Development of a Robust Mating System for Use in the Autonomous Assembly of Planetary Drill Strings

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Abstract

Volume constrained robotic missions seeking to obtain samples from beneath a planetary subsurface may wish to utilise a rigid drill string, consisting of multiple, individual drill bit sections connected together as opposed to a single, lengthy drill bit. In order to ensure that drill strings can be assembled and disassembled reliably, it is essential that a robust connection system is used. The authors herein propose a geometry which seeks to address the requirements of such a mating interface. The proposed solution is based on the bayonet interface, using 'L' and 'T'-shaped 'female' grooves and 'male' studs which are connected and disconnected together through a series of clockwise and anti-clockwise rotations and single-point clamping events. This routine allows both the transfer of percussion through the drill string and torque in both directions of rotation, while permitting the accurate disconnection of individual drills bits at the required location. Sustained laboratory and field drilling operations suggest that bayonet-style connections offer a reliable solution to the problem of autonomous assembly and disassembly of drill strings in a planetary exploration setting. This paper shall discuss the development of such a connection system, based on the bayonet connection, which has been implemented into the overall architecture of the Ultrasonic Planetary Core Drill (UPCD). The design trade-off study, which sought to evaluate the use of the bayonet system over the more conventional screw thread interface will be discussed, alongside experimental results from percussion transmission testing and drill string assembly testing.

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1.0 Introduction

1.1 Ultrasonic Planetary Core Drill (UPCD) Project

As robotic spacecraft seek to explore to greater depths beneath the surfaces of the terrestrial planets, moons, asteroids and comets of our Solar System, ever-more capable sample collection systems are required. The University of Glasgow seeks to address this demand by means of the Ultrasonic Planetary Core Drill (UPCD), an ambitious project to develop a highly capable sample collection and caching technology. The UPCD system employs the ultrasonic-percussive drilling technique, developed by NASA JPL at the turn of the 21st century (Bar-Cohen et. al 2000), coupled with the ability to autonomously control the weight on bit of the drill system through the use of a novel control algorithm (Li et. al 2015). The ultrasonic-percussive drilling technique offers a 'low footprint' approach to planetary drilling, whereby the force which must be reacted by the host lander or rover is in the region of 10-50 N. It is of note that the portion of the reacted force attributed to the weight on bit requirement is, in fact, minimal, and may only account for a small portion of the summation of the total reacted force. The majority of the force that must be reacted is a result of the recoil felt upon the delivery of percussive loading to the target terrain. As the load path of the recoil is transferred through a series of rear-mounted springs, the force which is transferred to the drill deployment structure is tuneable, at the expense of drilling performance. A maximum total drilling power as low as 50 W (Worrall et. al 2017) is commonplace, though there is an intrinsic link between the physical properties of the terrain to be drilled and the power consumed by the drill system. Furthermore, the system possesses the ability to reliably assemble and disassemble a drill string consisting of three or more individual drill bit elements using autonomous routines. The development of this robust connection system was perhaps one of the most challenging aspects of the design, and is directly translatable into future sample acquisition systems. When all of the merits of the UPCD system are considered holistically, it is possible to conclude that the

UPCD may be well suited as the primary scientific payload of a NASA Discovery or ESA M-class mission, whereby strictly imposed budgetary limits demand smaller scale missions with constraints on the landed mass and/or volume.

1.2 Drill Strings for Planetary Applications

Although multiple spacecraft have robotically drilled, excavated or abraded the surface of various terrestrial planetary bodies to date, these mechanisms have required only a minimal level of in-situ assembly in order to ready themselves for use. The use of a drill string with a minimum of three individual drill bit elements contributes a great deal of complexity to the drilling process due to the high levels of autonomous control required. In order to increase the reliability of the system, both the assembly routine and the hardware must be robust against the failure mechanisms which are associated with the isolation of planetary exploration and the trials of spaceflight.

2.0 Historic Missions Utilising Subsurface Exploration Systems

Robotic missions to the terrestrial planetary bodies have observed a trend towards the exploration of the subsurface as a means of sampling virgin terrain, preserved from the effects of prolonged radiation exposure, aeolian erosion, or seasonal cycling. To date, only a handful of spacecraft have successfully fulfilled this goal. The USSR achieved early success by utilising multiple iterations of a rotary-percussive drill system launched on-board the Luna missions to the Moon. This series of missions successfully culminated in the return of unconsolidated core samples from Luna-24 in 1976 (Barsukov 1977). Later Soviet ventures within the Solar System, instrumented with a sample collection system, include the Venera and Vega missions, which were successful in obtaining samples from depths of a few centimetres beneath the Venusian surface in 1985, a venture yet to be repeated. Early NASA robotic missions to Mars commenced with the 1976 landings of the Viking programme. These highly-capable landers featured robotic arm-mounted scoops for regolith excavation and sample collection. This system delivered samples to an on-board suite of instruments, including a gas chromatographer – mass spectrometer, as part of a direct search for life. Although the life-seeking objective of the mission ultimately proved inconclusive (Klein 1998), the presence of perchlorate salts in the regolith was speculated. Following an extended period of dormancy, the launch of the Mars Exploration Rovers (MER), Spirit and Opportunity, in 2003, marked a new era of subsurface exploration. The Rock Abrasion Tool (RAT) mounted to the robotic arm of each of these twin rovers enables the operator to abrade the weathered surface of rock and terrain targets, exposing pristine surfaces deemed more suitable for in-situ analysis by the on-board, geology-focussed science package (Gorevan et. al 2003).

The RAT operates by means of a grinding wheel, tipped with PCD resin, which is loaded against the target in order to remove up to 15 mm of material from the surface, while analysis of motor current data has allowed for the characterisation of the physical properties of the target (Thomson et. al 2012). The NASA Phoenix spacecraft, which landed in the northern regions of Mars in 2008, utilised an architecture analogous to that of the earlier Viking landers, though the scoop sample collection system received an upgrade in the form of a rasp tool, used to penetrate the ice-cemented terrain which lay beneath the loose layer of desiccated overburden (Chu et. al 2008).

