EVOLUTION OF AN INTEGRATED ACTUATION MECHANISM FOR PLANETARY EXPLORATION USING DUAL-RECIPROCATING DRILLING

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ABSTRACT

Accessing the subsurface of extraterrestrial bodies using drilling techniques plays a vital role in the search for life and understanding the history of the solar system. The Dual-Reciprocating Drill (DRD) is a biologically-inspired technology based on the drilling concept of the Wood Wasp Ovipositor. By using two backwards-facing teethed halves that reciprocate in opposition to one another to grip the surrounding substrate, it is able to generate a traction force that reduces the overhead force required to achieve penetration.

Previous experimentation of the DRD using a proof of concept test bench has shown that lateral forces created by sideways movements significantly contributes to drilling performance. The system is also evolving to include an actuation mechanism integrated into the drill heads. A new integrated design is being developed which will actively generate simultaneous reciprocating and lateral motion of the drill, allowing the investigation of the benefits of lateral forces and the testing of two new burrowing mechanisms.

1. INTRODUCTION

Subsurface exploration plays a critical role in the search for the markers of life and furthering our understanding of the solar system by obtaining data that can only be found below the surface. Examples include the search for biomarkers on Mars, found below a 2m sterile surface layer of decayed organic molecules [1], and the search for hydrogen-rich volatiles such as water-ice in the lunar south pole region, which is likely to exist below a dry layer 60cm deep [2].

Past planetary drilling missions, such as Apollo, and those currently in development, including ExoMars [3] and InSight [4], use the traditional rotary or rotary-percussive drilling techniques. However, rotary drills require a large overhead force, achieved by using a large mass to increase the weight on bit, while the combined rotary-percussive drills are heavy, power-hungry and complex. This is exacerbated by the microgravity environment reducing the force that can be generated on the drill bit. As the mass constraints on a spacecraft are extremely stringent, low-mass solutions are being investigated. Ultrasonic percussive drills are able to penetrate hard rocks to shallow depths [5], while self-penetration percussive moles such as that used on the Beagle 2 lander are effective at penetrating regolith [6].

In an attempt to improve the efficiency of extraterrestrial drilling, a biomimetic solution inspired by the ovipositor of the *sirex noctilio*, or wood wasp, has been proposed. The ovipositor reciprocates two halves with backwards-facing teeth in opposition to one another to drill into wood in order to lay its eggs, a technique known as dual-reciprocating drilling (DRD). A traction force is generated in the receding half by the teeth, which engage with and grip the surrounding substrate and resist being pulled upwards. This is converted to an equal and opposite compressive force in the penetrating half, helping it to overcome the required penetration force and pushing it further into the substrate. The forces are generated within the two halves and as such no external forces are required [7], as shown in Fig. 1.

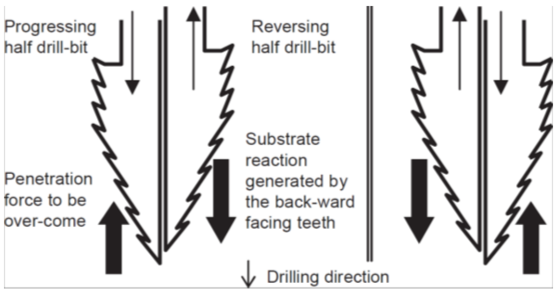

Figure 1. Diagram of the DRD mechanism [8]

A proof of concept test bench built by the Surrey Space Centre (SSC) has shown the potential of DRD in regolith and low strength rocks [7]. However, the current design has exhibited high levels of slippage (>95%) when drilling into regoliths, caused by the receding drill half's teeth not gripping the substrate and consequently moving back upwards [8]. This results in traction forces generated that are one to two orders of magnitude lower than the penetration force. The progression of the DRD can instead be explained by lateral forces caused by the presence of sideways movements of the drill heads, which are calculated to be at least 0.1 times the penetration force, and as such have a significant role in drilling performance [9].

The design of the DRD is now progressing from a proof of concept to an integrated system prototype. A system architecture was created to utilise an internal actuation mechanism, using a simple quad cam drive rail to facilitate the reciprocating motion and a bi-stable composite deployment mechanism [10, 11]. The work presented here has resulted in the design of a fully functional internal actuation mechanism which enables simultaneous reciprocating and lateral motions of the drill head. The aim of this is to investigate how variations of these motions affect the traction and penetration forces acting on the drill heads.

