ULTRASONIC PLANETARY CORE DRILL: OVERVIEW AND RESULTS FROM FIELD TRIAL

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ABSTRACT

In the effort to explore the subsurface of terrestrial bodies, we seek to obtain better samples from ever greater depths. Many organisations are working towards technologies that can achieve this goal whilst ensuring compatibility with the likely requirements of planetary landers in terms of mass, power, and dimensions.

The Ultrasonic Planetary Core Drill (UPCD) was an FP7 funded project which aimed to develop such a planetary sub-surface sample acquisition system, developing the required drill hardware and testing it in a Mars analogue environment in Antarctica.

The objective was to reach 30cm and containerise the samples using the least possible power, while operating at low weight-on-bit. This has been broadly achieved within a conceptually-deployable package.

1. INTRODUCTION

UPCD uses ultrasonic percussive technology to penetrate icepack, permafrost, and rock. This drilling is achieved using a self-assembled drillstring with novel bayonet-style interfaces, autonomously deployed at an appropriate weight-on-bit by means of a feedback loop. However, human-in-the-loop command is still required for discontinuous functions such as drillbit selection.

The system is required to drill to a depth of 30cm and containerise an equal length of core-sample, using a drillstring assembled from three separate sections to demonstrate the expandability of the concept. The core sample is ~7mm in diameter. This drillstring is then disassembled and cached, with core samples still inside, within three silos that are sealed with three separate lids to preserve the samples for return or in-situ analysis.

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.

This paper presents an overview of the UPCD and presents results obtained from the field campaign.

The consortium consisted of the University of Glasgow (UK), SSF (Finland), Lidax (Spain) and Magna Parva (UK).

2. ULTRASONIC PLANETARY CORE DRILL

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

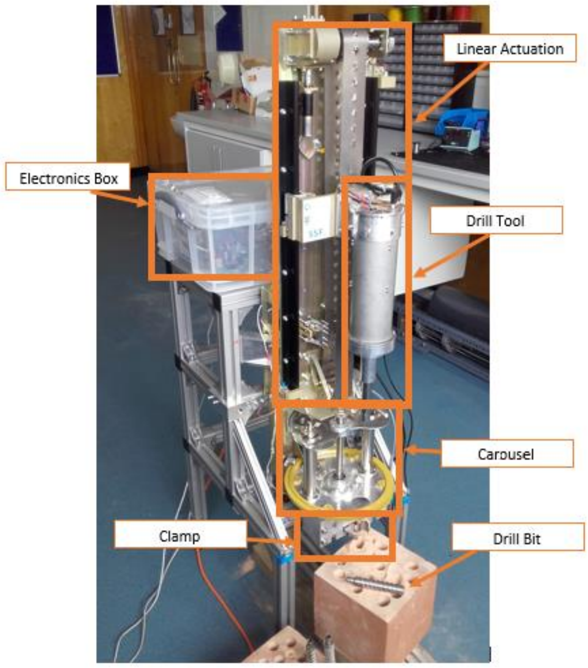

Figure 1. The UPCD

Table 1. UPCD Current Specifications

Parameter	Value
Mass	25kg
Volume	88L
Power (Idle)	10W
Power (Drilling)	Peaks 120W Average 60-80W Minimum observed 40W

2.1 Drill Tool

The Drill Tool (DT), developed by the University of Glasgow (UoG), is the ultrasonic assembly and its associated support structures. The concept uses the ultrasonic-percussive technique [1] where the transducer assembly is free to travel as a sprung mass (via the 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 drilling assembly. Internal preload (provided by the spring pairs) acts to ensure that the transducer, free-mass and drillstring come together again after each impact. The transducer operates at around 20 kHz (micron-scale amplitude, as driven by the signal generator) and percusses at around 30-40 Hz (mm-scale amplitude, as governed by drill-string mechanical dynamics).

The travel range is additionally exploited to permit the relative vertical movement needed to connect and disconnect the drillstring elements after a rotational bayonet locking or unlocking operation.

2.2 Linear Actuator

The Linear Actuator, developed by Lidax, provides the vertical motion required for drilling progress as well as the mechanical travel required for drillstring assembly and disassembly operations. This motion is belt-driven to reduce the overall vertical footprint whilst also providing an increased degree of dust tolerance.