The commencement of the use of a more classical form of drilling as a means of sampling the terrain on Mars began with the NASA Mars Science Laboratory (MSL) spacecraft in 2012. MSL was tasked with the objective of examining the potential habitability of the planet by means of a study of its geology and climate. The rotary-percussive, full faced drill system developed allows MSL to obtain powdered samples of target terrain up to depths of 65 mm

(Okon 2010) using a single-bit drilling architecture. Figure 1 details the successful use of the MSL drill system in excavating two holes in the form of a test hole for mechanical calibration followed by the hole intended for sample retrieval, at the Gale Crater site on Mars.

While the MSL drill utilises a single bit during any of its shallow drilling operations, these bits can be swapped out when the cutting face is worn. To do so, the system makes use of a cam-driven 12-point chuck mechanism. The successor to MSL, the as-yet unnamed Mars 2020 mission, is set to be the first stage in the Mars sample return timeline. The rover, a modified re-flight of the MSL architecture, shall be equipped with an upgraded drill system capable of obtaining core samples from a required depth of 50 mm (Mustard 2013). These core samples are then hermetically sealed and either immediately deposited on the surface of the planet or temporarily stored and deposited in clusters at a more suitable location. This 'adaptive caching' approach has been adopted in order to improve the robustness of the mission while minimising the risks associated with single-point caching (Beaty et. al 2015).

Perhaps the most ambitious planetary drilling operation to date is the 2-metre-class rotary drill

Figure 1: MSL drilling operation at Gale Crater. Note, test hole and sample retrieval hole. Image Courtesy NASA/JPL-Caltech/MSSS.

system to be included on the astrobiology-focussed ESA ExoMars 2020 rover. The rover is to be delivered to the mid-regions of Mars, either the lowlands of Oxia Planum or Mawrth Vallis

(18-22° degrees north, respectively). Remote sensing of these areas has proven them to be rich in stratified clay minerals, ensuring that these areas are desirable in an astrobiological sense while being free of harder, less drillable igneous terrain. The drilling technology which has been developed for the mission, though is as yet unpublished, features a drill string system comprising of multiple (approximately metre-long) drill bits mated together robotically, in-situ (Magnani et. al 2010). Connection of these drill bits is accomplished by means of a screw thread interface, assisted by data from on-board thrust and torque sensors. An overview of the use of conventional threaded interfaces in connecting drill bits will be discussed in detail in section 3, highlighting the pros and cons of using such a connection method.

3.0 Drill String Connections

3.1 Making and Breaking Drill Strings

Connecting individual drilling elements together to form a drill string is a task most commonly associated with seafloor drilling activities related to energy prospection. The coupling and decoupling of such drill strings, connected by a threaded interface, is accomplished by an abundance of manpower and ruggedized equipment, with the human-in-the-loop element a key component of the process. It is only through the training and intuition of the workforce present that the drill string can be processed in an efficient and safe manner. The operator’s ability to make real-time decisions based on visual or tactile feedback dramatically reduces the potential for lengthy disruptions to the assembly or disassembly process. Human-in-the-loop also allows for the drill string to be less physically constrained, as the operator can easily manipulate the drilling elements in multiple degrees of freedom without difficulty. While a number of technology developments implemented within this industry has resulted in an improvement in the autonomous capabilities of industrial drilling rigs, the availability of hands-on assistance provides reassurance in the most challenging cases. In the context of planetary drilling, whereby the drilling site in question is typically in exceedance of the range of tele-operation due to light speed delays (with the possible exception of lunar missions), any attempt to bridge this gap without autonomy would prove impossible. Furthermore, as with Earth-based settings, ancillary hardware required to make and break drill strings such as clamps and other temporary retraining mechanisms can be heavy and complex by design. Clearly, in the absence of an in-situ human operator and with heavily constrained mass and volume budgets, such a challenge is only amplified. Thus, any system designed for in-situ robotic assembly must be equipped with an autonomous control system, fed by a steady stream of data from a sensor suite while ensuring that the design is as mechanically simple as possible in order to reduce the risk associated with single point failures.

3.2 Threaded Connection Operations

Upon analysis of each individual operational element required to make and break a threaded connection, and the subsequent feedback signals which would be required to convert the system to one which is fully autonomous, it is apparent that the task of making and breaking a threaded connection is non-trivial. In order to appreciate the complexity of such an operation, it is essential that the individual steps which compose the complete drill string assembly process are considered. The steps required to make a threaded connection are as follows:

1) Axially and radially constrain female-ended (tapped interface) drilling element.

2) Axially translate male-ended (threaded interface) drilling element until contact is made with female-ended element.

3) Ensure that the start of the male and female threads are aligned.

4) Rotate male-ended element while axially translating in the natural direction of the thread helix. Translation rate to be set to match RPM of rotation and thread pitch.

5) Cancel all rotation and translation at maximum thread engagement.

Without prerequisite, baseline intuition or ‘feel’ for such operations, the robotic control system must, instead, rely on a suite of sensors and actuators to carry out the tasks which are commanded of it.

Step 1, the constraint of the female drill bit, requires that the system be equipped with a means of recognising the position of the clamping mechanism and can establish when the criteria for the successful clamping of the drill bit has been met. Typically, it is preferable that the requirement for sensor data is met by at least two independent sources in order to ensure certainty in the success of the operation and redundancy in case of sensor error. In the case of the first step, a typical sensor suite may include encoder data coupled with the use of limit switches to indicate when the motorised clamping operation has reached the required position. Furthermore, evidence of a surge in motor current, as the clamps fully engage with the drill bit, would provide further confirmation of success.

