit of 2A. Hence the DT was operating at the maximum power that could be drawn. With limited torque the drilling could not progress to the desired depths. In the field the maximum depth achieved in rock was 20mm and in regolith 60mm.

To test the full functionality of the UPCD the snowpack was drilled to demonstrate the full operational concept of the UPCD. This test was successful, and an entire drillstring was assembled and driven to the desired depth of almost 300 mm. The drillstring was then disassembled and cached. Small samples of still-frozen core were cached.

POST FIELD TEST RESULTS

With the complications encountered during the field trial the decision was made to ship back samples of the rock to allow the team to further test the drill. Due to the nature of the samples, only a small amount (8 kg) was retrieved.

With this rock two further tests were planned: Recreating the drilling of a field trial rock sample with the field DT, and at attempt to overcome the difficulties experienced with an upgraded DT.

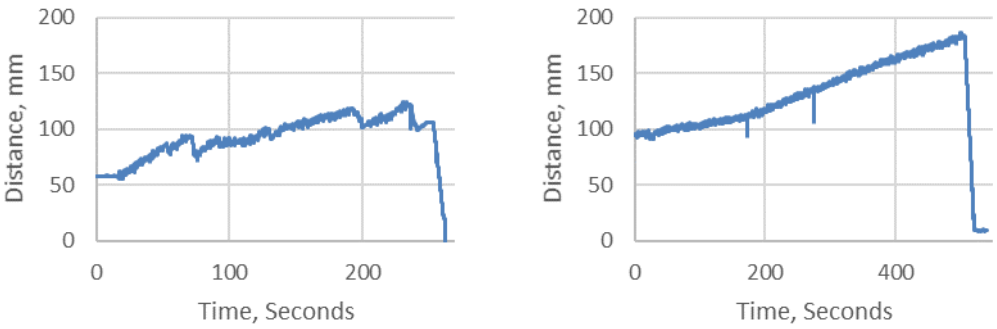
The rock sample used is shown in Figure 7. This figure shows the field trial drill attempts.

Figure 7. Antarctic Rock Sample

The field DT used in the test had no changes made and used the motor driver previously used in the field.

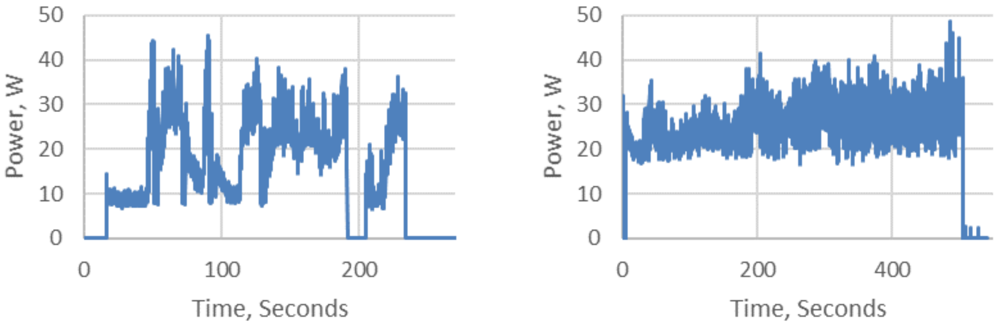
However, for the second test the motor in the DT was replaced with a 100W version of the original motor and the motor drive electronics were upgraded to deliver 15A instead of 2A.

The first comparison test was carried out in limestone, to obtain a baseline before damaging the valuable field samples. The impact of the upgrades can be seen in Figure 8 and Figure 9.



A. Field Drill **B. Upgraded Drill**

Figure 8. Distance Drilled in Limestone



A. Field Drill **B. Upgraded Drill**

Figure 9. Overall Power Draw in Limestone

Using the same control parameters throughout, we find that the Field DT is not able to drill to the target depth of 10cm, but the Upgraded DT does achieve this objective. This is not unexpected because, in previous limestone drill tests, the control parameters have required alteration to slow the rate of progress through the softer material.

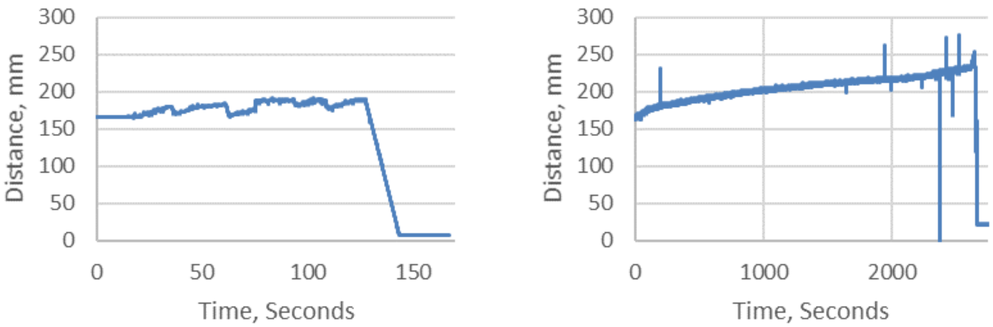
This test shows that the same parameters for sandstone can be used to drill limestone with the Upgraded DT and, although not shown, similar results were found in permafrost. This is a significant advantage as the drill parameters may not need to be changed depending on the material, and the reason for the success is the additional torque of the auger motor. This additional torque allows the system to maintain rotational speed, ensuring that the spoil is removed, even when additional weight on bit is applied.

