Advancing the Dual Reciprocating Drill Design for Efficient Planetary Subsurface Exploration

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Abstract

Accessing the subsurface of planetary bodies with drilling systems is vital for furthering our understanding of the solar system and in the search for life and volatiles. The extremely stringent mass and sizing mission constraints have led to the examination of novel low-mass drilling techniques. One such system is the Dual-Reciprocating Drill (DRD), inspired by the ovipositor of the *sirex noctilio*, which uses the reciprocation of two halves lined with backwards-facing teeth to engage with and grip the surrounding substrate. For the DRD to become a viable alternative technique, further work is required to expand its testing, improve its efficiency and evolve it from the current proof-of-concept to a system prototype. To do this, three areas of research were identified. This involved examining how the drill head design affects the drilling depth, exploring the effects of ice content in regolith on its properties and drilling performance, and determining the benefits of additional controlled lateral motions in an integrated actuation mechanism.

The tests performed in this research revealed that the cross-sectional area of the drill head was by far the most significant geometrical parameter with regards to drilling performance, while the teeth shape had a negligible effect. An ice content of $5 \pm 1\%$ in the regolith corresponded to an increase in drilling time and a clear change in the regolith’s physical properties. Finally, it was demonstrated that the addition of lateral motions allowed the drill to achieve greater depths. This work has advanced both the understanding and design of the DRD considerably. It has continued the exploration of the geometrical and substrate parameters that affect drilling performance and provided the first characterisation of the properties of an icy lunar polar simulant. The construction and testing of the complex motion internal actuation mechanism has both evolved the DRD design and opened a new avenue through which the system can be further optimised.
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Nomenclature

Abbreviations

ABS  Acrylonitrile Butadiene Styrene
ASTM American Society for Testing and Materials
CB Circular Burrowing
DB Diagonal Burrowing
DC Direct Current
DCMM Dual Complex Motion Mechanism
DEM Discrete Element Model
DRD Dual-Reciprocating Drill
ES-1/2/3 Engineering Soil Simulants 1, 2 and 3
ESA European Space Agency
GPU Graphics Processing Unit
HP Heat Flow and Physical Properties Package
IAM Integrated Actuation Mechanism
JSC Mars-1 Johnson Space Centre Mars Simulant 1
JSC-1 Johnson Space Centre Simulant 1
JSC-1A Johnson Space Centre Simulant 1A
L-GRASP Lunar Generic Regolith Acquisition/Sampling Paw
LHS Lunar Highland Simulant
MDH Mono-Block Drill Head
MMUM    Moon/Mars Underground Mole
MSFC    Marshall Space Flight Center
NASA    National Aeronautics and Space Administration
NU-LHT-1M    NASA-USGS Lunar Highlands Type Pilot Simulant
NU-LHT-2M    NASA-USGS Lunar Highlands Type Prototype Simulant
O HF    Overhead Force
PLUTO    Planetary Underground Tool
PSDDS    Powdered Sample Dosing and Distribution System
SD2    Sampler, Drill and Distribution system
SE    Specific Energy
SPDS    Sample Preparation and Distribution System
SSC-1    Surrey Space Centre Mars Simulant 1
SSC-2    Surrey Space Centre Mars Simulant 2
USDC    Ultrasonic/Sonic Driller/Corer
USGS    United States Geological Survey
WOB    Weight On Bit

Greek Symbols

\( \alpha \)    Cone half-apex angle
\( \alpha_1 \)    Cone teeth rake angle
\( \alpha_2 \)    Cylinder half-apex angle
\( \delta \)    Actual progression distance of the drill head
\( \Delta \)    Progression distance of the drill head with no slippage
\( \rho \)    Density
\( \rho_{\text{max}} \)    Maximum density
\( \rho_{\text{min}} \)    Minimum density
\( \sigma'_h \)    Effective horizontal stress
\( \sigma'_v \)    Effective vertical stress
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi'$</td>
<td>Internal angle of friction</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Angular frequency</td>
</tr>
</tbody>
</table>

**Roman Symbols**

- $a$: Reciprocation amplitude
- $a_h$: Amplitude of horizontal reciprocation
- $a_v$: Amplitude of vertical reciprocation
- $A_h$: Area of drilled hole
- $D_r$: Relative density
- $D_f$: Final depth
- $f$: Reciprocation frequency
- $F_c$: Net force required by the crankshaft
- $F_e$: External force
- $F_{\text{comp/tens}}$: Total force acting on the sensor
- $F_i$: Inertial force
- $F_{\text{int}}$: Force produced by internal friction
- $F_p$: Net force acting on the piston
- $F_{\text{motor}}$: Force produced by motor during drilling
- $F'_{\text{motor}}$: Force produced by motor during free running
- $F_r$: Friction force
- $F_{\text{res}}$: Force produced by regolith resistance
- $F_w$: Weight of the reciprocating parts
- $i$: Figure of merit
- $K_0$: Coefficient of Earth pressure
- $L_2$: Cylinder height
- $L_{\text{att}}$: Drill stem attachment
- $L_{\text{cf}}$: Cone face length
- $L_t$: Tooth length
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{tot}$</td>
<td>Drill head length</td>
</tr>
<tr>
<td>$m$</td>
<td>Mass</td>
</tr>
<tr>
<td>$N_1$</td>
<td>Number of cone teeth</td>
</tr>
<tr>
<td>$N_2$</td>
<td>Number of cylinder teeth</td>
</tr>
<tr>
<td>$p$</td>
<td>Main effect/first-order interaction</td>
</tr>
<tr>
<td>$p_r$</td>
<td>Rate of penetration</td>
</tr>
<tr>
<td>$P$</td>
<td>Power</td>
</tr>
<tr>
<td>$R_{ext}$</td>
<td>Cylinder and teeth radius</td>
</tr>
<tr>
<td>$R_{int}$</td>
<td>Cylinder radius</td>
</tr>
<tr>
<td>$R_p$</td>
<td>Radius of protrusion</td>
</tr>
<tr>
<td>$R_t$</td>
<td>Tooth width</td>
</tr>
<tr>
<td>$R_{tot}$</td>
<td>Total radius</td>
</tr>
<tr>
<td>$t_l$</td>
<td>Tooth lower face length</td>
</tr>
<tr>
<td>$t_u$</td>
<td>Tooth upper face length</td>
</tr>
<tr>
<td>$T_c$</td>
<td>Calculated torque</td>
</tr>
<tr>
<td>$T_m$</td>
<td>Measured torque</td>
</tr>
<tr>
<td>$v_{actual}$</td>
<td>Actual drill progression speed</td>
</tr>
<tr>
<td>$v_d$</td>
<td>Drilling speed</td>
</tr>
<tr>
<td>$v_{max}$</td>
<td>Drill progression speed with no slippage</td>
</tr>
<tr>
<td>$V_E$</td>
<td>Volume of engaged regolith</td>
</tr>
<tr>
<td>$V_P$</td>
<td>Volume of regolith by one drill head half</td>
</tr>
<tr>
<td>$V_{PT}$</td>
<td>Total volume of penetrated regolith</td>
</tr>
<tr>
<td>$w$</td>
<td>Weight, importance rating</td>
</tr>
<tr>
<td>$x$</td>
<td>Rating value</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

Many of the major goals for exploration of the solar system in the near future can only be achieved by accessing the subsurface of planetary bodies. These include confirming the presence of water ice and other volatiles in the lunar polar regions indicated by observations made by remote sensing instruments, which can be used as consumables for future robotic and manned exploration missions to other planets, moons and asteroids, or for establishing long-term extraterrestrial bases. Additionally, in-situ measurements of the bodies’ interiors and analysis of obtained samples will lead to an increased understanding of their composition and formation, which will in turn reveal further information about the history of the solar system, and can also be used in the search for the signs of past or present life.

