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EVOLUTION OF A NEW PLANETARY DRILL DESIGN USING BIOINSPIRED DUAL RECIPROCATING DRILLING TECHNIQUE

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As we explore our solar system and other bodies, access to the subsurface plays a vital role. It allows us to peer back into the history of that body, looking for life or signs that it may have been habitable. In order to gain access to this buried treasure a form of drill or penetrator is required. In a microgravity environment this presents a number of engineering issues that the technology proposed in this paper can assist with. Dual-Reciprocating-Drilling (DRD) is a new biologically inspired technology based on the drilling concept of the Wood Wasp Ovipositor which can burrow deep into wood in order to lay eggs. The DRD is a scalable system consisting of two backward facing teethed halves that reciprocate in opposition to one another in order to generate a drilling force that reduces the overall force required to achieve penetration. From the results of previous experimentation the DRD system developed here at the Surrey Space Centre (SSC) is evolving to include the drive mechanism within the head of the drill, as well as including bays for scientific instrumentation that can be delivered below the surface.

I. INTRODUCTION

In order to explore extraterrestrial bodies gaining access to the subsurface is required as it allows the history of the body to be revealed, exploration of the bodies composition and the search for the markers of life to be realised [1]. This is particularly notable in the search for life on Mars, as the harsh conditions makes the search for signs of life focus on traces that may exist below the surface. In order to gain access to the subsurface a form of drill or penetrator is required.

Traditional drilling solutions such as rotary drilling require that an overhead force is applied that pushes the drill down into the subsurface [2]. In planetary drilling this is achieved by using larger masses to effectively increase the weight on bit, or anchoring the drill as in the MSL [3]; however these are not desirable attributes for extraterrestrial exploration where one of the main drivers is low mass. The microgravity environment also reduces the available forces that can be generated on the drill even further.

In a bid to improve the efficiency of extraterrestrial drilling, the exploration of a biologically inspired solution based on the Ovipositor of the Wood Wasp has shown promising results in chalk type substrates [4]. The Ovipositor of the Wood Wasp has evolved a mechanism that significantly reduces the reactionary force of the substrate by reciprocating a pair of teethed elements in opposition to one another [5, 6]. It is this principle that is termed Dual Reciprocating Drilling (DRD).

Penetration with the principles of DRD uses two halves that are reciprocated with opposing linear motions. In the case of the Surrey Space Centre (SSC) DRD two halves of the head and tip of the system are reciprocated.

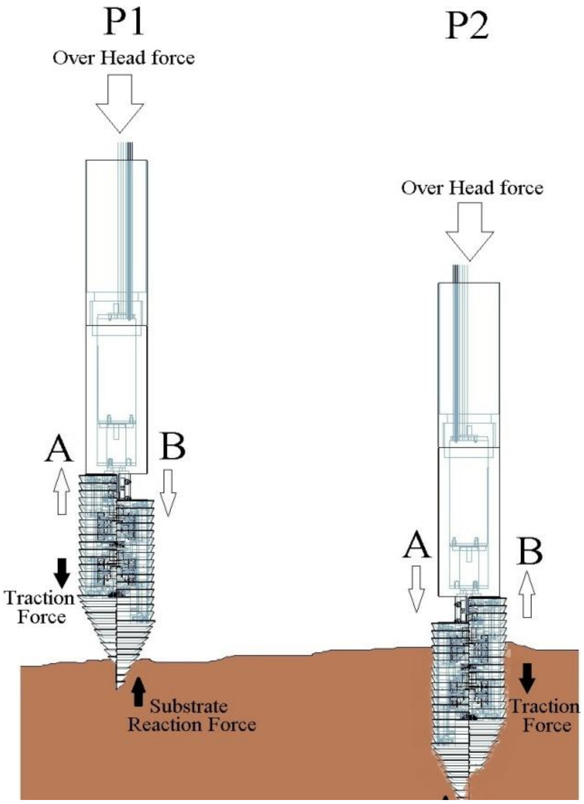

Fig. 1: Diagrammatic representation of the DRD action for two phases.