2. PRESENCE OF LATERAL FORCES

Lateral movements of the drill heads were initially observed in the first experimentation of DRD in regolith, which demonstrated the DRD's ability to penetrate further than static penetration [8]. It was seen that slight lateral movements of the drill stem occurred, caused by the soil applying non-vertical forces due to the conical shape of the drill heads as they are pushed into the regolith, as shown in Fig. 2.

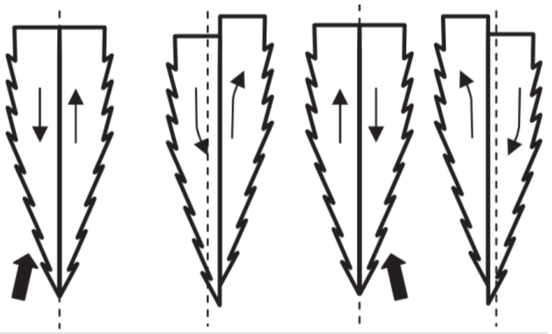

Figure 2. Lateral motion (thin arrows) caused by the force applied by the soil (thick arrows) to the asymetrical drill head [8]

The forces applied to the DRD were examined by a force sensor test bench. The motion of the DRD was replicated by reciprocating a single mono-block drill head (MDH) using a hydraulic ram. The penetration and traction forces were measured with a force sensor attached between the MDH and the hydraulic ram [9]. The two drill head designs can be seen in Fig. 3.

These experiments found that the traction force generated by the teeth of the MDH is one to two orders of magnitude lower than the penetration force. This explains the high levels of slippage observed, but does not account for the increased penetration depth that the DRD achieves. It was proposed that this difference was caused by the lateral movements observed in the DRD experiments being absent, due to the axial symmetry of the MDH. An analytical estimation calculated that the lateral force acting on the DRD drill heads is at least 0.1 times the penetration force. This confirmed that lateral forces play a much more significant role than traction forces in accounting for DRD performance [9].

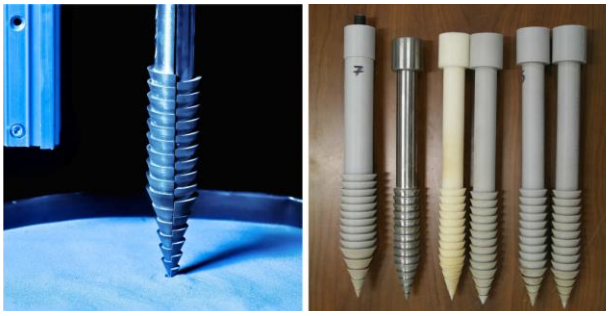

Figure 3. Pictures of the DRD (left) and the various mono-block drill heads (right) used in experiments detailed in [8] and [9] respectively

The most recent series of experiments investigated the effects of DRD bit design on performance, in particular the depth vs. time profile and maximum depth achieved. A modified version of the original proof of concept test bench was used to drill to depths of up to 800mm [10]. This required a 1m long drill stem which, due to its flexibility and the difficulties in judging a perfectly vertical entry angle, would often bend. Slight bending generally did not affect the results, however significant bending, such as that shown in Fig. 4, would lead to depth profiles entirely different to those of experiments in which the drill stem remained straight.

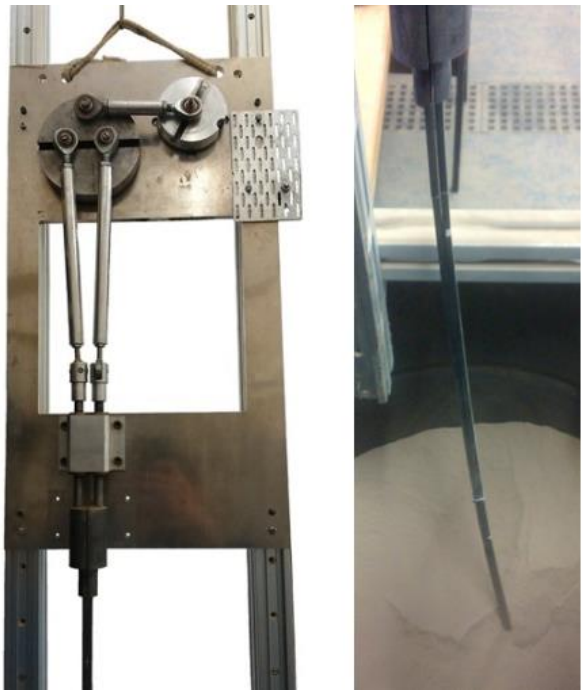

Figure 4. Pictures of the proof of concept test bench (left) and the bent drill stem after taking a curved trajectory whilst drilling (right)