To access the subsurface, a drilling system is required. While drilling operations on Earth are a common and daily occurrence, the mission constraints and extraterrestrial environments present numerous unique and difficult challenges. A drill must follow very stringent mass and sizing constraints, and be able to operate autonomously in extreme temperatures and pressures. The rotary, percussive and rotary-percussive terrestrial drilling techniques have been adapted and used for past and present subsurface exploration missions. However, their respective disadvantages of high overhead force, low penetration depth and heavy, complex systems have led to the exploration of non-traditional drilling techniques. By taking inspiration from biological systems, the Dual-Reciprocating Drill (DRD) has been developed as an alternative drilling technique.
1. Introduction

The ovipositor of the *sirex noctilio*, or wood wasp, uses the reciprocating motion of two halves lined with backwards-facing teeth to drill into wood in order to lay its eggs. By engaging the wood with the teeth, the receding half generates a traction force that is then transferred and added to the compression force available to the penetrating half, resulting in a self-contained system that theoretically requires no external forces.

The DRD is a novel drilling technique inspired by this mechanism, with an initial feasibility study prototype demonstrating its potential for drilling in low-strength rocks. Since then, numerous experiments have been performed using a dedicated test rig in regolith, which have shown its ability to dig further than static penetration, with factors such as slippage and lateral movements being shown to have a significant bearing on the drilling capabilities. This thesis will continue the research into the DRD, furthering its design and bringing it a step closer to becoming a viable alternative to the current drilling technologies.

1.1 Motivations

For a drilling technique to be a viable technique for consideration in future planetary subsurface exploration missions, it must be able to demonstrate clear advantages over the current techniques used, its performance in the target substrates must be well characterised and a fully developed system prototype must be built and tested. At the start of this research, while the performance of the DRD in regolith has been well studied, the design is very inefficient, with the gripping of the backwards-facing teeth being largely ineffective. The DRD design is also still at the proof-of-concept phase, and is still very far from having a system prototype developed.

The DRD is still a relatively new technology, and will require significant development before it may be considered for future missions. By continuing the experimental testing, and with a desire to evolve the design of the DRD, it will be possible to further the understanding of its behaviour in regoliths, improve the drilling efficiency and progress from the current proof-of-concept stage. By continuing to use an experimental approach to collect data, the behaviour of the DRD as its design is altered and progressed can be observed and quantified. The major focus of this research will be investigating the as-
pects of the drill head and actuation mechanism design that can improve the drilling performance, along with furthering the understanding of how regolith behaviour changes in extraterrestrial environments. By advancing the development of the DRD, this can be used to propose new system prototypes and avenues of research that can further improve the potential of the DRD as a future alternative drilling technique.

1.2 Objectives

The overarching aim of this research is to further improve the performance and understanding of the DRD, and to continue its progression towards a viable system prototype. This can be broken down into several objectives.

- Investigate the geometrical parameters that define the drill head design
- Demonstrate the capability of the DRD to drill up to depths of over one metre
- Investigate the properties of icy regolith, and determine how the presence of water ice can affect drilling
- Experimentally confirm the importance of lateral motions in drilling performance
- Build and successfully test an integrated internal actuation mechanism

1.3 Novelties

The work that will be performed to achieve these aims will result in the following novelty:

- A full exploration into the effects of the drill head geometry on drilling performance, complementing the previous experiments that studied the operational and substrate parameters, and continuing the analysis of the parameters influencing drilling
- The first testing of the DRD in both lunar and icy simulants, expanding its range from the clays and dry Martian substrates currently used
• A characterisation of the properties of an icy regolith simulant of the lunar polar regions, and the proposal of a new preparation method for the creation of simulants with a controllable water content

• A first study of implementing actively controlled lateral motions into the vertical reciprocation. This results in the examination of new burrowing motions never before considered in drilling experiments

• The design and building of the first fully functioning actuation mechanism integrated within the drill heads. By moving the reciprocating mechanism from the test rig system to an internal design, the drill moves further to the design of a true system prototype

• The last two novelties are combined, resulting in the first drilling experiments in which lateral motions are implemented. This is done both with the burrowing motions and by performing diagonal drilling tests at a fixed angle, and leads to the investigation of the mechanics of these new types of drilling

1.4 Thesis Overview

The material covered in the thesis is organised as such:

Chapter 2: Literature Review The thesis begins with a detailed discussion of the current state of the art with regards to extraterrestrial exploration. The range of drilling systems, with a focus on the DRD, is discussed, demonstrating its potential as a low-mass planetary drill.

Chapter 3: Research Rationale and Philosophy The three areas of research that will make up the work performed for this thesis are detailed. The rationale behind each is discussed, with the unanswered questions of the previous research detailed in the literature review used to provide the goals and aims for each.

Chapter 4: Drill Head Design Here, the work performed in examining how the geometrical parameters that govern the design of the drill heads can affect the performance of the DRD. This presents a continuation of the investigation into the effects of the parameters that define the entire DRD
operation while the presence of bending of the drill stem results in the proposition of the mechanics of drilling at an angle.

Chapter 5: Characterisation of Icy Regolith Simulants This chapter examines the substrate parameter of water and ice content of regolith. Here, the effect of varying water and ice contents of a lunar highlands simulant is examined. From this, a preparation procedure for creating icy simulants with controllable water contents is found, and is subsequently used to analyse the change of properties seen in regolith with varying degrees of saturation.

Chapter 6: Integrated Complex Motion Mechanism This details both the construction of the first fully integrated internal DRD actuation mechanism, and the first investigation into the creation of complex motions. This is achieved by the design of a new mechanism based upon the original DRD prototype, which has been evolved to allow the addition of controlled lateral movements. The performance of this new mechanism is analysed by examining the forces experienced during its operation, while the depths achieved by these complex motions are compared to the original reciprocation. The importance of regolith compaction and the angle of drilling are also examined.

Chapter 7: Recommendations for Future Work Here, potential avenues for further work in the development of the DRD are discussed. This includes both research into the new drilling motions examined, and the continued development of the DRD into a true system prototype.

Chapter 8: Conclusions The thesis is summarised here, with the final conclusions and the contributions that have been made to the field of planetary drilling discussed, and the publications that have resulted from this work are also listed.
Chapter 2

Literature Review

In this chapter, the literature relevant to this particular field of research is discussed. Firstly, the relevance of planetary exploration, and the past and present missions that have penetrated extraterrestrial bodies and performed drilling operations, are summarised. The drilling techniques used for these missions are analysed, with their respective strengths and weaknesses highlighted. This leads on to the alternative drilling techniques inspired by biological systems, of which one is the Dual-Reciprocating Drill. The evolution of this mechanism from its initial concept design, and the related experiments that have been performed with it, are detailed. Finally, a summary of the lunar and Mars regolith simulants that have been developed for use in instrumentation testing is given, with the current gaps in knowledge with regards to the presence of water ice highlighted.