The next test carried out is on the rock sample from the field trial. The results are shown in Figure 10 and Figure 11.

As with the previous test, and in line with the field test, the Field DT is unable to progress through the rock, constantly stalling, whereas the upgraded version succeeded. For each stall the DT was manually recovered to show the consistence with which the stalls occur.

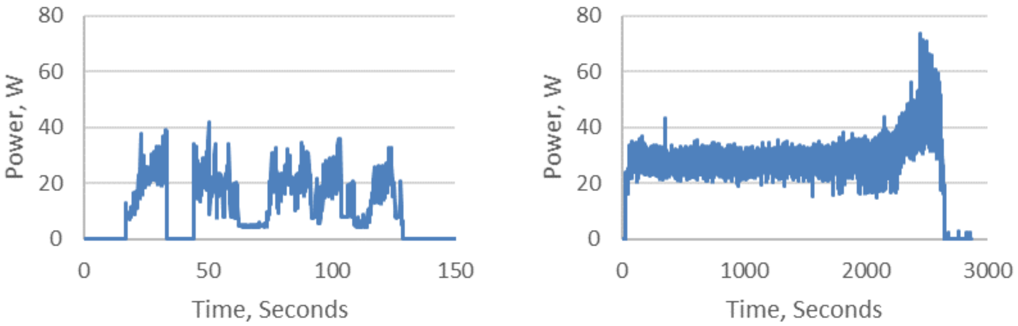
This shows that the upgraded motor and motor drive electronics can provide the necessary power to potentially complete the desired depths at the field site. For example, in Figure 11 there is an increase in the auger power draw near the end of the run as rate of progress was decreasing. The US power was increased to counter the decrease in the rate of progress, which had the effect of increasing the WOB and, consequently, the torque demand. However, this increase in torque demand is now easily within range of the upgraded motor. This result indicates that the motor also has the margin when higher drill powers are required.

There is therefore a positive impact in having a high power (100W compared to 40W) auger motor. For the DT this increased auger power allows for increased rates of progress, increased WOB's, and the ability to remove spoil at higher rates of progress. In addition, the increased torque handling capability allows the UPCD to use the same control parameters for a selection of materials where previously this was not the case. This results in an easier deployment in unknown rock.



A. Field Drill **B. Upgraded Drill**

Figure 10. Distance Drilled in field rock sample



A. Field Drill **B. Upgraded Drill**

Figure 11. Overall Power Draw in field rock sample

FURTHER WORK

With the improvements made to the DT the UPCD will continue to be tested. Currently a number of different avenues of work are being pursued. The control algorithm for the DT has been demonstrated to work in a number of different materials, however the algorithm does not detect nor react to errors or poor drilling performance (slow rate of progress). One avenue of research is the addition of downhole temperature measurements and resistance reading into the control loop, the aim of which is to avoid freeze events and tip glazing. Also the rate of progress is to be used as a control measure where the user can select a maximum or minimum rate of progress and the DT will operate as desired.

During the project various parameters were tracked. One was the shape of the cutting teeth. It was demonstrated that the shape of the teeth impacted the rate of progress of the drill. Further investigations are being carried out into this.

CONCLUSION

This paper has presented an overview of the UPCD project and the testing undertaken in the laboratory pre- and post- field trial and during the field trial. The pre-field trial tests demonstrated the basic functionality of the complete system and provided confidence that the system would operate as intended. During the field trial the conditions encountered were not as expected due to higher temperatures and ground water. The UPCD was demonstrated to operate on Coal Nunatak, Antarctica though the aim of drilling to a depth of 30cm was not achieved. On return the UPCD DT failed to drill a sample of rock retrieved from the field. The field results indicated that the auger motor required more power than expected. For this reason the DT auger motor was upgraded and the same test carried out. This test resulted in the successful drilling of the rock using the field trial control parameters. Due to the environmental conditions in the field, the conclusion that the UPCD would have drilled in-situ with the upgraded motor cannot be drawn, but the results presented do demonstrate that the new auger motor is more capable with more margin and could have enabled the UPCD to have drilled deeper during the field trials.

ACKNOWLEDGEMENTS

The research leading to these results has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) under Grant Agreement No. 607015. The University of Glasgow, SSF, Lidax and Magna Parva developed the UPCD. The field testing in Antarctica was supported by the British Antarctic Survey.

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