It was consistently seen that the runs which experienced this bending would show a significant increase in their final depth reached and overall penetration speed. This can be seen in Fig. 5, where the penetration with the bent stem would continue well beyond the final depth reached by the straight stem. It is proposed that this increase in performance is due to the direction the regolith is compacted by the receding drill half. When drilling at an angle, the engaged regolith is pushed vertically into the sheared regolith directly above and horizontally into the surrounding regolith, of which there is a much larger volume. This results in a large horizontal resistive force acting alongside the vertical resistance. The engaged regolith thus experiences more resistance when being pushed upwards, generating a greater tensile force that allows the drill to penetrate further.

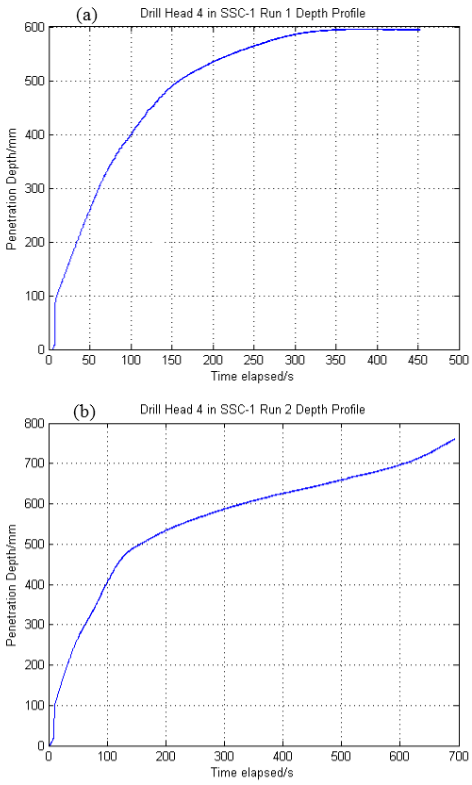

Figure 5. Depth profiles of a drill head with (a) a straight stem and (b) a bent stem

It is clear that lateral forces play a significant role in increasing the penetrating performance of the DRD. So far, the sideways movements have not been controlled, and their effects have been measured indirectly. It is proposed that a full investigation can be performed by developing a mechanism which enables control of the reciprocating and lateral motion of the drill heads.

3. INTERNAL ACTUATION MECHANISM

The DRD has begun evolving into a fully integrated system. A number of trade-off studies discussed in [11] concluded that an internal actuation mechanism should be used to create the reciprocating motion of the two drill heads. This mechanism would be a quad cam drive, which links the rotary motion of a conventional motor drive via a shaft and bevel gear transfer box to two cams per drill head. The cams are connected to a drive rail coupling, converting the rotary motion to linear and removing any other radial motions. The mechanism is contained within the hollow drill heads, as seen in Fig. 6, however no fully integrated system has yet been built. The DRD would be deployed by a bi-stable composite mechanism, which would also provide a constant overhead force.

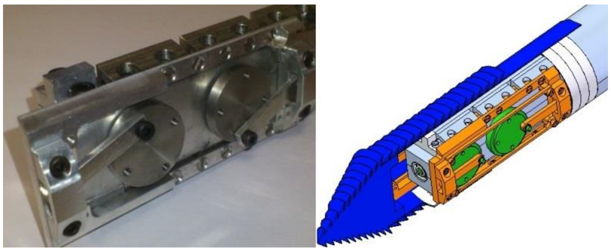

Figure 6. Prototype of the DRD cam and drive rail coupling mechanism and integrated system model [12]

3.1. Dual Mechanism Concept Trade-Off

To facilitate the need to further examine the benefits of lateral motion, and to continue the progression of the DRD system, a new internal actuation mechanism will be designed. This mechanism will be able to produce the reciprocating-only motion of the previous designs as well as simultaneous reciprocating and lateral motion. These motions will be referred to as single and double motion from this point. The mechanism will be inserted into two hollow drill heads and powered by a motor.

The mechanism must be able to switch between the two motions with minimal changes to the other components that make up the design. This requirement will keep the overall mass, force distribution and operational requirements as equal as possible. This will also allow comparisons of the performance of the single and double motions to be as accurate as possible.