Steps 2, 3 and 4, the translation of the threaded, male-interfaced bit towards the clamped female-interfaced bit and the subsequent mating of these two bits requires an entirely different set of sensors. It is likely that the axial translation stage, if driven by a belt or ball screw-based system, will be able to make use of encoder feedback alone for positional data. Furthermore, the use of a linear potentiometer for redundant position feedback. Furthermore, initial engagement of the two bits is easily identifiable through the inclusion of a force transducer in the axial direction and limit switches for added protection against overrunning. The combination of multiple sensors also acts to ensure the system can compensate for unforeseen degradation in any one of the sensors, such as backlash in motor-gear systems or zero-point floating. Such compensation is particularly important in deep space applications, where the instruments may spend extended periods of time in dormancy during interplanetary cruise. Arduous surface conditions caused by extremes of temperature, radiation exposure and dust ingress also leaves sensors suites vulnerable to erroneous readings. Perhaps unsurprisingly, the most risky element of the complete mating operation involves the matching of axial translation with rotation during thread engagement. In order to achieve a successful mating of bits, multiple sensors must work in unison to allow the control system to rapidly respond to off-nominal states.

The nature of the threading operation, in a situation where the female-ended bit is fully constrained, is such that the male-ended bit may be forced into tension by means of a corkscrew-like action through an axial under advance. Unless the axial translation of the bit is carefully matched, this could result in an overstress of the system, resulting in damage to the axial stage or belt-slippage, if a pulley-based axial stage is utilised. While tension in the system is clearly undesirable, a net compressive force caused by an over advance of the axial translation stage may also result in the formation of another unwanted error state. As the compressive force applies axially-directed pressure to the female threads, the resulting rise in friction may induce a periodically increased torque demand. The resulting motion is physically analogous to that of the ‘stick-slip’ condition, whereby the threading motion may temporarily stall until the rotary element catches up and reduces the axial load on the bit. In extreme cases where ‘stick’ is particularly high and rotation is sufficiently impeded, an unchecked axial translation may only compound the problem and result in rotary motor stall, necessitating an abort of the operation. It is of note that both an axial over advance and an under advance share may share common failure mode in rotary motor stall, impeding efforts to diagnose the fault and remedy it. Clearly, the action of threading drill bits together through an interplay of translation and rotation is only made possible by real-time data from a large suite of sensors, working to identify fault states as they arise.

Despite the intricate nature of making threaded connections, missions such as the upcoming ExoMars 2020 rover do intend to utilise this method as the primary means of forming drill strings of at least two individual drill bit elements. While control-based assembly problems may be overcome by the inclusion of a complex sensor package, threaded connection methods have inherent features which may complicate the overall drill system architecture.

3.3 Practical Limitations of Threaded Interfaces

While the process of disconnecting threaded bits may seem relatively trivial when compared to the difficulties posed by connecting threaded bits, there are challenges intrinsic to this operation. Of primary concern when utilising a threaded system is an inability to rotate the drill string in the counter-clockwise direction without disconnecting one bit interface from another. This is particularly problematic given that the solution to multiple downhole drilling faults requires the application of a reversed drilling direction. Furthermore, upon attaining the required drilling depth, it is typical that the mission will require the disassembly of the drill string and the caching of used drill bits for sample preservation or later use. In doing so, the system must remove the drill bits piece by piece, starting with the uppermost bit. In order to ensure that only the uppermost bit is removed, the threaded system requires that both the bit to be removed and the bit immediately attached to it are clamped. This ensures that, when an anti-clockwise rotation is applied, only the connection between the uppermost bit and the bit to which it is directly attached is broken while the connection between the uppermost bit and the drill mandrel itself is maintained. This necessity for multiple clamps only expands the overall system complexity and increases the likeliness of single point failures occurring.

While the ease of manufacturing both male and female interfaces allows parts to be produced quickly and with a high degree of reproducibility, the physical nature of threads makes them extremely prone to harbouring dusty fines and other particulates which may be present on the planetary surface. As the surface of Mars experiences frequent aeolian activity, wind-borne fines are readily deposited on all parts of the spacecraft. Although so-called “cleaning events” act to clear surfaces, the complex geometries of threads means that once contaminated by dust, the surfaces often remain coated indefinitely. Simple experimentation suggests that dust on threads can increase the torque demand on the motor as a result of increased friction forces. In the worst case, a failure will occur whereby the threaded connection that can be made but cannot be undone. While this problem is certainly ubiquitous across all mating connection types, it is the large surface area of threaded connections which magnifies this effect and is therefore particularly worrisome.

Drilling systems which are required to penetrate hard terrain often make use of percussive hammering as a means of increasing the rate of penetration of the system without increasing the required weight on bit. In the experience of the authors, the vibration caused by percussion may result in threads shaking loose – a potential risk to the system which is difficult to predict. It is therefore possible to conclude that, while threaded systems can be utilised in a planetary exploration setting, the inclusion of such a system requires an acceptance of certain risks which may drive mission planning and operation

3.4 Bayonet Connection Interfaces

Having examined both the pros and cons of a threaded mating system, it is clear that, although such systems show a degree of capability, they do not represent an ideal solution to the problem of making and breaking drill strings robotically.

The Ultrasonic Planetary Core Drill (UPCD) project aimed to develop a system which was less mechanically and operationally complex than other existing designs. The architecture of the system is as detailed in Figure 2. During the developmental stages of the design process, it was established that the key technologies which would add complexity concerned the need to make and break drill strings. As such, a trade-off study indicated that the benefits which could be had by undertaking the development of an alternative system, based upon the bayonet system, outweighed the negatives conferred by such an approach. As previously detailed, the most challenging element of the threaded drill string system is the high level of control required to make connections (worsened by dust contamination) and the limitations imposed by the inability to rotate the drillstring counter-clockwise (limiting fault tolerance and the ability to selectively disassemble individual drill bits without the inclusion of a mandrel clamp, with the associated mass and complexity savings associated).