2.1 Rationale for Planetary Subsurface Exploration

Subsurface exploration plays a critical role in furthering our understanding of the solar system by obtaining data that can only be found below the surface. By using in-situ methods, such as extracting samples or the insertion of scientific payloads, it will be possible to determine a body’s history and composition [108], detect the presence of resources for use in future robotic or manned exploration [11] and for the detection of the markers of life. Subsurface exploration is also required in the cases where the harsh conditions have contaminated the surface layer. For example, the detection of biomarkers,
which can be used in the search for life on Mars, may only be possible at depths greater than 3m, as the oxidation of the soil due to UV flux creates a sterile surface layer 2 - 3m deep [30]. The presence of water ice in the lunar south pole regions, believed to exist below a dry layer 60cm deep [80], can only be confirmed by drilling down and detecting it in-situ. Subsurface exploration has been performed in many past missions, and is still one of the major aims of future missions, with very strong cases for renewed exploration of the Moon and continued exploration of Mars and other bodies [67, 24]. Many missions have explored the subsurface of planetary bodies, with more currently under development, which are summarised in this section.

2.1.1 A History of Planetary Drilling

Penetrating the surface of extraterrestrial bodies has often been one of the goals of planetary exploration missions. The first spacecraft to take a geotechnical measurement of an extraterrestrial surface was the Soviet Union’s Luna 13 in 1966, the third spacecraft to successfully land on the Moon [122]. Mounted on the end of one of its three spring-loaded booms was a penetrometer with a 5cm long cone, which was driven into the ground to measure the mechanical soil properties [61, 62]. A few months later, the National Aeronautics and Space Administration’s (NASA) Surveyor 3 spacecraft was the first to dig the lunar regolith with a scoop, which was able to hold up to 100cm$^3$ of granular material. It performed bearing, trench and impact tests to determine the top soil’s bearing strength and related excavation forces [103].

The Apollo 15 mission was the first to use a manned drill, the 500W rotary-percussive Apollo Lunar Surface Drill, shown in Figure 2.1. It was one of the first battery-powered drills, rotating at 280rpm and impacted at 2270 blows per minute with an energy per blow of 4.4J [122]. The drill was used to create holes for heat flow probes and to retrieve subsurface sample cores. Though the general performance of the drill was good, a lack of knowledge of the substrate being drilled into and the insufficient auger flutes at the stem joints resulted in the regolith slowing down at these points, eventually causing the drill to stall at 60% of the desired depth, locking it inside the borehole. Removal of the drill required the full strength of the astronauts, and as such it was subsequently redesigned to have a continuous auger to remove the dense soil, and included a jack for removing the drill stem [75]. As a result,
the Apollo 16 and 17 missions had no issues drilling and excavating core samples. Each mission was able to take numerous core samples, with the deepest being the 292cm-deep core taken by Apollo 17 [1].

![Image of Apollo astronaut practising with the Apollo Lunar Surface Drill](image1.jpg) ![Image of Luna 24 lander](image2.jpg)

Figure 2.1: Pictures of an Apollo astronaut practising with the Apollo Lunar Surface Drill [122], and the Luna 24 lander, with the drill mounted along its left side [12].

At around the same time, the first fully autonomous drilling operation, and to date the only sample return mission, was achieved by the Soviet Union’s Luna 16, 20 and 24 landers. The 16 and 20 landers two had short drills for obtaining samples from shallow depths, acquiring 101g at 35cm and 50g from 27cm respectively. Luna 24 had a 2m drill, as shown in Figure 2.1, allowing it to collect a 170g sample from 160cm deep [122, 123].

NASA’s Viking project was the first mission to safely land a spacecraft on Mars in 1976. Its two landers collected data from the surface by collecting samples of material using a scoop mounted on a robotic arm. However, it took until 1997 for another successful Mars landing, with NASA’s Sojourner rover, which was then followed by the Mars Exploration Rovers, Spirit and Opportunity, in 2003. The Mars Phoenix lander also used a scoop, or Icy Soil Acquisition Device, which acquired samples in the northern Martian planes [123, 69]. The Curiosity rover became the first mission to drill into and obtain a subsurface sample from Mars, by drilling a 6.5cm hole into Martian bedrock in February 2013, shown in Figure 2.2 [116].
In addition to the Moon and Mars, other drilling missions have included the Soviet Union’s Venera 13 and 14 landers, which penetrated a few centimetres into the surface of Venus and collected samples at the uplands and lowlands respectively [111]. Most recently, the European Space Agency’s (ESA) Philae lander, as part of the Rosetta mission, attempted to land on Comet 67P/Churyumov-Gerasimenko and drill into it with the Sampler, Drill and Distribution (SD2) system [31]. Whilst the drill operated nominally, extending to its full length and performing the sampling sequence, the positioning of Philae after the landing means that it is possible that no penetration of the comet or sample collection occurred [72].

Two planned missions to Mars are the InSight lander and ExoMars rover, planned for launch in 2018 and 2020 respectively. InSight will use the Heat Flow and Physical Properties Package (HP³), a self-penetrating mole, to penetrate to 3 - 5m and plant sensors to measure the subsurface’s temperature gradient [108, 56]. ExoMars will use a multi-rod drilling mechanism to collect samples at depths of up to 2m [94, 69].

2.2 Challenges of Extraterrestrial Drilling

In order for a drill to be useful in an extraterrestrial environment, it must be able to overcome the challenges associated with operating at such remote locations and extreme conditions. Given the limited choice of drilling sites,
and the uncertain nature of the ground to be penetrated, it is important that the drill is able to progress in any terrain rather than be optimised for a particular material [123].

2.2.1 Drilling Performance

Conventional drilling, typically performed using the rotary technique, consists of two processes that occur simultaneously: breaking the drilled formation and moving the broken cuttings to the surface. If the formation cannot be broken by the bit, or the cuttings are not cleared away, the drill cannot advance [125]. As well as bit design considerations, two operational parameters that affect the progress of the rotary drill are rotational speed and Weight on Bit (WOB). For a given WOB, the rotational speed is directly proportional to the penetration rate and drilling power, and higher speeds can improve an auger’s cuttings removal [123, 124]. Overhead force (OHF), defined as the total force acting on the bit from above, can also be used in place of WOB.

Two more easily controllable parameters that must be considered are power and energy. The total drilling power is the sum of the power required to both drill the hole and remove the cuttings. A high power requirement results in the need for large actuators and battery cells. Drills are most often powered by batteries, which are charged by solar arrays or radioisotope thermal generators; for example, the Mars Phoenix lander used two Li-ion batteries each providing 346W [124, 88]. A more significant factor than power is the drilling energy. Specific Energy (SE) represents a drilling efficiency and takes into account drilling power, $P$, rate of penetration, $p_r$, measured in ms$^{-1}$, and the area of the drilled hole, $A_h$, measured in MJm$^{-3}$, and is found using Equation (2.1). SE indicates the total amount of energy required to drill a volume of rock, and is a function of many variables, such as the strength of the rock formation, drill bit design, bottom hole clearing, type of drilling and atmospheric pressure. Because of this, SE is usually found empirically [123, 125, 88].

$$SE = \frac{P}{p_r \times A_h} \quad (2.1)$$

SE can be used to compare different bits that are drilled into the same material under identical conditions, as well as measuring the drilled material’s physical properties if the operational variables remain constant [123].
One such example is an optimisation study of the number of cutting teeth used to interact with the substrate in a percussive drill bit. By deriving the SE as a function of the teeth number, an optimal solution was found that minimised the SE and maximised the drilling rate [71].