The as-designed belt has a range of 530mm, but the concept of operations is such that any number of drillstring elements can be assembled without the need to extend the vertical range of the actuator any further.

2.3 Carousel

The Carousel, developed by the UoG, is the drillbit retention unit, housing the drillbits before use and then storing each 10cm sample in one of three Silos. The Carousel also holds the Lids used to retrieve the drillstring sections and seal the Silos after caching.

The Carousel is designed to be rotated with a stepper motor to achieve high precision movement. Each circumferential site (silo (x3), lid (x3), and operating aperture) has an associated magnet, with each magnet set at a different height from a Hall Effect sensor. This allows the control system to establish the position of the carousel and can enable autonomous selection of the desired location.

2.4 Electronics Box

The Electronics Box houses the control and power electronics for the UPCD, which were provided by SSF. The main elements of the Electronics Box are:

• Localised power conversion. The UPCD is designed to run from 28V and local power regulation is required for the different elements of the control system.

• Ultrasonic control system electronics. These are required to control the output of the transducer system (a Sonic Systems L500) used in the Drill Tool.

• Embedded Control board. This handles communication with a base station and the control of the complete UPCD system. The software was provided by SSF, and included the user interface on the base station.

• Stepper Motor driver. This is used to control the movement of the Carousel.

• BLDC controllers. Three BLDC controllers are used to operate the DT motor, the Linear Actuator, and the Clamp.

2.5 Clamp

The Clamp, developed by the University of Glasgow, is required to hold the drillstring in place during the assembly and disassembly operations, where it reacts the torque and vertical forces applied to operate the bayonet connections.

The Clamp consists of a motor with worm-gear train and a set of uncoated pincers that are designed to clasp the drillstring when commanded. The clamp is able to self-centre the drillstring and accommodate any minor misalignment because both the drillstring and the clamp pincer surfaces are circular and of equal diameter. End-stops are provided to prevent excessive movement.

Once the desired drillstring operation has been completed the direction of the motor may be reversed and pincers opened, releasing the drill string.

2.6 Drilling Control Loop

The drilling control loop governs progress during drilling itself, monitoring the ultrasonic power drawn and commanding the Linear Actuator's progress accordingly. Once initiated, the system will proceed autonomously until a set depth is attained or an error occurs.

This control system is possible because the power drawn, at the constant current issued by the amplitude-tracking ultrasonic control system, is related to weight on bit (WOB). This means that the control loop can seek to maintain a constant power draw and hence manage the force applied using power as a proxy.

On operations, when the power level drops below a preset level (with a ~10% margin) the DT will be advanced until the desired power level (within the margin) is re-attained. Should the mechanical advance prove to be excessive, too much power will be drawn and the margin will be exceeded. The opposite movements will then be commanded and a mechanical retraction made until more drilling has been conducted.

This bang-bang control has been demonstrated to work and further discussion is provided in [2].

In summary, the major parameters of the drilling control loop are:

• Desired power level. This value depends on the material being drilled, but algorithms for adjusting the value in real-time are being investigated.

• Margin. The upper and lower margin placed on the power level set the sensitivity of the controller.

• Movement time. The time taken to advance or retract the DT, and any dead time, can be selected.

2.7 Bayonet

Bayonet connectors [3] are designed to connect the drillbits to the base of the silos during outbound cruise, to allow connection and disconnection of the drillstring sections during assembly and disassembly of the drillstring, and to connect the lids to the drillbits during extraction and caching.

The bayonet design is a simple stud-and-groove connection, as shown in Fig 2.

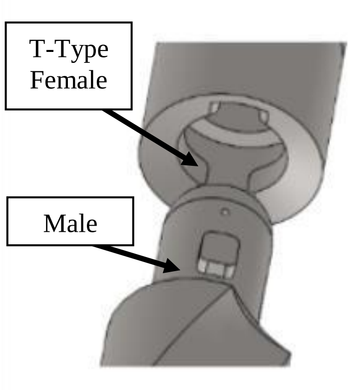

Figure 2. T-Type Bayonet connection with male stud.