The motion created by the mechanism must also be taken into account. Ideally the drill head will push horizontally outwards, then recede upwards, before pulling inwards and finally penetrating down. This will maximise the horizontal force, and by extension the overall tensile force, by pushing it into the surrounding regolith before retracting. It will also minimize the penetration force required by reducing the volume of regolith being penetrated by the drill heads.

To this end, a number of options based upon the original mechanism shown in Fig. 6 were explored, and five concept designs were created and subjected to a trade-off study. These concepts are:

1. 90 ° Cam and Gearing. Double motion is achieved by rotating the cams 90 ° around the motor shaft.

The cams are directly attached to a fixed drive rail in the drill heads, creating a circular motion.

2. Shaft Base Third Cam. Double motion is achieved by attaching another cam and drive rail perpendicular to the base of the motor shaft. This cam pushes out and pulls in the drill heads independently from the two reciprocating cams.

3. Tilted Cam. For double motion, the bevel gears are replaced with a series of angular gears, allowing diagonal linear motion of the cam and drive rail.

4. Tilted Cam with Linear Actuator. This uses a linear motor instead of the rotary motor used in the Tilted Cam. The cams are replaced by a series of shafts and gears which reciprocate the drive rail either vertically or diagonally.

5. Quadruple Cam. Similar to the Shaft Base Third Cam, this produces lateral motion alongside the reciprocation using two additional cams and drive rails positioned perpendicular to the original cams, both of which will push and pull the drill heads.

Each concept design was modelled in its simplest form to demonstrate the motion created by the selected mechanism. Based upon these models a trade-off strategy was used to determine the most suitable design, with a scoring system defined by Eq. 1:

$$Rank = \sum_{i=1}^{n} w_i x_i \qquad (1)$$

Each performance criterion, *i*, is given an importance rating, or weight, *w*, between 1 and 5, with the sum of the normalised weights being equal to 1. The concepts' ability to satisfy each criterion was estimated and given a rating value, *x*, between 0 and 10. Where necessary, the values are normalised. The concept with the highest score, *Rank*, is the one that shall be selected. The ratings and total scores of each concept are given in Table 1. The performance criteria are described below:

- Number of Parts. The total number of parts, excluding bolts, motors, etc., that make up the mechanism as shown by the concept design, and acts as a guide to the design's complexity. The normalised value is found by Eq. 2. Weight: 2.5.

$$x_i = 10\left(1 - \frac{Sum\ of\ concept\ i\ parts}{Sum\ of\ all\ concept\ parts}\right) \qquad (2)$$

- Ease of Implementation. This describes the intricacy required and the ease by which the mechanism can be assembled from the ground up and the ease by which the single or double motions can be modified. Weight: 3.

- Coupling of the Reciprocating and Lateral Motions. To maximise the range of motions the mechanism can produce, the reciprocating and lateral amplitudes must be able to be independently changed. Mechanisms allowing this are given a score of 3. If the amplitudes cannot be changed without altering the other, the motions are defined as coupled, and the mechanism is given a score of 2. If the amplitudes are coupled and dependent on multiple factors, the mechanism is given a score of 1. As this prototype will study the performance of different drilling motions, the range of motions available has the highest priority. Weight: 5.

- Ease of Changing Between Motions. This is determined by the changes required, in terms of additional parts, orientation of parts and the amount of disassembly required, to change from single to double motion, and vice versa. Weight: 2.

- Overall Drill Diameter. This is an estimate of the minimum inner diameter of the drill heads required to accommodate the mechanism. Weight: 3.

- Even Distribution of Force. To minimise the buckling effects and the friction on the mechanism-drill head connections, and maximise the overall efficiency of the mechanism, the reciprocating and lateral forces provided should be distributed throughout the drill heads as evenly and/or with as large a contact area as possible. Weight: 4.5.