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Fig. 1 shows the two different phases of the DRD action (P1 and P2). During P1 drill head A retracts away from the regolith while head B drives down into the regolith displacing the material around its teethed area. Once B is fully extended the cycle moves into P2 with B retracting away from the regolith and A extending down. The Wood Wasp reduces the *Substrate Reaction Forces* by generating a *Traction Force* on the opposing drill head that is of the same order of magnitude. This then allows the *Over Head Force* to be removed and the drill gains traction into the substrate through the reciprocating motion.

However the experimental work undertaken showed that in regoliths this is not the case, as the *traction forces* generated are an order of magnitude lower than the forces required to overcome the *Substrate Reaction Forces* due to the high amounts slippage when drilling into regoliths (in the order of 95% in the case of the SSC-2 simulant given in Table 1 [7, 8]). This means that unlike in the Wood Wasp's case, most of the traction force generated by the opposing drill head is used to move the regolith upwards, rather than forcing the other drill head down further.

II. EVOLUTION OF THE SURREY SPACE CENTRE DRD

The Surrey Space Centre (SSC) Dual Reciprocating Drill is a biologically inspired system that is evolving to provide a low mass high efficiency penetration technology that reduces the overhead force, (commonly referred to as the Weight on Bit), required to gain penetration into planetary regolith for exploration and in-situ experimentation. This section discusses the design flow and considerations that were made in order to arrive at the solution currently under fabrication.

DRD Architecture

The reciprocating motion of the DRD can be achieved using two differing architectures, namely surfaced based and internal to the drill head based. A case can be made for both such architectures:

- *Surface Based Actuation* - This implementation would use an articulated drill string (term borrowed from classical drilling techniques), that is the length of the depth to be drilled. This architecture would require that the linear reciprocating motion be transferred through this drill string to the drill head that is then actuated. Experimentation that considers the amount of force that each drill head requires in order to achieve penetration suggests that this could be in the order of 300 to 500 N (depending upon drill profile desired and material in which the drill is operating). This force could result in buckling and deformation of the drill string, leading to reduce efficiency or even jamming. In order to mitigate this it is foreseen that the size of the drill string would be sizeable, leading to an increase in the overall mass of the system which is one of the advantages that the DRD technique aims to reduce. The advantage of this type of architecture however is that a larger space is available (when compared to the special envelope available within the drill head), in which to fit the actuation mechanisms to achieve the reciprocating motion. Also, since some form of drill string is required to transfer the overhead force to the DRD this would also need to be incorporated making this mechanism very complex with two components of force having to be transferred through a single drill string.

- *Internal Actuation* – If the actuation mechanism were to be placed inside the drill heads of the DRD then there would be no need for a complex articulated drill string to transfer the required reciprocating motion and force to the drill heads. This would mean that a simpler drill string would only be required to transfer a single component of force, (the overhead force), down to the DRD penetrator. The space available for implementation of this type of architecture is significantly lower than that available for the surface based alternative.

When considering both of these options it was decided that the internal actuation option would be most applicable to this drilling technology as it fits the ethos of DRD and could allow it to be more compatible with a range of platforms.

Unlike previous iterations of the test bench used to demonstrate the concepts of this drilling technique [7, 8], the drill heads will be hollow to allow the reciprocating drive source to fit inside. Therefore technologies that would be appropriate to this application were considered.

DRD Mechanism Design Trade-off

Before undertaking the design and development of the internal actuation of the DRD motion a number of considerations were made with regards to the drive source that could be integrated into the drill heads. A number of concepts were explored before settling on five to be explored and then used in a two phase trade off exercise.

These design concepts are intended address and include elements shown in the schematic of Fig. 2.