2.2.2 Cuttings Removal Techniques

Planetary drills almost exclusively use dry augers with helical flutings for cuttings removal. However, these have the disadvantages of high power consumption and poor efficiency with low rotational speeds or small-diameter drills. An alternative cuttings removal method that has been experimentally examined is the use of pressurised gas in small bursts. By drilling at low energy levels, the fine cuttings generated can be lifted with little force. Replacing augers with gas bursts improves both the overall power and drilling efficiency, while the lack of an auger could greatly reduce the drill’s mechanical complexity. However, this technique has the disadvantages of potential contamination of samples with the gas used and dust accumulation on solar panels and other sensitive equipment caused by the blowing out of the cuttings, which could result in serious system issues [123, 124].

2.2.3 Subsurface Media Characteristics

The type of medium that is being drilled into is one of the most important parameters that define drilling speed, required power, bit durability and the ability to acquire and deliver samples. The type of formation, its hardness and the abrasiveness dictates the method of excavation, cutter tooth material and bit geometry. Planetary media includes rocks, ice, permafrost and regolith, which are distinguished by their hardness, level of consolidation and characteristics dependent on factors such as gravity, temperature and pressure [123]. Accounting for this is often made much more difficult by the uncertainty of the geology. For instance, Mars’ surface largely consists of regolith with a range of strength parameters [10], but appears to have blocks of hard rocks such as basalt distributed in the soil and dust. Other locations have found sedimentary terrain that could contain evaporites, which would be much softer and more uniform, making it easier to penetrate. As such, the drilling environment may be variable on both a large scale and on a centimetre-by-centimetre basis [124]. It should be noted that, while the terms ‘soil’ and ‘regolith’ have different definitions, soil will also be used to
refer to regolith for the purposes of this thesis. Additionally, regolith itself is defined by the layer of granular material covering planetary bodies, and does not include the rocks and ice that may be found within these layers.

Rocks are solid, cohesive aggregates of at least two types of mineral formed by various geological processes. Estimates made using basalt analogues suggest that Martian rocks have strengths of over 130MPa, though this value could vary considerably depending on the extent of surface weathering [67]. Whilst using very sharp-toothed and abrasive bits can allow for drilling with a relatively low WOB, small amounts of wear will generate flats on the cutter teeth, spreading the drill load until the pressure exerted by the teeth on the rock is lower than the rock’s crushing strength [123].

Soft rocks and soils pose different difficulties, with problems occurring when the material is easy to penetrate, producing so many cuttings that the bit and cuttings removal system chokes. Often the greatest problems in soft materials are hole stability and sideways skating of the bit caused by encountering harder materials, which can lead to the drill becoming stuck. Drill stems with smooth surfaces and bits with backwards-facing teeth at their widest points, allowing them to drill their way out of the hole, can be used to reduce this risk [123, 124].

Dust is also present on planetary bodies. On Mars, dust is transported by winds and static charging, with a storm season lifting dust into the atmosphere. On bodies with no weather, such as the Moon, static charging can result in loose dust clouds. Dust can cause complications in a wide range of subsystems, including a spacecraft’s mechanisms. Its abrasive nature allows it to seep through the seals, clogging the mechanisms and eventually jamming them and causing failures [38].

The best estimates of the lunar materials are provided by the cored samples brought back by the Apollo and Luna missions. The lunar environment, and its lack of weather, resulted in highly abrasive, adhesive and cohesive regolith, dominated by angular shards and rounded melt fragments with an average grain diameter of 45 - 100μm. Agglutinates, such as the one shown in Figure 2.3 and which can make up 60% of the soil volume, can present problems for joints, seals, etc. due to their jagged nature and small size [122].
On Mars, in places where the atmospheric pressure is above the triple point of water, particularly at the Northern Polar Region, it is possible that the subsurface contains ice. There is also likely to be ice in the lunar subsurface, discussed in more detail in Section 2.5.3. If the temperature at the bit causes the ice to melt, any reduction in power could allow the temperature to fall below freezing, causing the bit to become frozen in place. A mixture of ice and clay-like material or cuttings can cover the drill, causing it to resist being removed or stop the penetration. Such a situation is almost impossible to clear without removing the bit and heating it to melt the ice [123, 124, 125].

Such variations in the media that can potentially be encountered mean that careful selection of the landing site is required. The engineering challenges of the surface geology, and the extent to which morphological measurements and analysis of images can accurately characterise the surface and subsurface, must be measured against the mission aims, such as astrobiological interest [67, 66].

2.2.4 Environmental Constraints

Another major driver in the design of a drilling system is the planetary environment in which it will operate. The Moon and Mars are planetary bodies with very different environments from Earth, which directly affect the drilling performance and design approaches.
The Moon and Mars have very low atmospheric pressures. The Moon’s hard vacuum results in many materials becoming brittle, while fluids would freeze or sublime very quickly, ruling out the use of water or muds as used in terrestrial applications \cite{125, 122}. The pressure on Mars ranges from 0.1 - 1.5kPa, bracketing the triple point of water at 0.63kPa and 0°C. When drilling ice, this low pressure, combined with the heat of the drill, could cause liquid water formed in the borehole to immediately vapourise, reducing drilling power and increasing the risk of refreezing as described in Section 2.2.3. The low pressure also affects the surface friction and heat dissipation, particularly on the Moon, requiring a strategy that uses modest rotary speeds and OHF values, as well as intermittent pauses to allow the heat to dissipate and the bit to cool down \cite{124, 125}.

Temperature also plays a large role in choosing the drilling approach, as the substrates get stronger when they are colder. This is not a large issue for the Moon as, although the temperature of the top few inches can fluctuate between 123°C in the day and −153°C at night or in permanently shadowed craters, subsurface temperatures are relatively high and constant at −19°C \cite{122}. On Mars, thermal fluctuations of over 100°C can occur in under six hours, reaching −100°C at night and a maximum of 27°C in the summer, with subsurface temperatures at the Phoenix landing site starting at −25°C and quickly decreasing. This rules out a number of materials that become brittle when cold or are susceptible to thermal fatigue, while any samples taken must be kept within a certain temperature range to avoid thermal alteration \cite{123, 124, 125}.

Another problem for missions to Mars, Venus and planetary bodies in the outer solar system is the delay in autonomy operations caused by the great distances. The one-way delay to Mars can be up to 20 minutes, and there may be only two opportunities a day to contact the rover. As such, the drill cannot be teleoperated, and must be able to function, detect faults and utilise recovery protocols autonomously \cite{125}.

\section{2.3 Drilling Techniques}

There are a number of drilling techniques available for exploration missions, which are able to reach depths ranging from a few centimetres to over 10m
This section compares the advantages, disadvantages and heritage of the various drilling methods that use robotic systems and mechanisms to penetrate the surface. Consequently, kinetic penetrators, which reach the subsurface using only kinetic energy gained from falling from an orbiting spacecraft [43, 54], are omitted. Non-traditional techniques such as melting tips [65] or lasers [112] are also excluded, given their high energy demands and unavoidable contamination of the drilled substrate [41].