Table 1. Performance criteria scores and rankings of the internal actuation mechanism concepts

Performance Criteria, *i*	Number of Parts		Ease of Implementation	Coupling of the Reciprocating and Lateral Motions		Ease of Changing Between Motions	Overall Drill Diameter	Even Distribution of Force	**Rank**
Concepts	Value	Normal		Value	Normal				
1	7	8.83	9	2	6.67	6	9	5	**7.20**
2	13	7.83	6	3	10	8	6	6	**7.43**
3	9	8.5	4	1	3.33	4	7	8	**5.75**
4	11	8.17	5	1	3.33	5	6	8	**5.80**
5	20	6.67	5	3	10	7	5	9	**7.56**
Weight	**2.5**		**3**	**5**		**2**	**3**	**4.5**	**Total**
Normalised Weight, *w*	**0.125**		**0.15**	**0.25**		**0.1**	**0.15**	**0.225**	**1**

From Table 1 it can be seen that the two Tilted Cam designs performed very poorly. This is largely due to the reciprocating and lateral amplitudes being coupled together and additionally being determined by the orientations of the cams and drive shafts. Fitting the mechanisms accurately at an angle was also considered to be a significant difficulty. The other three concepts were closely ranked. The 90° Cam and Gearing was considered to be one of the simplest designs, as only two cams would be required. However this had the disadvantage of coupling the motions, and providing a poor distribution of force. The Shaft Base Third Cam and Quadruple Cam designs were very similar, and both are able to allow independent variation of the reciprocating and lateral motions. Due to the Quadruple Cam's extra cam, it is a more complex design and so scored slightly lower in a number of categories. However the two extra cams are able to provide a much greater force distribution along the length and width of the drill head via multiple connection points, whereas the Shaft Base Third Cam only provides lateral force across a single point. As a result of the greater importance of force distribution, the Quadruple Cam achieved the highest ranking score and thus was selected as the concept that would be developed into a working prototype.

4. QUADRUPLE CAM DESIGN

The current iteration of the Quadruple Cam design, shown in Fig. 7, uses a number of systems utilised in the design shown in Fig. 6. The drill heads are actuated by a commercially available off-the-shelf DC motor. This drives a motor shaft along which two transfer boxes are attached. These consist of three bevel gears; one is fixed to the motor shaft, and the other two are positioned at 90° and connected to a cam wheel on opposing sides. The cams are each linked to a drive rail, with one pair from one transfer box driving the reciprocating motion and the other pair driving the vertical motion. Each cam has three connection points to allow for lateral and vertical amplitudes of 4.5, 2.75 and 1mm to be selected, thus providing nine amplitude combinations. Each drive rail's movement is limited by supports, converting the rotary motion of the cam to a linear motion. The bevel gears are kept in position by sealed ball bearings which, along with the drive rails, are held inside a central structure. A single cam per drive rail is used, as opposed to the double cam design shown in Fig. 6, due to space and complexity restrictions.

The mechanism will fit inside two hollow outer shell structures, which themselves will be attached to the drill heads. The reciprocating drive rails fit within the outer shell in the same way as shown in Fig. 6, and attach to the top and base of one shell each. The lateral drive rails are positioned at 90° to the reciprocating rails, sitting across the two drill head halves, and attach to the sides of both outer shells. This allows the overall force provided by the motor to be distributed as widely along the drill heads as possible.

Whilst the four rails produce linear motions in one direction only, the outer shell will move in a number of directions. To allow this, the connection points between the drive rails and the outer shell include a precision slide bar linked to the drive rail, held in place by a support attached to the outer shell. In the case of the lateral drive, the slide bar pushes the support and outer shell laterally. As the slide bar is able to move within the support, it can also facilitate the vertical movement by allowing the support to slide up and down at the same time. The interaction between the slide bar and support caused by this motion will generate a lot of friction, however this is reduced by having multiple connection points for each drive rail.

A major advantage of the Quadruple Cam mechanism is that the two motions can be independently varied. In other words, the reciprocating amplitude can be changed without affecting the lateral amplitude, and vice versa. This section will examine the range of motions that can be produced by this mechanism. The left and right drill heads discussed here refer to those shown in Fig. 7.

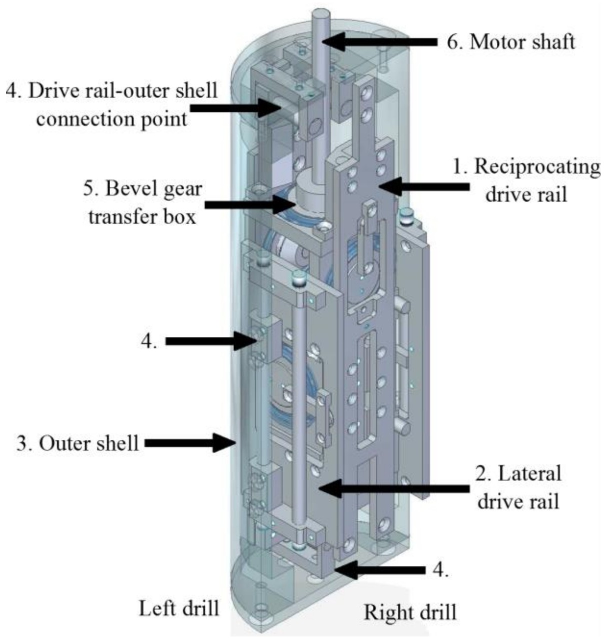

Figure 7. Model of the Quadruple Cam design, showing the integrated mechanism and left outer shell