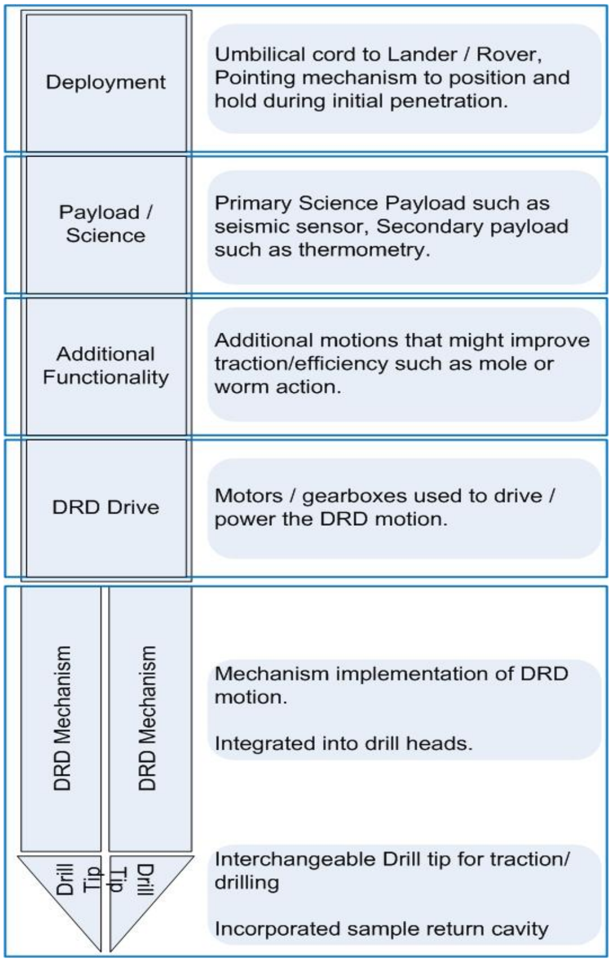

Fig. 2: Schematic showing the DRD penetrator with integrated drive mechanism.

The five concepts can be described as:

- *DRD_{001}* – This achieved linear actuation through commercially available off the shelf (COTS) piezoelectric linear actuators.

- *DRD_{002}* – Simple cam and gearing driven by a conventional motor source. Two cams drive the rear end of the drill heads.

- *DRD_{003}* – A bespoke electromagnetic drive was to be developed in conjunction with permanent magnets to achieve the linear motion.

- *DRD_{004}* – Simple quad cam drive that distributes the linear motion along the whole length of the drill shaft by driving four cam modules.

- *DRD_{005}* – Individual mole style drives were to be implemented in each drill half that using a combination of springs and masses with a rotating keyed shaft that controls the motion of the mass along a linear motion.

In order to begin the trade off some limits need to be defined. The test bench of [7, 8] had a drill head outer diameter of approximately 35 mm (to the extent of the teeth). Since we have a good understanding of the performance of this diameter DRD system it was desirable to limit the diameter of the new integrated system to around 40 mm. The length in some respects showed little influence on the performance of the DRD system; however for the development of the new system this was limited to 300 mm from drill trip to end of the chassis. Any umbilical elements are not considered at this stage.

The force that each reciprocating actuator will need to produce is in the range of 300 to 500 N. These are extrapolated from experimental observations and results in order to allow the DRD to operate at greater depths than previously studied. This force is not to be confused with the overhead force, which acts on the back of the entire DRD penetrator.

The strategy used to undertake the trade off uses a scoring system defined by Equation (1).

$$Rank_{xxx} = [IR_{01} * PC_{01}] \\ + [IR_{02} * PC_{02}] \ldots [IR_{xx} * PC_{xx}] \tag{1}$$

Where IR_{xx} is the importance rating of that Performance Criteria (PC_{xx}) and $Rank_{xxx}$ is the ranking of that concept ($_{xxx}$ denotes the concept identity).

This equation (1) allows us to set importance ratings (IR_{xx}), to each element of performance criteria (PC_{xx}). This allows the identification and representation of critical parameters to become more dominant in the trade off. The resultant score ($Rank_{xxx}$) represents the ability of the concept to satisfy our requirements. The concept with the highest overall value for $Rank_{xxx}$ represents the best match to the design requirements. In this instance the performance criteria are summarised below along with the importance rating for that particular criteria.

- *Mechanism Density (PC_{01})* – Describes the physical size of the mechanism, density of components and weight. For this project small size is desirable, therefore 1 is smallest size and -1 is largest. The importance of this criterion is very high and represented by a value of 0.8.