### 2.3.1 Rotary

Rotary drills are the most common terrestrial drills, and have been widely used in space applications. In conventional rotary drilling, two processes occur simultaneously: breaking the material and removal of the cuttings. A large OHF is used to allow the cutting bit to penetrate and crush the rock, and the cutters fracture the rock as the bit rotates. Cuttings removal is typically done using an auger with helical fluting, allowing the cuttings to be moved upwards and out of the hole with the drill’s rotation. This technique is able to drill through a large range of cohesive and non-cohesive soils and rock. There are a number of disadvantages to this technique, such as excessive bit wear at high rotation rates, high thrust values, the need for a long drill stem for deep drilling, power consumption and, most importantly, the need for a high axial force, resulting in a large overhead mass [10]. This is limited by the rover’s mass and the low gravity environment. For example, the 350kg Mars Phoenix platform could provide a maximum WOB in a Martian environment of 1300N. However, factors such as deployment of the drill via a robotic arm and various safety factors would likely reduce the practical available WOB by an order of magnitude, to a range of around 100 - 200N [125, 88].

### 2.3.2 Percussive Drills and Moles

Percussive drills are widely used to penetrate brittle material such as concrete, and can have faster penetration rates than rotary drills in some hard rock formations. This technique involves the drill bit vibrating and compressing the rock, propagating stress until the rock breaks. The drill bit is driven by a hammer, which is actuated by a spring/free mass system powered by a DC motor [123]. The major advantages over rotary drilling are a static and lower OHF, less contact with the rock (generally 1 - 2% of the total drilling time, resulting in lower bit abrasion) and easier control of de-
viation problems for straight hole drilling [10]. However, percussive drilling has a low penetration rate in soft rocks and a limited penetration depth due to the cuttings removal only being effective at shallow depths [5, 6]. There are also a number of uncertainties in percussive drilling, such as optimising the hammer type and vibrations, wellbore stability and less field evidence of reliable and continuous operations compared to rotary drilling, limiting the wider acceptance of this technique. Despite this, percussive drilling has been the optimum choice in a number of recent mission proposals [10]. An evolution of the percussive technique is ultrasonically assisted drilling, which uses ultrasonic oscillations to drive the hammering mechanism, as opposed to a conventional motor. The Ultrasonic/Sonic Driller/Corer (USDC), shown in Figure 2.4, uses a piezoelectric stack hammering mechanism to hit a free mass, which in turn hits the bit to fracture the rock [5, 9].

![Image of USDC](image)

Figure 2.4: Schematic of the USDC and photograph showing its ability to core sandstone with minimal axial force [9].

Another use of the percussion technique is the mole, a self-penetrating mechanism that drills into soil-like materials. The mole is a compact design which is able to reach depths that greatly exceed its length. The Planetary Underground Tool (PLUTO), a subsystem of the ill-fated Beagle 2 lander, inspired both the Moon/Mars Underground Mole (MMUM) and InSight’s HP3 mole. Each have similar designs, shown in Figure 2.5, consisting of an internal hammer, suppressor mass and outer casing [55]. The hammer transmits a shock via the casing which displaces and compresses the surrounding soil, while the backwards-directed impulse reaction to each shock, transferred via the mass acting against a second spring, allows forward motion of the
mole. The casing is tethered to a support mechanism which provides power and a retrieval mechanism [96, 110]. The mole has similar advantages to the other percussive drills, in that it has a low, continuous power requirement and needs only a small initial surface force. It is also much lighter than drills with similar depth capabilities and can reach depths far greater than drills of similar size. The major disadvantage is its inability to penetrate through rocks or hard materials [41].

Figure 2.5: Beagle 2 PLUTO mole cross-section (1: housing, 2: hammer mechanism, 3: sampling device, 4: back cover with tether connection) [96]

### 2.3.3 Rotary-Percussive

Out of the three major constraints for a rotary drilling mission (WOB, power and energy), WOB has the largest limitation. This can be addressed by using the rotary-percussive technique, which is well-used in industry to efficiently drill through hard rocks and concrete without having to apply a large OHF, and is a good option for deep drilling into unknown rock formations. The reduction in WOB is due to a stress wave generated by a hammering device within the drill head which momentarily increases the force exerted by the bit against the rock. Coupling this to a modest WOB is equivalent to using a much larger WOB [88]. The percussion produces impact forces to break off the rock, while the rotation removes the cuttings, resulting in a faster penetration rate and a system significantly more energy efficient than pure rotary or percussive drills [4]. However, the combination of the two techniques involves many complicated processes, which consequently increases the required drilling power, mass and complexity of the system. The decreased WOB and energy must therefore be weighed against the additional system mass and complexity [88].

The rotary-percussive technique is being used in a number of missions and prototypes. ExoMars’ drill, shown in Figure 2.6 (a), uses separate rotation and translation mechanisms with a multi-rod system, allowing drilling to
depths of up to 2m [94, 73]. Curiosity drills holes several centimetres deep to collect samples, using three independent actuators to produce synchronised rotation and hammering [85, 2]. Other rotary-percussive prototypes include CRUX [88] and PARoD [4]. A rotary mechanism has also been added to the USDC discussed in Section 2.3.2, shown in Figure 2.6 (b), in which the bit hammering and rotation are decoupled, allowing for independent control. This optimises the drill’s performance, enabling it to drill to 8.5cm in limestone and up to 0.5m in regolith [5, 6, 123].

Figure 2.6: Picture of the ExoMars drill (a) and a schematic of the evolved USDC (b) [94, 5]

2.3.4 Technique Comparison

The key properties for a comparison study of drilling techniques are mass, power, OHF requirements and the penetration rates in different drilled media. As the operational requirements change for each design, a qualitative comparison is made. Example penetration rates for each technique can be quantitatively stated. A comparison of these properties is given in Table 2.1. Depth is not considered, as this is subjective to the mission requirements. For example, both Curiosity and ExoMars use rotary-percussive drills, but have target depths of a few centimetres and two metres respectively.
2. Literature Review

Table 2.1: Comparison table of the general properties of the drilling techniques, and a comparison of the measured penetration rates of drills in different substrates [88, 9, 40].

<table>
<thead>
<tr>
<th>Technique</th>
<th>General Properties</th>
<th>Penetration Rate (ms$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OHF</td>
<td>Power</td>
</tr>
<tr>
<td>Rotary</td>
<td>High</td>
<td>Mid</td>
</tr>
<tr>
<td>Percussion</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Moles</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Rot-Per</td>
<td>Mid</td>
<td>High</td>
</tr>
</tbody>
</table>

An examination of Table 2.1 reveals the strengths and weaknesses of each technique. Rotary drills are able to drill through soil and rocks, but suffer from the large OHF required. While percussive drills tend to have lower mass and power requirements than rotary drills, their penetration rates are fairly low, and they suffer from limited penetration depths due to the issues with cuttings accumulation. Moles are able to drill to significant depths in regolith, and have very low operational parameters, but critically are unable to drill into harder material. Rotary-percussive drills are able to drill at fast penetration rates in hard rocks with a much lower axial force than rotary drills, however this is offset by a very heavy, complex and power-hungry system.

2.4 Development of the Dual-Reciprocating Drill Technique

Whilst rotary and rotary-percussive drills are capable of deep drilling in various substrates, their large respective masses mean that their use on missions is incredibly expensive. Conventional percussive drills, though much lighter, have very limited penetration depths, while moles are only able to penetrate regolith. In an attempt to create a low-mass, low-power drill able to penetrate far into a wide range of substrates, a number of biomimetic solutions were examined. One of these is the Dual-Reciprocating Drill (DRD). This section discusses the evolution of the DRD from the initial biological inspiration to the experiments performed with its evolving designs. The current status of the DRD mechanism design is discussed in Section 3.3.2.
2.4.1 Biomimetic Systems

Biomimetics can be described as the reverse-engineering of ideas and concepts from nature, implementing them into a field of technology to create novel solutions [77]. Numerous engineering problems are similar to those already solved through millions of years of biological evolution. However, care must be taken, as natural solutions are unlikely to be completely compatible with a specific engineering problem [10]. As such, whilst biomimetics does not try to copy these solutions directly, they are instead used as inspiration to create engineering systems that can then be optimised [78].