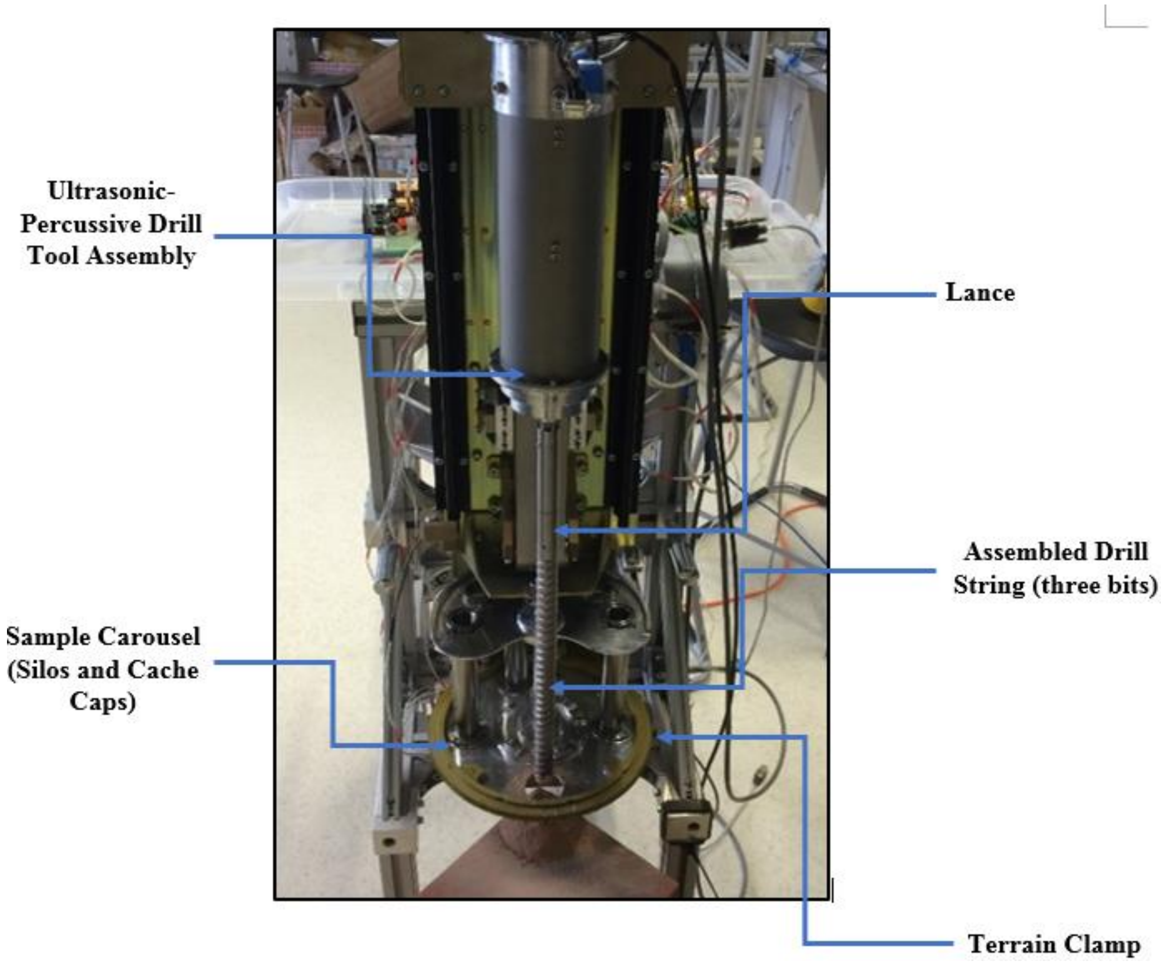

Figure 2: UPCD Architecture

3.5 Bayonet Connection Operations

The bayonet approach relies on a connection system based on the use of male studded features and female grooved features. When mated, a connection is formed which allows both the transmission of torque and percussion through the drill bits, with very little attenuation of the percussive energy delivered to the bit-rock interface. Through careful design, it is possible to develop a bayonet connection system which permits torque transfer in both drilling directions, aiding the system in the drill string disassembly process and fault tolerance. Furthermore, such a system can be designed with a high degree of dust prevention and tolerance, ensuring robustness. The need to reliably disassemble the drill string necessitates the ability to selectively disassemble only the uppermost drill bit in the drillstring without unlocking the lower elements of the string. A rethink of the standard bayonet system ultimately inspired the use of T-shaped female groove alongside the more conventional L-shaped groove. The developed system would rely on the inclusion of the T-shaped groove geometry in both the ‘lance’ of the drill tool and the ‘cache caps’ (the lids used to seal the top of each core-containing drill bit prior to caching). The lance component of the drill tool acts as both an anvil, transmitting shock loading from the ultrasonic-percussive hammer within the tool, and also as a connection interface to the drill bits, transmitting torque from the gearbox of the auger motor to the drill string. The implementation of T-shaped grooves in the cache caps allows the caps to operate effectively as a continuation of the lance itself, easing the caching process. While L-shaped grooves can be axially locked in only one direction, the T-shaped groove allows the stud to lock in either arm of the groove, thus locking the bits axially while permitting rotation in either the clockwise or anticlockwise direction.

Having established that a combination of multiple female groove geometries was the key to developing a robust drill bit connection system, a trade-off study of the various Concept of Operations was undertaken. Figure 3 (Timoney et. al 2016) details the process by which different groove geometries are utilised to allow only the uppermost drill bit to be disconnected from the drill string. The T-shaped female groove of the lance is shown coupled to the stud of the uppermost drill bit which is to be removed from the string, while the L-shaped female groove connects two lower drill bits. It is noted that the female groove features are internal to the drill string, reducing the likelihood of dust contamination. The manufacturing of these geometries was accomplished through the use of Electric Discharge Machining and required a rigorous quality control process to ensure that the required tolerances could be met. The rectangular stud features were manufactured using a similar technique but feature a sloped upper surface as a means of preventing dust build-up.