- *Power to Force Ratio (PC_{02})* – Describes the amount of force generated for a given amount of power consumed. -1 represents a design that takes a lot of power to produce a low drilling force, 1 represents a design using little power to produce a big drilling force. The importance of this criterion is paramount to the design choice and represented by a maximum value of 1.

- *Force to Drill Area* (PC_{03}) – As the force increases the size of the drill increases to accommodate bigger motors etc. Typically the bigger the drill head the more force is required therefore bigger drive mechanics. 1 is high force to small surface area, -1 is lower force to surface larger area. The importance of this criterion is very high and represented by a value of 0.8.

- *DRD Amplitude* (PC_{04}) – Describes the linear movement range of the DRD head due to the mechanism. 1 is a large movement range, -1 is low range. The importance of this criterion is relatively low as the range of movement is currently at 1.5 to 3 mm in the test bench. This is represented by a value of 0.2, as the amplitude of the reciprocating motion needs further investigation.

	Design Concepts				
Performance Criteria	DRD_{001}	DRD_{002}	DRD_{003}	DRD_{004}	DRD_{005}
PC_{01}	0.4	0.2	0.3	0.2	0.3
PC_{02}	0.2	0.2	-0.3	0.2	0.2
PC_{03}	-0.2	0.1	0.3	0.2	0.1
PC_{04}	0.3	0.3	-0.4	0.3	0.1
Rank	0.42	0.5	0.1	0.58	0.54

Table 1: Trade off table used in phase one using Eq. 1.

The values for each performance criteria (PC_{xx}) were estimated to give a representative expected outcome as a result of implementation of each concept (DRD_{xxx}). As an example, from Table 1 it can be seen that the concept DRD_{003} is expected to perform very badly under PC_{04} when compared to the others. This is because in order to achieve the force range (a higher importance than the amplitude), from the electromagnetic actuator the displacement range will suffer. This leads to a reduced amplitude range that can be generated from the electromagnetic actuator that fits into the spatial envelope of the DRD prototype, therefore since this amplitude is expected to be lower than the desired range it is represented by -0.4 in the trade off matrix. Conversely, the amplitude produced by the DRD_{004} concept is expected to achieve the amplitude range desired, and is represented by 0.3.

For this initial phase of the trade off study the DRD_{004} concept scored highest suggesting that this concept would best meet the requirements of this phase. A second round was then undertaken with the emphasis placed on different elements and initial computer aided design (CAD) work and modelling performed. This trade off resulted in the DRD_{004} concept being selected to take to the prototype stage.

Development of the integrated DRD drive

The design concept from the previous section (DRD_{004}) consists of four main elements.

- *Drive Source (A)* – In this particular iteration the drive source consists of a DC brushless motor that generates a torque of around 56 mNm, coupled to a gearbox that increases this torque to 3 Nm at the output. This is then coupled to a drive shaft and a pair of transfer gearboxes that, together with the drive rail coupling elements, allow a force of approximately 450 N to be generated on the teeth structure. This force can be adjusted together with the amplitude which is controlled through the position of drive pins and a scalable drive shaft.

- *Drive Rail Coupling (B)* – In order to facilitate the linear reciprocating motion while eliminating radial and other motions a form of linear rail is needed. This takes a similar form to that of the Wood Wasp, which has sections lots of sections of rails that interlock and allow the drill heads to slide under the influence of the drive source.

- *Teeth Structure (C)* – A critical element of this new type of drilling technology, the two teethed elements have been developed to form a sheath allowing the geometry to be changed without effecting the internal mechanism to which they mount. Together with the drive source two of the main parameters of DRD that influence the performance of the drill in different materials can be adjusted to alter performance.

- *Sealing/Isolation (D)* – In order to reduce contamination of fine regolith particles entering into the drive mechanism a number of sealing solutions are being explored. Current work is seeing the implementation of industrial felt gaskets that are traditionally found as bearing seals on rotating shafts that require a good boundary without introducing significant friction to the system [3].