There are three basic designs for the bayonet interfaces, and one special design. The male is a stud, as indicated in Fig 2, and the female exists as the T-Type (Fig. 2), the L-Type (Fig. 3), and the Special (not shown).

The L-type only locks in one rotational direction, whereas the T-type locks in either direction. These differences ensure that L-types disconnect when torque is in the reverse-drilling direction and longitudinal tension is applied, but T-types only disconnect when the actual torque reversal itself is made under tension. These subtly different behaviours allow the drillstring assembly and disassembly procedures to be executed using only one single clamp, even though there are multiple elements in the drillstring assembly.

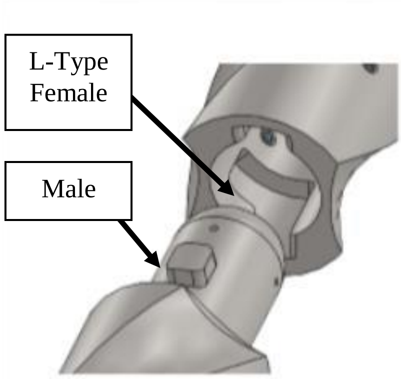

Figure 3. L-Type Bayonet connection with male stud.

Bayonet connections are secured by detent locks and their interfaces exist wherever the base or top of the drillbits interact. These sites, and the corresponding interface types, are:

• Base of silos to drillbits: Generally Male to female L-type, but a Special female connector is used for the cutting bit because the teeth carried by this first drillstring section make the usual geometry impossible.

• Drillbit to drillbit: Male to female L-Type.

• Lid to drillbit: Male to female T-Type.

• Lid to lance: Male to female T-Type.

• Drillbit to lance: Male to female T-Type.

An advantage of the bayonet concept is that the features are protected from dust ingress by the outer wall of the drillstring and, even internally, the bayonet feature is covered by the mating part. When the drillstring is disassembled there is a risk that dust will catch within the internal bayonet feature, but at this stage of the operational procedure the feature will not be reused and there are no negative consequences to the system.

2.8 Drill Bits

The drillbits consist of a single cutting bit and multiple pipes. All drillbits have an outer diameter of 21mm and an internal bore of 10mm, which accommodates the core. They also have male bayonet connectors on top so that they might be acted upon by the DT or another piece, and female bayonet connectors at the bottom (with the cutting bit having special arrangements to accommodate its tungsten carbide teeth).

In addition, each drillbit has an internal feature which holds and operates the core-catcher, which is a device that ensures the sample can be retained when the drillstring is withdrawn.

Fig 4 shows all the drillbits used.

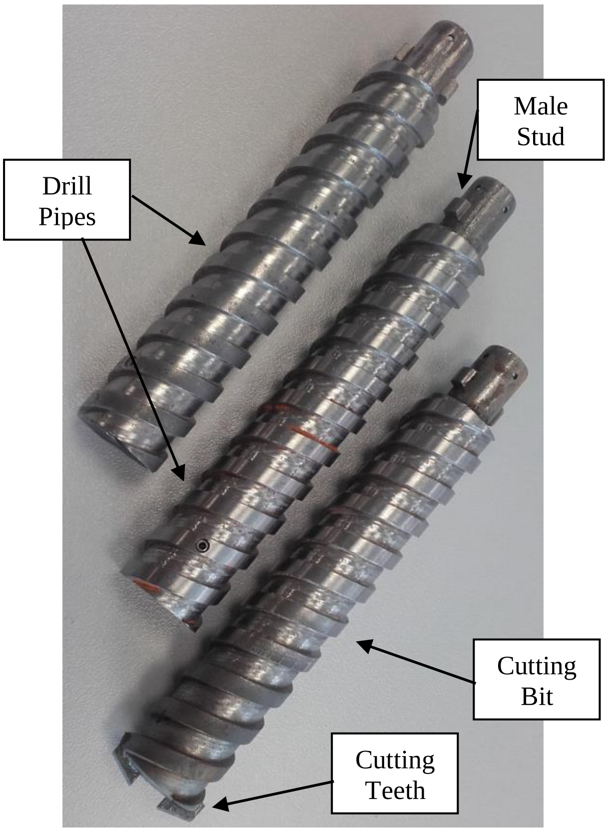

Figure 4. Drill Bits

2.9 Core Catchers

A principal aim of the UPCD is to retrieve cores, and therefore a miniaturised core-catcher design based on oil and gas industry approaches was created. The concept is shown in Fig 5.