4.1. Circular Motions

In the set-up shown in Fig. 7, the drill heads will undergo a circular motion. Care must be taken, as the piston-like movement of the drive rail created by the cam and connecting rod is not sinusoidal as may be assumed, which can be seen in Fig. 8.

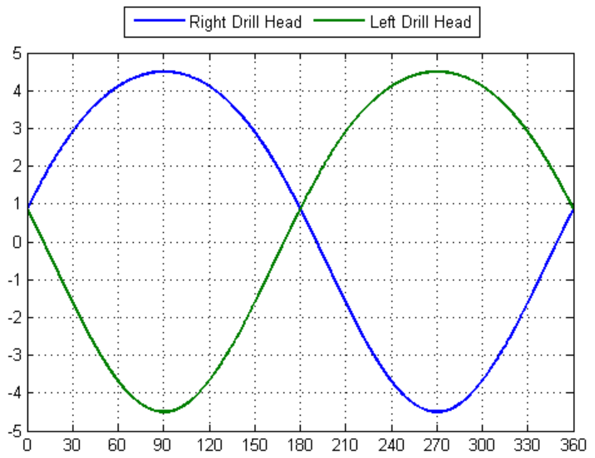

Figure 8. Vertical/horizontal displacement of the drill heads in one reciprocation cycle with 4.5mm amplitude

A perfectly sinusoidal motion would result in the drill heads moving in a circular motion. However the actual motion seen, when viewing the drill heads from the angle shown in Fig. 1 - 3, is actually a slightly squashed circular motion around a central point. Fig. 9 shows the paths travelled by the drill heads around their respective central points from a chosen starting position. The amplitudes available can be altered to produce nine different motions. Decreasing both amplitudes naturally results in a smaller circular motion. By reducing only the reciprocating amplitude whilst keeping the lateral amplitude constant, or vice versa, the motion of the drill heads becomes more elliptical, as shown in Fig. 10. In all cases, the shape of the path travelled becomes more regular as the amplitudes decrease.

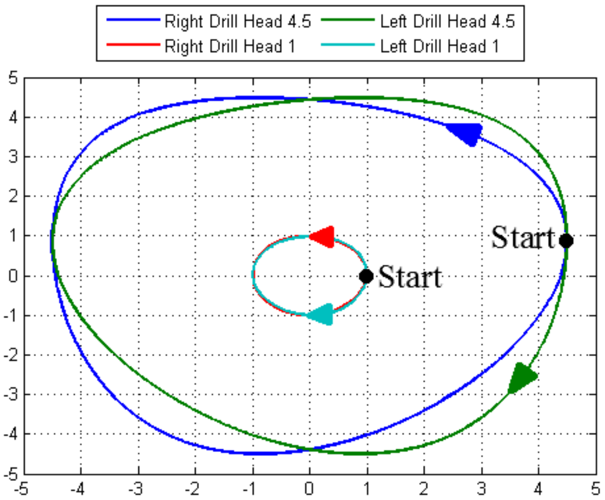

Figure 9. Circular path travelled by both drill heads with equal reciprocating and lateral ampltiudes

4.2. Diagonal Motion

Another major advantage of the Quadruple Cam design is that, by changing the position of some of the cams and connection positions, the drill heads will move in a diagonal motion. With this set-up, each drill head will move upwards and outwards, then downwards and inwards, as shown in Fig. 11.