As discussed in Section 3.2, the male to female threaded connection interface is difficult to establish using robotic manipulation. With the implementation of an axial compression spring, in line with the lance, the male to female bayonet connection is aided greatly. The compression spring allows the drill system to axially progress while any over extension is compensated for by the compression of the internal compression spring. As the spring will remain compressed until the male bayonet is located within the axial section of the female groove, at which point the decompression of the spring will act to propel the male bayonet into the axial section, this can be exploited as a means of ensuring a successful connection is made which does not require careful control based on encoder feedback. In fact, this method became the standard method of connecting drill bits together in the lab, such is its level of robustness. This simplicity is perhaps one of the main advantages of the bayonet mating system over threaded alternatives.

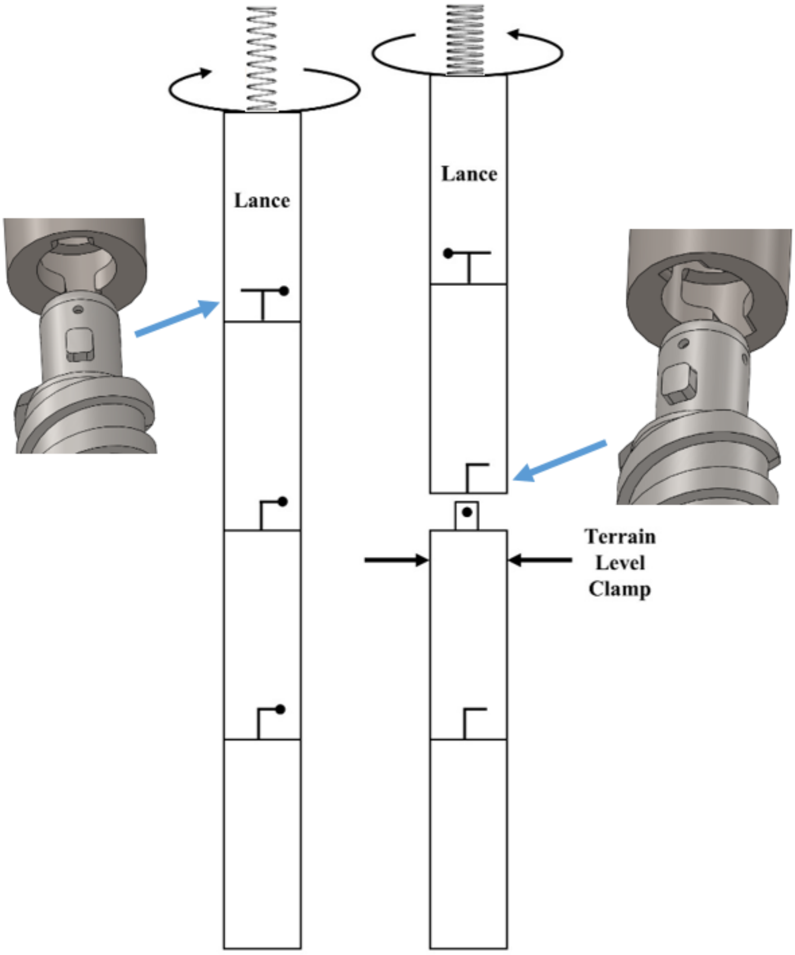

Figure 3: Drill bit disconnection procedure. Drill string in typical drilling configuration (L) and disconnection event (R). Image courtesy (Timoney et. al 2016)

4.0 Concept of Operations Study

The routine by which the drilling system connects and disconnects individual drill bits in order to achieve the required sampling goals is referred to as the Concept of Operations (ConOps). In order to establish the most suitable method of carrying out this task while attempting to minimise both system and operational complexity, a trade-off study was performed (Timoney et. al 2015). In this study, two competing ConOps were assessed for various criteria, balancing operational complexity with the mass and volume demanded. The selected operational mode, herein referred to as the Continuous Core Method (CCM), relies on the use of a single, hollow core cutting bit with multiple, hollow bits added as the length of the borehole increases as drilling progresses. Typical drill bit geometries utilised in this method are shown in Figure 4, with the assembly/disassembly routine shown diagrammatically in Figure 9.

The UPCD architecture is represented by various shapes in the ConOps diagrams. The green shape represents the drill tool itself, the blue rectangle represents the Sample Carousel (which contains the unused drill bits prior to use and also stores used bits and the collected samples in silos. A CAD model of the complete system, labelled with the appropriate colours, is presented in Figure 8. The terrain is represented by the grey hatched rectangle while the double set of red arrows are to be interpreted as a clamping event as carried out by the Terrain Clamp. The drill bits are denoted as white rectangles and the Cache Caps purple crosses. The drill tool connects to an unused cutting drill bit, stored in a silo in the carousel, through single axis translation and

Figure 4: CCM Drill Bits. Two Extension Bits shown (top and centre) and Cutting Bit (lower). Note: male stud interfaces visible, female grooves within internal bore.

a rotation manoeuvre to unlock the bit from its passive axial hold-down points. Through a series of axial translations of the drill tool and rotation of the carousel to a location known as the Drilling Aperture (an aperture in the carousel which allows the drill access to the terrain), the system proceeds to drill to a depth as determined by the length of the individual drill bits. Upon reaching the target depth, the bit is clamped by the Terrain Clamp, allowing the lance of the drill tool to disconnect from the cutting bit before axially translating to receive a second, extension bit. Upon reaching the desired drilled depth through the addition of the required number of drill bits to the string (in the case of Figure 9, three individual drilling bits), it is required that the drill string be disassembled and each core-containing drill bit be cached into a sealed silo. In order to do so, the bit which is to be cached is first sealed at its uppermost end by a Cache Cap. The Cache Caps fulfil a dual role in that they seal one end of the drill bit while allowing a hermetic seal to be formed with the silo itself, preserving the scientific integrity of the captured volatiles. In the case of the three-bit scenario pictured in Figure 9, the carousel must contain three silo positions and three Cache Cap positions to accomplish the procedure.