Figure 5. Initial Core-catcher Design

When drilling results in a solid piece of core the core-catcher operates as expected: the core pushes up, lifting the core-catcher into a widening internal feature that allows it to expand, permitting further passage of the core. No breakout of the core occurs at this stage.

However, when the drillstring is extracted the core-catcher is pulled into the narrower part of the feature, tightening and ultimately breaking and retaining the core sample.

However in practice it has been found that, with the method of drilling used, and the core-catcher design as currently realised, some problems occur.

For example, during the drill cycle, the core can become segmented as shown in Fig. 6. These smaller pieces of core can then (sometimes) jam into the core-catcher and prevent further collection. This appears to be the reason for the observed low core recovery/depth ratio seen throughout the formal tests.

Nonetheless, further designs are now being evaluated and since removal of the original core-catcher design and replacement with new, experimental designs, the core recovery/depth ratio has been a lot higher.

Figure 6. Example of Core Retrieved

2.10 Silos

The Silos are designed to hold the drillbits during cruise to the destination surface, and to store the sample-bearing drillbits at the end of the drill cycle.

At the start of drilling, the DT lance unlocks the drillbits from the male bayonet at the base of each silo, and on completion of drilling each drillbit (with its internal sample) is placed back within the Silos before the Lid is screwed into the Silo top to create a seal against a dovetail-seated o-ring feature.

2.11 Lids

The Lids are designed to be used to recover the drillbits from the ground and to help seal the samples within the Silos using their circumferential screw threads.

Additionally, the tops of the Lids have male bayonet connections that are used to interact with the DT lance, and at the bottom they carry a female T-Type bayonet connector which is used to mate with the drillbits.

2.12 Operational Concept

The operational concept is a key feature of the UPCD, setting out the sequence of movements required to achieve 30cm depth while assembling and disassembling the drillstring. A full procedure can be found in [4], but Fig. 7 shows the high-level sequence.

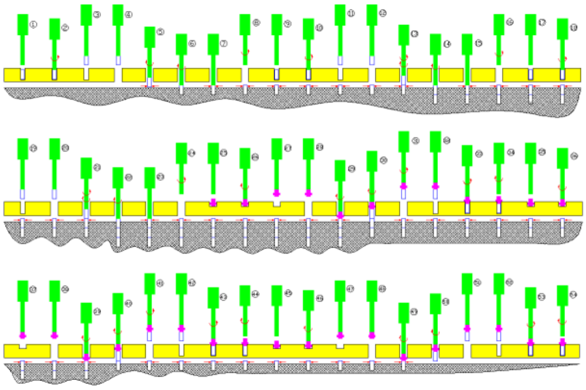

Figure 7. Operational Concept for the UPCD. Green is the DT and Lance, yellow is the Carousel, white is the drillbits, and pink is the Lids.

3. LABORATORY TESTING

Within the Laboratory two test setups are used, the UPCD and the Science Rig.

The UPCD is as described above, but the science rig allows the DT to be tested in isolation, facilitating the development of the control loop and measurement of key parameters. The science rig consists of:

- Ultrasonic control system electronics. These are required to control the output of the transducer system used in the Drill Tool.

- BLDC motor driver. This is required to run the DT motor for auguring purposes.

- DC motor driver. This is required to run the Linear Actuator.

- Embedded System. This is an interface to a PC and all external equipment. It also runs the control loop.

- Force Sensor Amplifier. This is used to measure weight-on-bit for data acquisition purposes.

3.1. UPCD Testing

A range of laboratory tests were conducted to ensure that all aspects of the UCPD operate as expected in both sandstone and permafrost substitute, which was a frozen mixture of sand and water.

The full test campaign is not repeated here, but it did demonstrate that the drill could drill to 30cm using the relevant aspects of the operational concept. This is illustrated in Fig. 8, while Fig. 9 shows the desired ultrasonic power being maintained at 9W during this same drilling and sampling process.