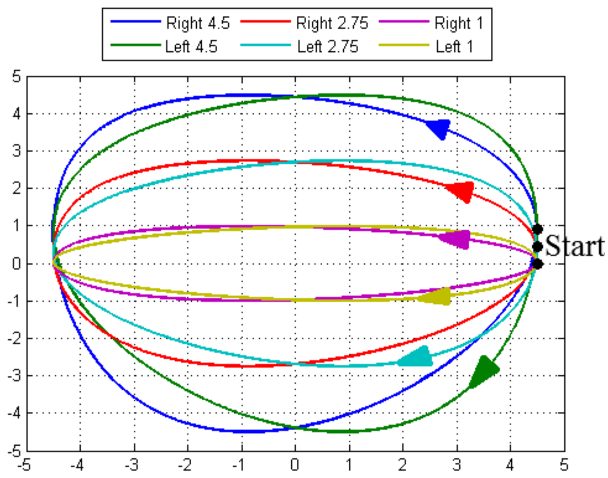

Figure 10. Circular paths travelled by both drill heads under different reciprocating amplitudes and a constant lateral amplitude of 4.5mm

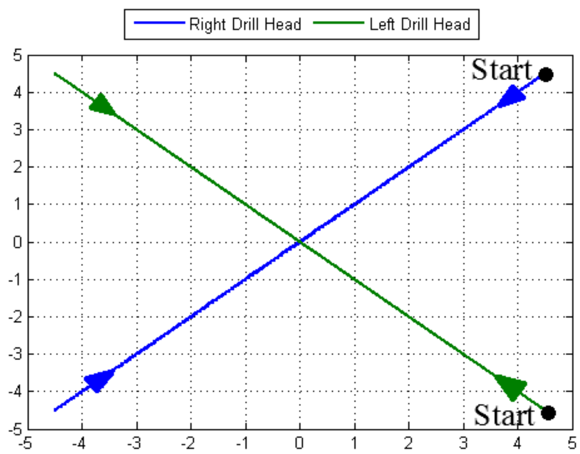

Figure 11. Diagonal path travelled by both drill heads with reciprocating and lateral amplitudes of 4.5mm

As with the circular motion, there is a range of nine amplitude combinations that each produces different diagonal motions. However, when keeping one of the amplitudes constant, in the case of Fig. 12 the lateral amplitude, there is a slight change in the paths travelled by the drill heads. As the difference in the two amplitudes increases, the path begins to curve. This is most noticeable when the drill heads move to the right hand side, becoming more pronounced the greater the difference in amplitude. It can also be seen that the point at which the drill heads' vertical displacement is zero shifts to the right. Similar changes are also seen when keeping the reciprocating amplitude constant. Though these changes are slight and unlikely to create a significant difference in performance of the two drill heads, this must still be taken into account.

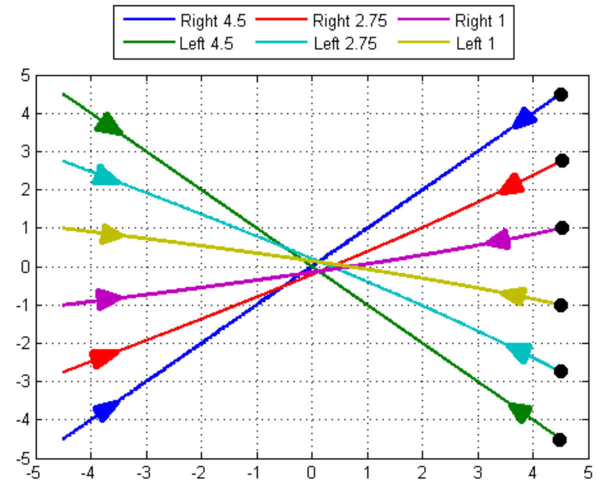

Figure 12. Diagonal paths travelled by both drill heads under different reciprocating amplitudes and a constant lateral amplitude of 4.5mm

4.3. Experimental Plan

The aim of the addition of active lateral motion is to increase the drilling performance and efficiency of DRD, by increasing the traction force generated by the backwards-facing teeth on the receding drill half. This will reduce the slippage and the required penetration force, and as a result increase the drilling depth compared to a reciprocating-only system. This will be evaluated by developing a new test bench which will measure the penetration and traction forces experienced by the DRD as it drills into regolith.

This will be calculated by measuring the penetration and traction forces experienced by the drill heads. To do this, a tension-compression load cell will be inserted between the reciprocating drive rail and the slide bar support of one drill head. The sensor will therefore reciprocate only and all forces will be applied to it axially. The position of the sensor represents the drilling depth limit, as a gap must be left since it is too large to fit within the drill heads. Ideally a second force sensor would measure lateral forces, though due to the extremely limited space available this is not possible.