As the CCM architecture allows each individual drill bit to store a core sample, the total number of carousel sites required equates to the number of drill bits plus the number of caching lids, ensuring a minimised carousel volume and mass. Planetary sampling missions are often limited by scientific requirements which insist on a reduction in stratigraphic mixing during sample acquisition and a need to avoid cross contamination between samples (Mustard 2013). As the CCM consistently maintains a drill bit within the borehole, there is little risk of borehole disruption and the subsequent introduction of surface contaminants.

While the CCM reduces operational complexity through a reliance upon a single cutting bit in order to accomplish its drilling objectives, there exists the possibility that a gradual dulling of the cutting teeth may reduce the efficiency of drilling operations at greater borehole depths. Although uncertainty in the tooth wear existed during the trade-off study, it was decided that the benefits conferred by the CCM by means of a reduction in the number of operational steps led to its selection for use in the UPCD system.

Although the ConOps architectures studied allow simultaneous anticlockwise rotation and axial translation due to the tendency of L-shaped female grooves to disconnect under such motion, the replacement of L-shaped grooves with T-shaped grooves throughout would allow complete flexibility in translation and rotation at a cost of operational complexity, requiring an extra clamping operation at each connection stage. It is of note that, in order to break and retain core sections in each ConOps scenario, core breaking/catching devices would be inserted into each bit. These devices, commonly used in geological sampling, act to break core samples in tension and retain the core via a flexural grip.

5.0 Transmission of Percussion

In the context of percussive drilling, whereby the repeated hammering of the drill bit generates a stress wave in a drill bit which causes rock fracture through various mechanisms, there are intrinsic sources of inefficiency which cannot be avoided and are a by-product of the technique. In fact, energy which is lost to the generation of heat and in drill bit rebound far exceeds that which is spent on the breaking of the terrain (Szwarc 2013). Thus, it is essential that an attempt is made to minimise any losses which may occur between interfaces in the multi-bit drill string assembly. Insufficient structural rigidity in the string could lead to rattle and the poor transference of the percussion wave across the bit to bit boundary, limiting the effectiveness of the drill system in penetrating stronger terrain. In order to achieve a high quality mating interface, attention was paid to the fit between the male and female parts, aiming to maximise the rigidity of the string while ensuring that the drill bits could be robotically disassembled with ease when required. This was further complicated by the implementation of electric discharge machining (EDM) in the production of the connection interfaces. EDM, or spark erosion, can attain high tolerances, though each application must be assessed on a case by case basis. Close attention to quality control and standardisation was essential in ensuring a high level of repeatability between drill bits and resulted in the production of bits which show little sign of energy loss when stacked in a formation of three or more bits. Furthermore, small ball detent features were installed into each drill bit in order to provide a small locking force and reduce rattle when the string is not under compression (when not drilling).

Figure 5 (Timoney et. al 2016) details the results of a series of tests designed to experimentally characterise and percussive losses due to the use of a bayonet connection system. The figure shows a comparison between the performance of a rigid, single bit and a bayonet-connected bit combination when penetrating three different sandstone variants using three different ultrasonic power levels. The results suggest that there is little percussive attenuation caused by the use of multiple bits connected through the use of a bayonet connection, providing confidence in the technology developed.

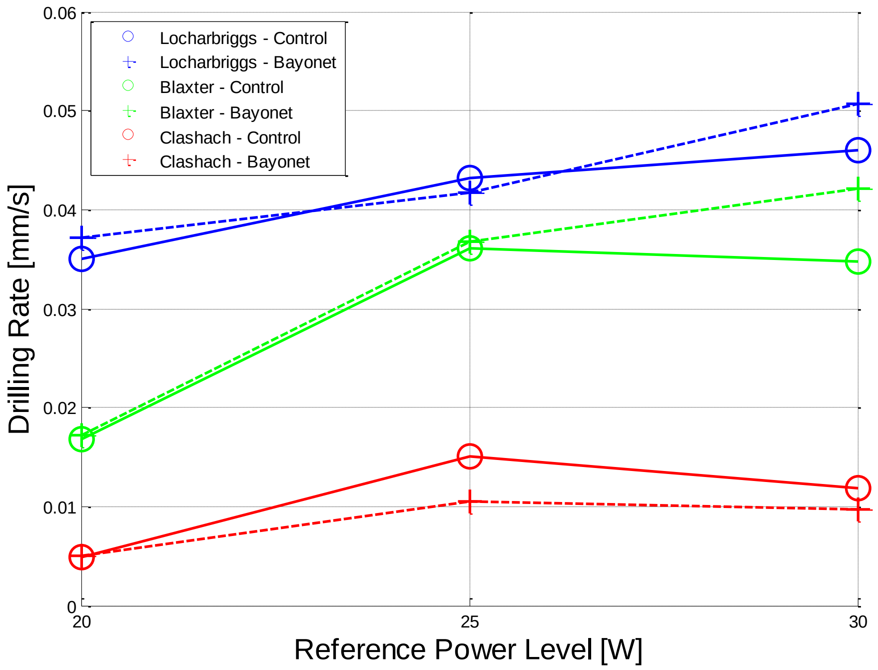

Figure 5: Experimental comparison of a single bit (control) and a drill string consisting of two bits connected together through a simple bayonet connection. Results suggest little attenuation of the percussive output through the use of the bayoneted bits. Image courtesy (Timoney et. al 2016)

6.0 Results from Field Testing

The UPCD system was tested in Coal Nunatak, Antarctica (73° S), a flat-topped rocky outcrop located on Alexander Island in the Antarctic Peninsula, during the summer season 2016 (Figure 6). This opportunity allowed the full UPCD architecture to be tested in an analogous polar environment and exposed the system to real-world situations.