Although biological systems have evolved to survive on Earth, they often display characteristics that are very desirable for space applications, including drilling [77, 78]. Penetration of solid objects, such as rocks and wood, has been achieved by plants and creatures for millions of years, and this capability can be used as inspiration for the design of new drilling technologies [8]. Digging mechanisms have been inspired by the ovipositor valves of the female locust, with a concept design built that mimics the cyclical digging action of the valves [77, 78], while the design of the USDC was influenced by the digging action of the gopher [8]. The Dual-Reciprocating Drill was inspired by the digging mechanism of the ovipositor of the sirex noctilio, or wood wasp.

2.4.2 Wasp Ovipositor Mechanisms

The sirex noctilio has an ovipositor approximately 0.26mm in diameter and 10mm long, and uses a motion known as two-valve reciprocating drilling to dig into wood in order to lay its eggs. As shown in Figure 2.7, it is split into two halves; one has backwards-facing cutting teeth, the other has pockets for transporting sawdust upwards [45, 41]. The teeth are designed to provide little resistance when pushed into the substrate, but engage with it when moving upwards. As the ovipositor’s diameter is within the same order of magnitude as the wood cell size (0.1mm), the penetration mechanism is likely to involve the teeth hooking against a cell, which is then broken in tension when the ovipositor pulls upwards. The tensile force required to break the cell wall is added to the available compressive force, which helps to stabilise any buckling and create larger end loads. The teeth guide sawdust onto deeper teeth in the two ventral valves, which have rows of sawdust-removing pits.
on either side. Downward forces provided by the wasp’s abdomen are also used to assist penetration. The wood wasp has also been observed to move its body up and down which, coupled with the elastic lateral movements of the ovipositor, aids in the transportation and removal of the sawdust [117].

Figure 2.7: The wood wasp and a cross-section of its ovipositor [41].

As well as *sirex noctilio*, there are a number of other parasitic wasps which use ovipositor mechanisms. The *hymoneptera* wasp’s ovipositor consists of two lower valves that are normally able to slide beyond the apex of an upper valve. The *gasteruptiidae* and *aulacidae* families have a series of protrusions and ridges which prevent this, shown in Figure 2.8. Attempting to extend beyond the upper valve apex leads to the respective interlocking mechanisms forcing the ovipositors to bend [27].

Figure 2.8: Micrographs of the *gasteruptiidae* and *aulacidae* ovipositors [27].

This variety of ovipositor mechanisms has inspired a number of concepts for neurological probes for use in soft tissue surgery. Recent advances in surgical tools and imaging and modelling methods have given rise to the minimally invasive approach, which uses long, rigid and thin instruments to
access deep brain areas through a small aperture in the skull. In this case, a reciprocating probe is able to grip and displace the surrounding tissue with the teeth, thus minimising the damage caused. However, the straight-line paths that traditional tools must take limits the number of safe entry paths. To address this, a novel flexible, steerable probe is being developed. This takes inspiration from both the *sirex noctilio* and *hymoneptera* ovipositors, consisting of reciprocating interlocking mechanisms, allowing it to travel through the tissue with minimal force. A smart actuator mechanism at the tip is then able to steer the probe along curved trajectories [34, 35, 87].

### 2.4.3 Adaptation of the Wood Wasp Ovipositor

The key aspects of the *sirex noctilio*’s ovipositor mechanisms were considered to be the reaction generation and tension stabilisation. The receding drill half’s backwards-facing teeth create a reaction force of the substrate in the direction of drilling, creating a tension force in the receding half. By having the two halves linked, the tensile force is used to help pull the penetrating half downwards, as demonstrated in Figure 2.9. As a self-contained system, the potential of being able to generate forces with no external force required is of great interest to the space community.

![Diagram of the forces acting on the ovipositor halves](image)

**Figure 2.9:** Diagram of the forces acting on the ovipositor halves [49].

Initial studies into the development of a bioinspired drill examined its potential as part of a micro-penetrator system [78, 40, 39]. From this, a first concept design of a DRD was created, shown in Figure 2.10 (a). As well as the drill bit and actuation mechanism, a sample extraction method was also included. This system uses angled bristles in-between the metal
strips connecting the drill heads to the actuation mechanism. By utilising the reciprocation, particles trapped beneath the bristles at the bottom of the strips are lifted up, as demonstrated in Figure 2.10 (c). A simplified prototype, (b), was built and tested in chalk, mortar and clay, proving its capability for drilling low strength rocks [40, 41].

Figure 2.10: (a) The DRD drill and sample concept design (a), the constructed drill bit (b) and the sample extraction mechanism (c) [40, 78].
2.4.4 Experiments performed with the DRD

The DRD was remade into a simplified design, shown in Figure 2.11, with a general form consisting of a cone atop a cylinder split into two halves, with backwards-facing cutting teeth running up the length of the cone and cylinder.

![Figure 2.11: Picture of the drill halves.](image)

The first full experimentation of the DRD involved the design of a test bench able to control the OHF acting on the halves, and allowed the independent exploration of a large number of operational parameters, discussed further in Section 3.1.1. The test bench consists of a reciprocation mechanism and motor attached to an aluminium plate guided by supporting rails, with a counter mass pulley system used to determine the acting OHF, shown in Figure 2.12. The reciprocation motion was achieved by transforming the rotation of a conventional motor using a double pin and crank rocker mechanism [45, 49, 47]. The test bench was used to vary the OHF, the frequency and amplitude of the reciprocation motion and the substrate properties [48, 51].

These experiments focused on determining the effects of these parameters on the absolute and relative depth increase achieved by the DRD compared to static penetration. Other results included the change in force vs. depth and the effects on final depth, the power and current consumed during drilling, and the initial velocity [45, 47]. A major observation of these experiments was the presence of slippage, in which the receding drill half moves upwards a significant distance instead of gripping the substrate, thus reducing the drilling efficiency, shown in Figure 2.13. Ideally, the gripping of the teeth into the substrate would hold the receding drill half in place, and force the penetrating half further down. However, this is not the case, with little
2. Literature Review

Figure 2.12: Test bench set-up and one full reciprocation cycle [49].

gripping occurring, and as such the drill head moves upwards. Slippage is defined as the total amount of backwards movement, with a fully receding drill head resulting in no penetration. The levels of slippage seen in these experiments were very large, with the best results giving values of 0.9 [49].

Figure 2.13: Diagram of the progression of the DRD with and without slippage [49].

Further experiments were performed with a reciprocating mono-block drill head (MDH), using a new test rig consisting of a hydraulic ram and force sensor. By varying the operational conditions, including slippage, the extent of the penetration and traction forces experienced was assessed. The major
conclusion from these experiments was the importance of lateral motions and their resultant forces on the drilling performance. This is discussed in further detail in Section 3.3.1 [50]. To complement these experiments, a numerical model was developed using the Discrete Element Models (DEM) on the Graphics Processing Unit (GPU) hardware, with the aim of simulating the compaction of the regolith seen during the experimental work. Whilst it is now possible to create million-plus particle simulations, and the DEM was able to recreate the behaviour of regolith under different levels of compaction, the penetration simulations using the MDH were not considered satisfactory, with the levels of the traction forces observed being much too high [45].