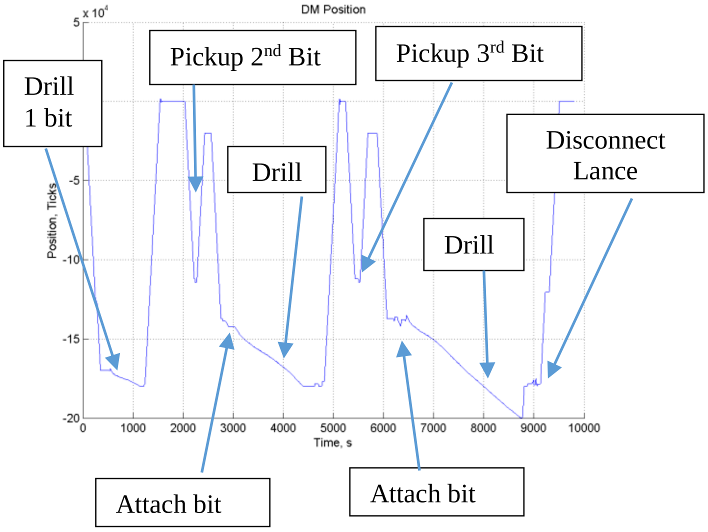

Figure 8. 30cm Drill Cycle carried out in the Laboratory.

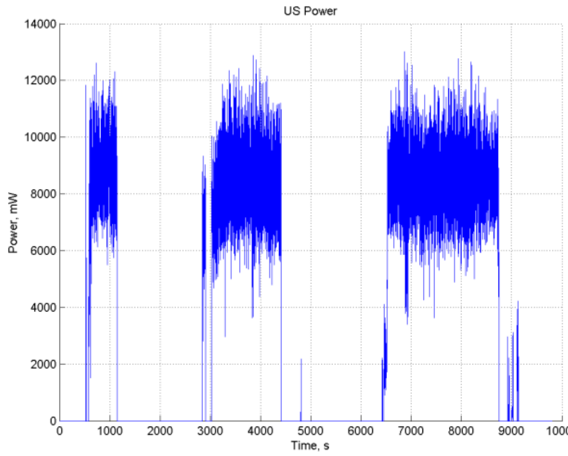

Figure 9. US Power from a 30cm Drill Cycle carried out in the Laboratory.

3.2. Weight on Bit Testing – Science Rig

Fig. 10 shows results from six 10cm runs in sandstone, with each run maintaining 10W of ultrasonic power as shown in Fig. 11. It can be seen that the DT can drill with around 20N WOB while maintaining the desired power level.

This is an important aspect of extra-terrestrial drilling, because it reduces the mechanical footprint of the device upon its supporting lander.

The spikes that are seen in one run represent points at which the drill cycle control loop advanced the drill too quickly.