In keeping with the schematic of Fig. 2 a number of payload bays have been incorporated that can contain scientific instrumentation such as micro seismometers [9] for in-situ experimentation. Each bay has a volume of approximately 10500 mm^3 with power and connections provided through the main umbilical cord, and connections incorporated into the chassis of each bay.

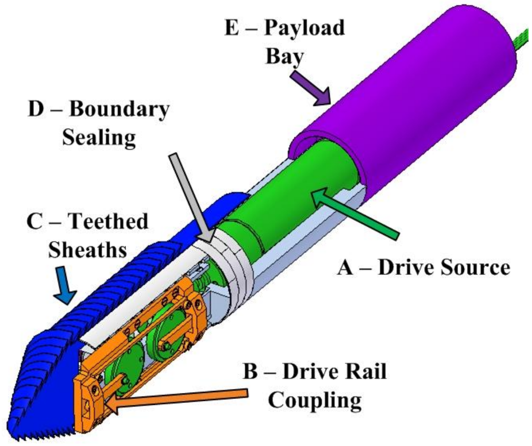

Fig. 3: Model of the DRD004 prototype under construction with main elements labelled.

One of the advantages of a penetrator utilising the DRD technique is that the levels of shock that instrumentation is exposed to, is reduced when compared to other similar drills and probes.

DRD Deployment Mechanism Trade off

In order for the DRD technique to be effective an overhead force needs to be present on the drill and acting in the direction of drilling. This works in the same way as the weight on bit in conventional rotary drilling systems, and is of the order of 25 to 50 N when drilling through the SSC-2 simulant material that is prepared through a systematic pouring procedure to try and ensure a repeatable density profile for each experiment [10]. In order to provide the required over head force a form of drill string needs to be implemented that will not buckle when transmitting the force to the drill. Ideally this would consist of one solid piece of material in order to minimise this buckling, however this is not a practical solution. We are therefore developing a solution that takes inspiration from deployable structures. Two such systems are under development, namely a Bi-stable composite solution and an interlocking tracked solution.

Bi-stable Composite Deployment Mechanism

The use of bi-stable composites is emerging as an elegant solution to deployable space structures [11]. An actuator based around the bi-stable composite material would allow the drill string to be stored flat and coiled, and then deployed to form a rigid hollow tube through which the over head force is transmitted. The system under investigation is shown in Fig. 4.

Fig. 4: DRD deployment mechanism utilising a bi-stable composite developed by Rolatube™.

This method for transmitting the overhead force down to the drill head uses a force generated by the natural uncoiling of the bi-stable composite material that is wrapped around a spool that is driven by a motor in order to generate a coiling/uncoiling force that determines the magnitude of the overhead force applied to the DRD drill. The bi-stable composite solution under development in Fig. 4 uses a carbon fibre based composite that is capable of withstanding a 500 N overhead force before buckling. The whole deployment mechanism weighs approximately 4 kg, and can reach a depth of 4 m. The inner diameter of the deployed tube is 34 mm and allows the borehole to be stabilised providing access to the subsurface. It also allows the development of instrumentation to be incorporated into the walls of the tube for additional experimentation over a range of depths as the DRD probe advances.

Interlocking Track Mechanism

The second solution developed provides the OHF using a rigid belt (Rigibelt™) solution developed by Serapid. This consists of two separate teethed belts that when locked together form a rigid shaft.

When the two belts are formed together into one they form a semi solid shaft that can withstand a greater deformation force due to the walls of the borehole when compared to the bi-stable composite solution. This mechanism has an expected mass of approximately 10 kg. The overhead force of this mechanism is delivered through drive wheels that push each half of the belt together and down onto the rear of the drill.

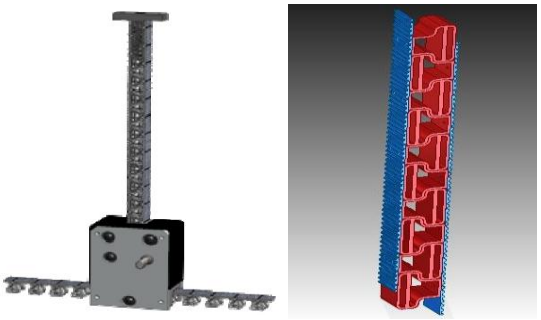

Fig. 5: Interlocking track based deployment mechanism utilising the Serapid™ technology.