As well as the nine amplitude combinations each for the circular and diagonal motions, the mechanism can also perform reciprocation-only drilling by disconnecting the lateral drive rails. This brings the total range of possible drilling motions to 21. It is expected that these motions will have varying levels of efficiency when drilling in substrates with different densities and particle sizes. Each motion will therefore be tested twice in poured SSC-1 and SSC-2 regolith simulants, the properties of which are given in Table 2. If possible, a number of experiments will also be performed in SSC-3 and vibrated SSC-1 and SSC-2. Each experiment will record the drilling depth and the tension/compression force acting on the load cell over time, up to a maximum depth of 22cm. By comparing the force measurements of the single and double motion experiments, the improvement in performance provided by the lateral motion can be measured, and it may also be possible to indirectly measure the lateral forces experienced.

Table 2. Properties of the SSC-1 and SSC-2 regolith simulants [8]

Property	SSC-1	SSC-2
Mineral	Quartz	Garnet
Particle Density (kgm^{-3})	2394	3154
Particle Size (μm)	100 - 1000	30 – 150
Particle Shape	Sub-rounded	Sub-angular
Poured Density (kgm^{-3})	1413	1945
Poured Relative Density (%)	7.4	-0.4
Vibrated Density (kgm^{-3})	1687	2344
Vibrated Relative Density (%)	74	74
Internal Angle of Friction (°)	35	41
Cohesion (kPa)	910	1190

The drill heads will be fixed to the outer shells, and both must have a form of sealing to prevent regolith from entering the mechanism. This could potentially be achieved by the use of industrial felt gaskets, which can provide a good boundary without significantly increasing friction and have been used in previous DRD experiments [12]. Both the internal mechanism and the motor will be fixed to a small plate. This plate will itself be attached to two guiding rails, similar to the set-up of Fig. 4, and weights will be used to provide a selected overhead force. This system will also be able to be set at an angle, allowing for diagonal drilling. A schematic of the planned set-up is shown in Fig. 13.

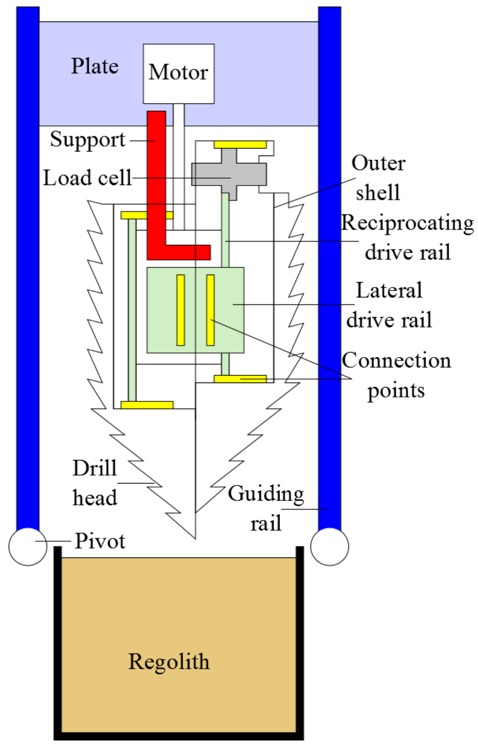

Figure 13. Schematic of the experimental set-up

5. CONCLUSIONS

The evolution of the Dual-Reciprocating Drill from a proof of concept to an integrated system prototype using an internal actuation mechanism has been presented, along with the results and key observations made in previous experiments. These showed that the traction forces created by the backwards-facing teeth were one or two orders of magnitude lower than the required penetration force. It was seen that sideways movements caused by the asymmetrical shape of the drill heads created lateral forces significantly larger than the traction forces. This was supported by the results of a number of later experiments, in which non-vertical drilling created by drill stem bending caused significant improvements in drilling depth and speed.

Combining the need to further investigate the effect of sideways movements and to continue the development of the internal actuation mechanism, a new mechanism is being designed which will allow simultaneous reciprocating and lateral movements of the drill heads. The Quadruple Cam design was chosen for the wide range of drilling motions it can perform, including a variety of circular and diagonal burrowing mechanisms as well as reciprocation-only drilling. A new experimental set-up is being developed which will allow the testing of these motions in regolith. This will measure the traction and penetration forces experienced by the drill heads. These experiments will aim to demonstrate and quantify the improvement in drilling performance that the addition of active lateral motion brings, and to determine the optimal burrowing mechanisms required for different regoliths. This will allow for the development of an internal actuation mechanism which will enable the DRD to drill further and more efficiently.

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