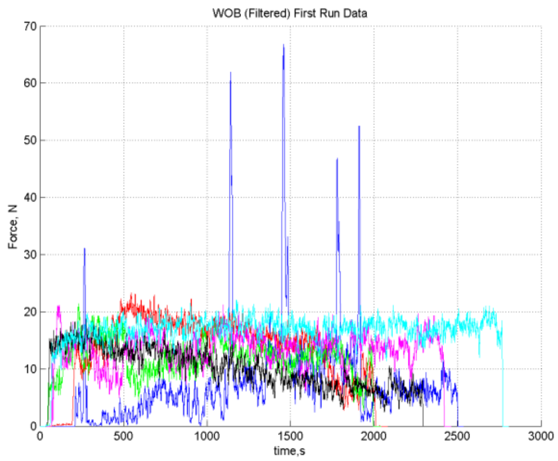

Figure 10. WOB of UPCD DT

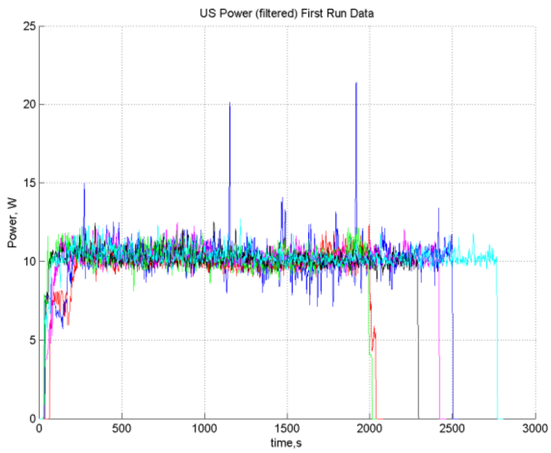

Figure 11. Ultrasonic power drawn during WOB measurement

4. FIELD TESTING

The field test site was Coal Nunatak on Alexander Island, Antarctica. The site was selected due to 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. However, it should be noted that while testing was undertaken it was unseasonably warm (-3°C to 0°C), with even higher ground temperatures. This led to extensive soil moisture and even some surface water being present.

To support the campaign a test procedure was developed to allow each part of the system to be tested. A summary of the tests carried out is provided in Tab. 2.

As can be seen from the results, the UPCD did not meet all expectations in the field. On the first 10cm drill run the UPCD did not achieve depth, and neither was depth achieved on any additional runs drilling into rock. Analysing the data from the field, it is now considered that a lack of torque in the auger was key to this shortcoming, with the excessive torque requirements perhaps being associated with extensive moisture in the regolith, or other unknown factors.

In an attempt to resolve this issue changes were made to increase the auger torque in the field, but ultimately a lack of power stopped the tests. A maximum of 60mm achieved in the regolith, as shown in Fig. 12.

Table 2. Tests Carried Out in the Field

TEST	RESULT
Initialise – Ensure system operating	PASS
Calibrate – Retrieve data to allow the calibration of the UPCD	PASS
Run Linear Actuator – Ensure Correct operation	PASS
Run Carousel – Ensure Correct operation	PASS
Run Clamp – Ensure Correct operation	PASS
Run US – Ensure Correct operation	PASS
Run DT Motor – Ensure Correct operation	PASS
Test External Sensors – Ensure Correct operation	PARTIAL PASS
Drill to 10cm	PARTIAL PASS
Drill to 30cm	PARTIAL PASS
Drill to 30cm Retain samples	NOT TESTED
Angled Drilling	NOT TESTED
Martian Gravity Drilling	NOT TESTED

Figure 12. Hole drilled in Antarctic regolith

However, rock- and regolith-drilling is not the only function of the UPCD. A demonstration of the full-depth operational concept was carried out in the icepack, and indeed a sample of ice was duly recovered and containerised, indicating that the ultrasonic drilling process does not cause excessive heating to the sample.

This is important for sampling volatile-bearing material.

The positional data of the DT is provided in Fig. 13, where each stage of the operational concept is shown.

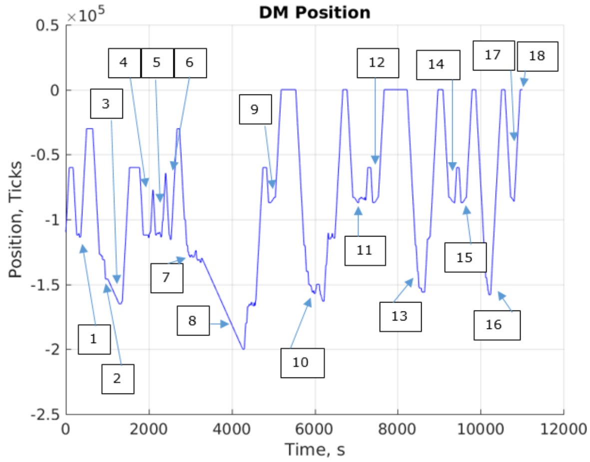

Figure 13. Position of belt during the Antarctic trials.

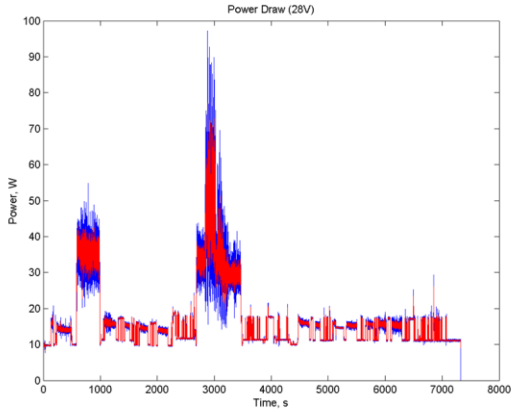

Figure 14. Power draw of system during the test presented. The blue line represents raw data with the red line being filtered data.