A trade off between these two concepts was undertaken in a similar fashion to Table 1. In order to compare these mechanisms the following performance criteria were applied.

- *Deployment Mechanism Size (PC_{01})* – Represents the physical size of the deployment mechanism, density of components and weight. For this project small size is desirable, therefore 1 is smallest size and -1 is largest. The importance of this criterion is very high and represented by a value of 0.6.

- *Power to Overhead Force Ratio (PC_{02})* – Represents the amount of force generated for a given amount of power consumed. -1 represents a design that takes a lot of power to produce a low overhead force (< 300 N) through the drill string, 1 represents a design using little power to produce a large force (> 500 N). The importance of this criterion is very high and represented by a value of 0.8.

- *Complexity (PC_{03})* – Describes the complexity of the deployment mechanism in terms of number of components, control required and intricacy of implementation. 1 represents a low complexity and ease of implementation, -1 is a high complexity and difficulty in implementation. The importance of this criterion is paramount to the design choice and represented by a maximum value of 1.

- *Robustness (PC_{04})* – Describes the anticipated robustness of the deployment mechanism. 1 represents a robust design that is considered reasonably resistant to issues such as contamination from regolith and -1 represents a poor robustness. The importance of this criterion is considered paramount to the system and represented by a value of 1.

	Design Concepts	
Performance Criteria	*Bi-stable Composite*	*Interlocking Tracks*
PC_{01}	0.8	0.2
PC_{02}	0.4	0.8
PC_{03}	0.8	0.2
PC_{04}	0.8	0.1
Rank	2.4	1.06

Table 2: Design Trade off table for deployment mechanism concepts.

From Table 2 the bi-stable composite design concept was selected to proceed with. One of the main reasons was the simplicity of the design compared with the other. It was also envisaged that contamination of the teethed elements with regolith could be detrimental to the operation.

DEMONSTRATION OF THE DRD

The DRD test bench was developed to allow the evaluation of the DRD technique under a range of overhead forces, reciprocation amplitudes and frequencies. In its current configuration the simulant is contained in a drum with a diameter of approximately 1 m, and allows the drill to reach depths of up to 800 mm. The image in Fig. 6 shows the latest iteration of the DRD test bench that uses a surface based actuation mechanism to drive the reciprocating motion of the drill heads. This drill string allows DRD to be evaluated at a depths of up to 600 mm.

The DRD probe shown in Fig. 6 uses an industrial felt gasket to reduce contamination of the interlocking mechanism that keeps the drill heads together. It was found that this solution eliminated jamming that was experienced in earlier iterations of the test rig, and especially prevalent at depths greater than 250 mm. The same gasket was used in 80 drilling operations before it was replaced. On inspection the gasket was worn on the interfaces with the drill heads and the simulant had penetrated 2.5 mm into the edges of the felt. The inner surfaces of the drill heads were also noticeably shinier than before where the penetrated felt was, indicating that they could be polishing the surfaces. This could also explain the small improvement in power consumption after a number of runs when compared to initial operation.

The most influential parameters of DRD were found to be the overhead force acting on the drill heads (Fig. 7) and the amplitude of reciprocation (Fig. 8).

These tests were all undertaken using the simulant SSC-2 that was prepared using a poured technique from an average height of 40 mm from the surface of the simulant. Details of the simulant used can be found in [10]. This was repeated until a depth of 600 mm was attained.