Figure 7 details the position of the Deployer Module, the belt-driven z-axis translation stage used to progress the drill in to the terrain, against time. This figure shows that the drill is capable of completing an entire drilling operation which includes a drill string assembly, disassembly and bit caching in less than four hours, a realistic timeframe for planetary missions seeking to utilise multi-bit drill strings.

Note, Figure 7 commences with a single drill bit at its maximum drilling depth in the terrain with the system ready to collect the second bit for attachment to the string. An operational breakdown of the figure is as follows:

1) Collect Bit 2
2) Attach Bit 2 to Bit 1
3) Drill to 20 cm depth with newly formed drill string
4) Collect Bit 3 (Failed at first attempt)
5) Collect Bit 3 (Failed at second attempt)
6) Collect Bit 3
7) Attach Bit 3 to Bit 2
8) Drill to 30 cm depth with drill string consisting of three bits
9) Collect Lid 3
10) Attach Lid 3 to Bit 3
11) Cache capped Bit 3 into Silo 3
12) Collect Lid 2
13) Attached Lid 2 to Bit 2
14) Cache capped Bit 2 into Silo 2
15) Collect Lid 1
16) Attach Lid 1 to Bit 1
17) Cache capped Bit 1 into Silo 1
18) Return to Home Position

This drill run clearly shows that the Continuous Core Method of assembling, disassembling and caching drill bits can be implemented within planetary core drilling architectures and is capable of operating in analogous conditions. Furthermore, the recovery of the system from a fault state (points 4 and 5) proves the robustness of the system in overcoming difficult, off-nominal scenarios.

Figure 6: UPCD operating in icy terrain at Coal Nunatak, Antarctica.

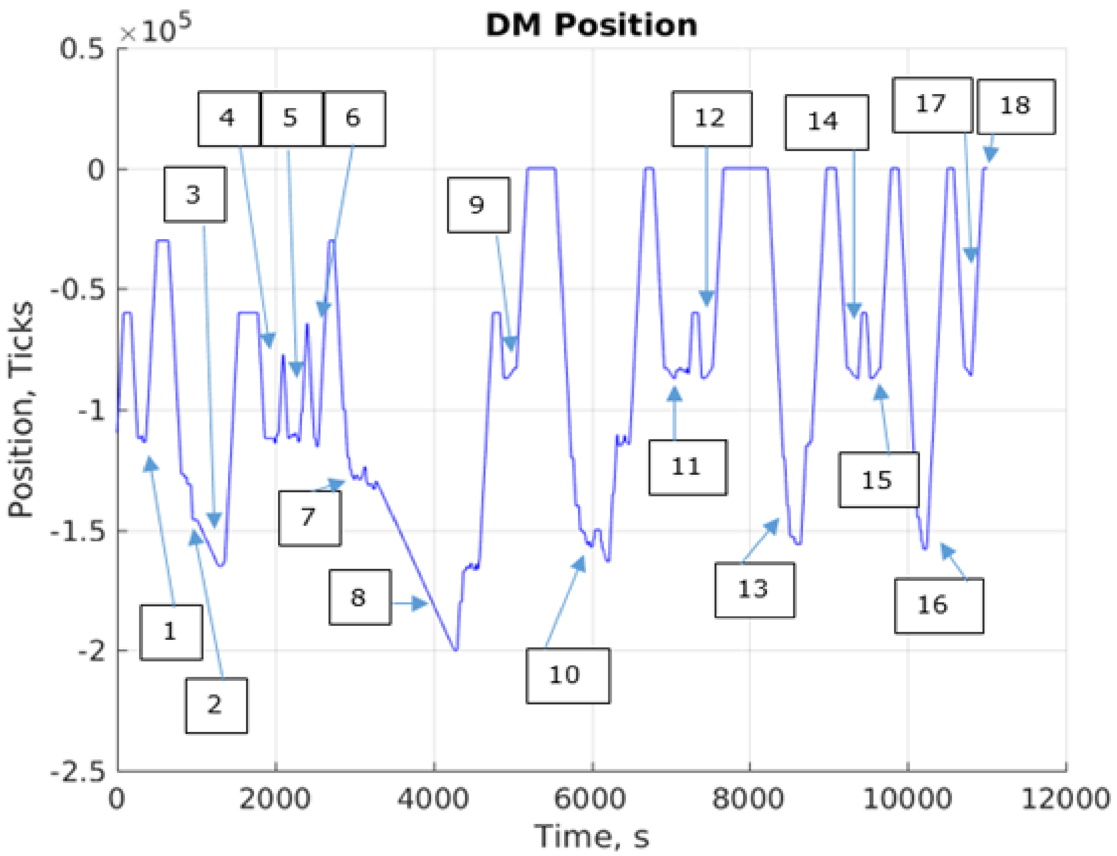

Figure 7: Complete UPCD run detailing the position of the Deployer Module against time.