2.5 Regolith Simulants

The ability of a spacecraft and its instruments to function in the extreme environments experienced in space exploration is dependent on the tests performed on the systems in simulated conditions. For rovers, drills, samplers and other in-situ instruments, this includes the regolith that they will interact with. Data provided by the samples brought back by Apollo and Luna, and the observations made by lunar and Martian rovers and orbiters, have enabled the creation of simulants that mimic as best as possible the various regoliths. The properties of regoliths are not constant throughout the entire body, with composition, density and water content varying from location to location. It is therefore necessary to ensure that the correct simulants are developed and used for each separate mission. The most significant of these are detailed in this section.

2.5.1 Lunar Regolith Simulant Development

Given the very limited amount of Apollo lunar samples, and the need for lunar materials that can be used in engineering studies for supporting future lunar activities, over 30 lunar regolith simulants have been developed [113]. The first to be created was the MLS-1 analogue, designed to match as closely as possible the mineralogy, chemistry and texture of the lunar mare regolith [104]. The most well-known simulant, the JSC-1, was developed by NASA’s Johnson Space Centre to complement this. The JSC-1 is a glass-rich, basaltic ash mined from a volcanic ash deposit in the San Fransisco volcano field, designed to approximate the properties of the lunar mare soil found at the
Apollo 14 site [76, 118]. After frequent use exhausted the supply, the JSC-1A was developed as a direct replacement, matching as closely as possible the properties of the original JSC-1 [93]. Fine and coarse variations of this were also created, known as JSC-1AF and JSC-1AC, giving the simulant a much smaller and larger average grain size respectively [98].

Rapid use of these simulants has presented a significant problem with regards to providing materials for future studies, resulting in prohibitive costs for obtaining large quantities. Because of this, numerous other simulants have been developed by other users, for example the GRC-1 [86], OB-1 [13], and CAS-1 [121] analogues. Each of these were used as reasonable first approximations for the specific applications for which they were designed, but are unsuitable for other lunar development studies [113]. The past usage and creation of these simulants has been criticised, with a call for a reform of the Marshall Space Flight Center (MSFC) Lunar Simulant Program [114].

2.5.2 Lunar Highland Simulant Series NU-LHT

There is a growing interest in the exploration of the lunar polar regions, and a collaboration between ESA and Roscosmos has resulted in the planning of a series of lunar exploration missions, involving landing on the south pole and analysing the subsurface materials [11], before culminating in the Lunar Polar Sample Return mission [32]. To the best of current knowledge, the soil covering the lunar polar regions is best approximated by the so-called highlands regolith. The only mission to date that has explored a site located in an area with a representative regolith is Apollo 16, which was situated over 200km away from the nearest lunar mare [109]. The presence of mare, potassium and other rare-earth elements in the cores taken from this mission prevent them from being true highland samples. Despite this, they are considered compositionally close, and the representativeness of the site regolith and intact nature of the 64001/64002 cores have resulted in them being chosen as reference materials to be used for initial Figure of Merit calculations for future highland simulant characterisations [101, 100].

With the aim of creating a simulant representative of the whole highlands regolith, as opposed to a single area, the MSFC agreed to develop a polar regolith simulant series produced by the United States Geological Survey (USGS). The average compositions taken from the Apollo 16 sam-
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Piles were used to create the NASA-USGS Lunar Highlands Type Pilot (NU-LHT-1M) and Prototype (NU-LHT-2M) simulants. These were created from crystalline, pseudo-agglutinate and glass component materials, with a larger agglutinate percentage used for the 2M, with the particle size ranging from dust to ≤1mm [109].

2.5.3 Presence of Water Ice in Lunar Regolith

There is a significant amount of evidence indicating that vast quantities of water ice and other volatiles are present within the lunar subsurface in the polar regions, particularly in the permanently shadowed craters near the south pole. The LCROSS mission observed the ejecta created by striking one such region, the south pole crater Cabeus, and measured concentrations of water ice in the regolith of 5.6±2.9% by mass [21, 80]. It is thought that the water ice could be present either in the form of particles, ice-cemented regolith or ice blocks, while other measurements have also noted the existence of water adsorbed at the surface in multiple other locations [57]. The existence of such volatiles has incredible potential for use in future lunar activities as an inexpensive source of propellants and other consumables. As a result, confirming these findings has become a major driver for future lunar exploration.

2.5.4 Mars Regolith Simulants

The most commonly used Martian regolith simulant is the Johnson Space Centre Mars-1 (JSC Mars-1), developed from material mined from a cinder cone at Pu‘u Nene, Hawaii, and chosen for its spectral similarity to bright regions on Mars. As with the lunar equivalent, high demand required the development of the JSC Mars-1A complementary material [104]. Another well-known simulant is the Mojave Mars Simulant (MMS), taken from the Saddleback Basalt in the Mojave Desert. This was created to simulate the basaltic regions seen by Pathfinder, Spirit and Opportunity, and has been used in the testing of instruments for both Phoenix and Curiosity [89]. Other simulants include the Salten Skov dust simulant, the silty sands Schwarzl UK4 and Fohnsdorfer Haldit [104, 128], and the CWRU-1 analogue [70].

The Engineering Soil Simulant series, ES-1, ES-2 and ES-3, was used for testing the trafficability of ExoMars. These represented the fine material found throughout Mars and the aeolian and coarser materials often found in
dunes [52, 18]. Another pair of simulants, the Surrey Space Centre Mars Simulant 1 (SSC-1) and Surrey Space Centre Mars Simulant 2 (SSC-2), were also developed initially for the ExoMars rover and locomotion testing [102]. SSC-1 is quartz-based, with medium-sized rounded grains and a small quantity of silt, while SSC-2 is a very fine-grained garnet mineral sand. The properties of both are summarised in Table 2.2. The SSC-1 and SSC-2 simulants were chosen as the most appropriate for the testing of the DRD, and have been used in all regolith drilling experiments [45].

<table>
<thead>
<tr>
<th>Property</th>
<th>SSC-1</th>
<th>SSC-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mineral</td>
<td>Quartz</td>
<td>Garnet</td>
</tr>
<tr>
<td>Particle Density (kgm$^{-3}$)</td>
<td>2394</td>
<td>3154</td>
</tr>
<tr>
<td>Particle Size ($\mu$m)</td>
<td>100 - 1000</td>
<td>30 - 150</td>
</tr>
<tr>
<td>Particle Shape</td>
<td>Sub-rounded</td>
<td>Sub-Angular</td>
</tr>
<tr>
<td>Poured Density (kgm$^{-3}$)</td>
<td>1413</td>
<td>1945</td>
</tr>
<tr>
<td>Poured Relative Density (%)</td>
<td>7.4</td>
<td>-0.4</td>
</tr>
<tr>
<td>Vibrated Density (kgm$^{-3}$)</td>
<td>1687</td>
<td>2344</td>
</tr>
<tr>
<td>Vibrated Relative Density (%)</td>
<td>74</td>
<td>71</td>
</tr>
<tr>
<td>Internal Angle of Friction (°)</td>
<td>35</td>
<td>41</td>
</tr>
<tr>
<td>Cohesion (kPa)</td>
<td>910</td>
<td>1190</td>
</tr>
</tbody>
</table>

Table 2.2: Properties of the SSC-1 and SSC-2 regolith simulants [49].