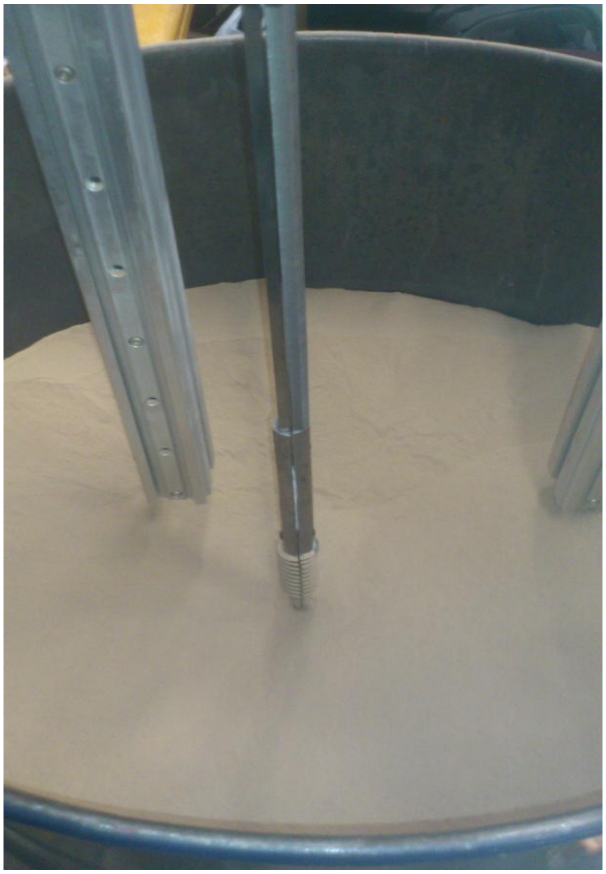

Fig. 6: Current iteration of the DRD test bench.

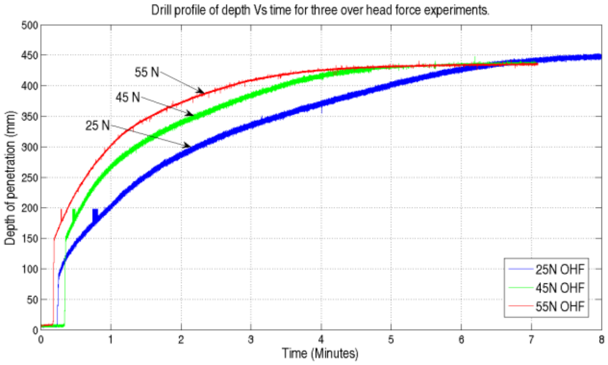

Fig. 7: Drill profile showing the effect of overhead force.

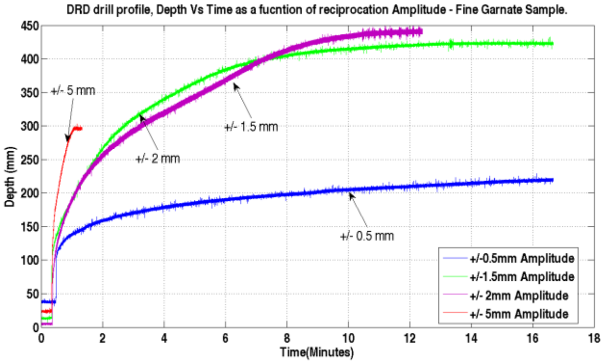

Fig. 8: Drill profile showing the effect of DRD reciprocating amplitude.

It can be seen from the drill profiles that the biggest affect of these two DRD parameters have, is on the rate of penetration and final depth. This is especially apparent in Fig. 8 where the final depths achieved range from 220 mm to 448 mm. In Fig. 7 the overhead force reduces the time taken to achieve the final depth but does not visibly increase the final depths achieved. The reasoning for this *stalling* of the drill is expected to be due to the high levels of slippage experienced and high compaction of the simulant at depths approaching 400 mm. A density profile of this test bench is the subject of current investigations in order to test this prediction.

CONCLUSIONS

The current status of the SSC DRD has been presented along with some of the future elements that are under consideration, such as the deployment and overhead force mechanism. New drill profiles indicate that for low overhead forces in the order of 25 N depths of 450 mm can currently be achieved. This shows that the DRD action introduces a gain of up to 500% compared to the static penetration depth achieved during the beginning of each test. The DRD technology is still in its infancy but is now moving from a proof of concept test bench towards a system level prototype. In order to address the potential limitations of the technology at compaction densities experienced at depths of over 400 mm an ultrasonic action is being incorporated into the individual drill heads. It is envisaged that this will improve the differential between the traction force and substrate reaction force, further improving the performance and final depths achieved.

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