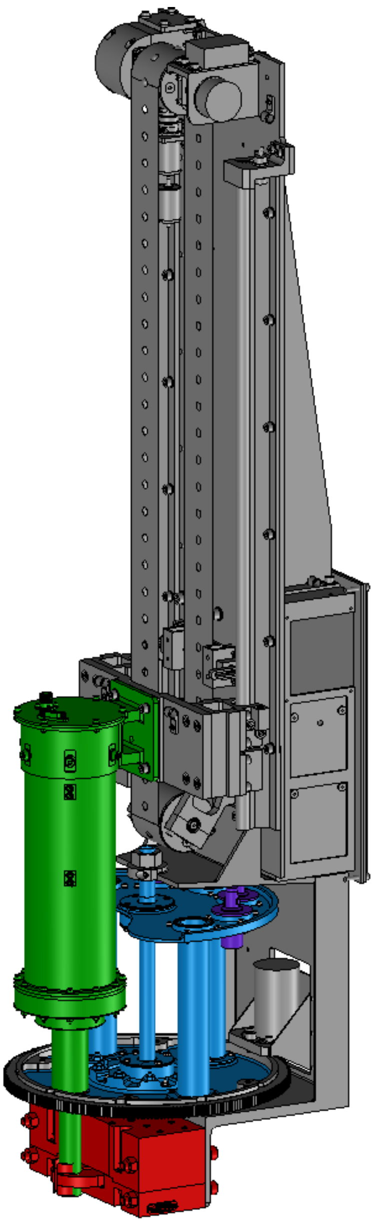

Figure 8: UPCD Complete Assembly colour coded to match ConOps Diagrams

Unfortunately, overly high temperatures at the field site meant that the active layer, the layer of unfrozen material above the permafrost layer, extended to a substantial depth such that obtaining still-frozen permafrost cores proved impossible. This can be attributed to the clay-like terrain proving exceptionally difficult to penetrate and auger using the drill bit geometry available. However, drilling within the ice pack proved more successful. Multiple complete drilling runs in the ice (as detailed in Figure 7) were accomplished.

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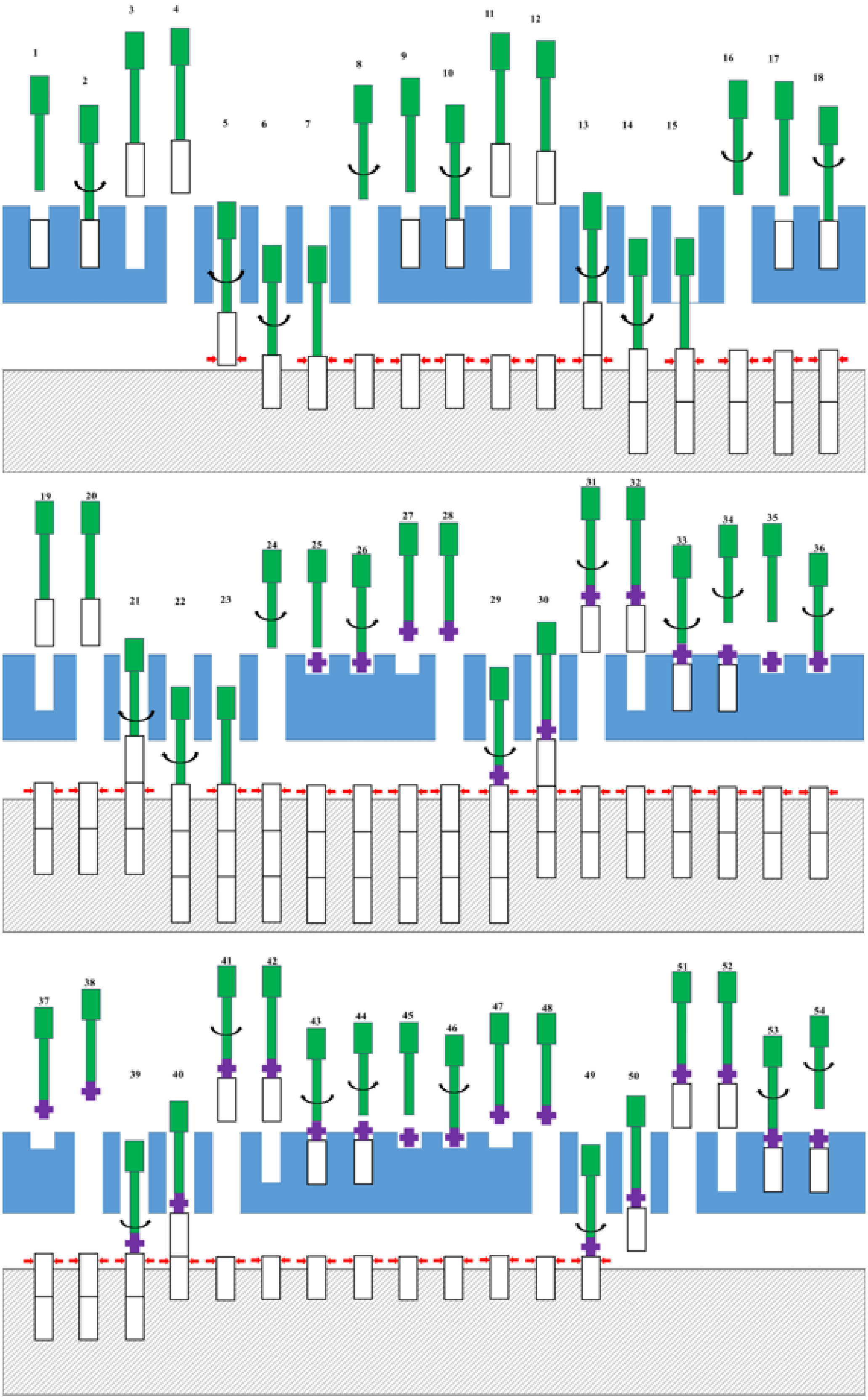

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Figure 9: Continuous Core Method ConOps

7.0 Conclusions

The task of robotically assembling drill string, made up of multiple, individual drill bit elements, is one which has not yet been attempted on another world. It is of no surprise that missions which seek to utilise such a capability will have to overcome the many technical challenges, and the associated risks involved in such an endeavour. In order to alleviate some of these difficulties, the UPCD project has developed a robust alternative to the conventional threaded connection interface which allows the tasks of assembling, drilling and disassembling using multiple bits to be accomplished with more certainty and using less mechanically intensive elements in the process. Furthermore, the bayonet-based system allows more flexibility through its ability to rotate in both clockwise and anti-clockwise directions while translating axially; an essential requirement in order to remedy typical fault states which may occur during drilling operations.

8.0 Acknowledgements

The Ultrasonic Planetary Core Drill consortium would like to acknowledge both the financial support provided under the European Commission Framework 7 scheme and also the invaluable feedback provided at reviews.

9.0 Data Availability Statement

All data, models, and code generated or used during the study appear in the submitted article.

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