The process begins with one drillbit in the ground and the second drill bit being picked up. The steps indicated are:

1. Pickup Bit 2
2. Attach Bit 2
3. Drill with two bits
4. Pickup Bit 3 (Failed)
5. Pickup Bit 3 (Failed)
6. Pickup bit 3
7. Attach Bit 3
8. Drill to 30cm
9. Pickup Lid 3
10. Attach Lid 3 to bit 3
11. Lock lid/bit 3 into Silo 3
12. Pickup Lid 2
13. Attach Lid 2 to bit 2
14. Lock lid/bit 2 into Silo 2
15. Pickup Lid 1
16. Attach Lid 1 to bit 1
17. Lock lid/bit 1 into Silo 1
18. Return to HOME

This drill run successfully demonstrated that the concept of operations can work, and also that the UPCD can assemble and disassemble a drillstring in the field.

Whilst the third drillbit proved difficult to pick up, the final attempt was successful and no human interventions (except electronic commands) were required in the recovery, which indicates a degree of fault tolerance and recoverability in the system. The success rate of commanded interface make/break operations in this run was 93%.

Finally, over the full run the average power draw was 17.08W with a peak of 97.24W. The power draw is provided in Fig 14, where the areas of higher power draw are the drilling cycles.

5. APPLIED TECHNOLOGY

Discussions with the British Antarctic Survey (BAS), when organising the trip to the field site, resulted in joint project to develop a tool for sampling bedrock beneath the West Antarctic Ice Sheet (WAIS). In their exploration of the WAIS with their Rapid Access Isotope Drill (RAID), the BAS have been able to drill through the ice sheet to depths in excess of 600m in timescales no longer than a week.

Whilst the RAID system is adept at cutting through the ice, it is largely unable to sample the bedrock beneath. This bedrock is of scientific interest as it contains information about historical glacial cycles.

The University of Glasgow/British Antarctic Survey Subglacial Bedrock Sampler (SBS) is therefore a new tool concept which can be attached to the existing wireline RAID when bedrock is encountered, extracting rock samples while reacting low forces into the softer ice above. The SBS relies heavily on heritage technologies from UPCD and other planetary drilling system as it seeks to provide a ‘low-footprint’ solution in an environment where field logistics are extremely challenging.

The SBS is a rotary-percussive drilling system, utilising the cam-hammer approach to fracture rocky terrain. It is designed to fit within the ~70 mm bore diameter of RAID, whilst consuming less than 600W total power and requiring reacted loads and torques not exceeding 400N and 10Nm respectively. Furthermore, the system makes use of brushless DC Maxon motors, further easing compatibility with the existing architecture. Whilst still under development at the time of writing, Fig. 15 details the system as it currently stands.

Figure 15. The Subglacial Bedrock Sampler, which is based on the UPCD architecture.

6. FUTURE WORK

The UPCD project formally came to an end in December 2016, but interest in the work has increased. Through a PhD project at the UoG the lessons learned will continue to be applied with the aim of increasing the performance and reliability of the drilling process.

An improved algorithm for drilling that relies on additional data being obtained (namely, the downhole temperature and conductivity) is also being developed with the aim of autonomously drilling through unknown materials with no user interaction required.

Finally, regarding the other autonomous processes discussed, tests are being developed to prove out the basic concepts and improve the performance accordingly.

7. CONCLUSIONS

An overview of the UPCD has been provided with each element of the system briefly introduced. A brief discussion of the testing carried out in the laboratory then in the field was provided with important results included. The issues from the field test were then introduced. Further work based on the UPCD, namely the BAS Bedrock Sampler, was discussed with further work for the UPCD system set out.

The UPCD met the basic aims of the project and has a clear further work path. Methods for improving the mass, volume and power are being considered, as are methods to increase the reliability of the full system.

At this time the full UPCD is considered to be at TRL 3 with some elements significantly further advanced.

8. ACKNOWLEDGEMENTS

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