### 2.5.5 Cementation of Martian Regolith

The presence of water on Mars is well documented, however the different chemistry and composition of the Martian regolith presents its own unique challenges, in the form of soil induration and surface crusts. The Viking landers were the first to observe this phenomenon, with both observing a layer of lightly cemented fine-grained sediments 1 - 2cm thick at their landing sites, with the Viking Lander 2 site seeing both a large area of fractured crust [84] and crusty to cloddy material, caused to some extent by cementation of the grains, occupying $\sim$86% of the sample field [82]. Further indications of this cemented soil, labelled as duricrust, include crusts found by Sojourner [14] and Spirit [3], observations of disturbed soils by Opportunity [58] and crusts and clods found by Phoenix [107].
The composition of duricrusts has yet to be conclusively observed, though there is evidence of clays [7] and sulphur and chlorine concentrations of 10% and 1% respectively [20, 105]. Several hypotheses as to the formation of duricrusts exist, with the process likely caused by mobile salts [60] and a cementation process caused by transient liquid water [23]. The water’s changing state allows the transportation and deposition of dissolved salts throughout the soil, which cement the dust and sand grains to form the crust. The extent and thickness is dependent on the total repetition and length of time the liquid water is present [68], while the amount of water required appears to be very small [19]. Experiments performed to determine the duricrusts’ properties include the examination of diffusion barriers and vapour transport under water-heavy conditions [59], and the effects of cementation on the soil’s spectral [23] and thermal properties [91, 83]. A model of the formation of cemented soils found that crusts with a high smectite content had thicker, harder crusts, while palagonitic soil created a thinner, more friable crust [15].

2.5.6 Regolith Preparation Methods

Alongside water content and composition, another key consideration for regolith simulant use is the preparation method. This determines the degree of compaction of the regolith, given by its relative density, which in turn greatly affects its mechanical properties. For example, the density of SSC-1 can range from 1383 to 1794kgm$^{-3}$ [102]. Regolith preparation procedures tend to vary from case to case, and the techniques are often not reported. This is also the case for the creation of icy regoliths, with the methods used in previous experiments lacking consistency [22, 74].

With numerous studies showing the impact of density on the performance of spacecraft systems, a study into various preparation techniques was performed in preparation for testing the DRD in regolith. The pour, vibration and rain techniques, shown in Figure 2.14, were tested on the SSC-1 and SSC-2 simulants to determine the relative densities and soil strengths they produce. These were demonstrated to efficiently vary the mechanical properties of the simulant used, allowing for repeatable and controllable test conditions [46, 45]. The pour technique, in which the substrate is poured from a fixed distance above the surface, and the vibrate technique, where the container the substrate is being poured into is being continuously vibrated, were used in the DRD and MDH experiments [49, 50].
2. Literature Review

2.6 Summary

This chapter has provided a summary of the literature relevant to the dual-reciprocating drilling technique. The value of drilling systems as a part of planetary exploration missions was discussed, evidenced by the numerous missions both past and present that include such a system. Also highlighted were the challenges that are present when attempting subsurface exploration, including the various substrate media and environmental factors that must be accounted for and overcome.

The various conventional drilling techniques that are currently available and in use have been summarised. An analysis and comparison of these techniques revealed their respective strengths and weaknesses. The desire to create a lightweight, low power drill capable of penetrating through various media resulted in the consideration of non-traditional drilling methods, in particular those inspired by biomimetic systems. A number of biologically-inspired options were considered, with the ovipositor mechanism of the wood wasp adapted to create the Dual-Reciprocating Drill. The research into this technique, including the various concept designs and experiments, has been detailed. This has revealed the importance of key factors such as slippage and sideways movements of the drill heads in the penetration performance.

This review has also detailed the various lunar and Martian simulants used in the testing of instruments. The properties of the regolith of a planetary body are dependent on location, density and water content, and as such the simulants used must accurately represent the target area. The various lunar and Martian simulants created are detailed, with particular emphasis placed upon the presence of water, believed to be present at the lunar south pole and the cause of Martian regolith cementation.
Chapter 3

Research Rationale and Methodology

In this chapter, the areas of research that will be explored in this thesis are detailed. The literature review has shown the work performed in designing and testing drilling systems for planetary exploration, and has detailed the analysis and evolution of the DRD technique. This is used to identify gaps in the knowledge of the dual-reciprocating drill technique. The work that can be done to bridge these gaps is then proposed, resulting in the identification of three areas of research. These are: an investigation of the drill head geometry, an analysis and use of icy regolith simulants in drilling experiments and an investigation of the addition of actively controlled lateral motions.

The overall aim of this research is to continue the analysis of the DRD technique, furthering the design from the initial concept test bench towards an integrated design that can be deployed and tested. To this end, the testing of drill head designs will use a series of experiments that explores the final group of parameters that could influence the performance of the DRD. Continuing from this, the effects of ice in regolith will be examined, both in terms of the drilling performance of DRD and the properties of the regolith as the water ice content changes. Finally, an internal actuation mechanism is designed, leading to the first testing of an integrated system. This will coincide with a study of active lateral movements of the drill head, in which novel drilling motions can be created and compared to pure reciprocation.
3.1 Geometrical Parameters

The current research into the DRD has focused on the interactions between the regolith and drill heads. This has included an exploration of how the numerous operational and substrate parameters can influence the performance and behaviour of the DRD in planetary regoliths. The work presented in this section acts as a continuation to this investigation by exploring the effects of the geometrical parameters. The parameter selection and drill head design are explained, before the results and analysis of previous experiments are presented, which highlight the concepts that should be investigated further.

3.1.1 Parameters Influencing DRD Performance

The parameters which define the design and operation of the DRD can be placed into three categories: geometrical, operational and substrate. The geometrical parameters give the shape of the drill head design, the operational parameters are defined by the technical implementation and experimental set-up and the substrate parameters describe the characteristics of the drilled substrate. The parameters defined for each category are listed in Table 3.1, and the geometrical parameters are shown in Figure 3.1.

<table>
<thead>
<tr>
<th>Geometrical</th>
<th>Operational</th>
<th>Substrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinder radius, $R_{int}$</td>
<td>Overhead force, $OHF$</td>
<td>Particle size distribution</td>
</tr>
<tr>
<td>Cylinder + teeth radius, $R_{ext}$</td>
<td>Reciprocation frequency, $f$</td>
<td>Particle shape/angularity</td>
</tr>
<tr>
<td>Cylinder height, $L_2$</td>
<td>Reciprocation amplitude, $a$</td>
<td>Density</td>
</tr>
<tr>
<td>Cone half-apex angle, $\alpha$</td>
<td>Drilling speed, $v_d$</td>
<td>Porosity</td>
</tr>
<tr>
<td>Cylinder half-apex angle, $\alpha_2$</td>
<td>Actuator input current</td>
<td>Humidity content</td>
</tr>
<tr>
<td>Teeth depth, $R_{ext} - R_{int}$</td>
<td>Actuator input voltage</td>
<td>Mineral nature</td>
</tr>
<tr>
<td>Number of cylinder teeth, $N_2$</td>
<td>Actuator input power</td>
<td>Ice content</td>
</tr>
<tr>
<td>Tooth height, $L_2/N_2$</td>
<td>Drill depth</td>
<td></td>
</tr>
<tr>
<td>Number of cone teeth, $N_1$</td>
<td>Free drill stem length</td>
<td></td>
</tr>
<tr>
<td>Cone teeth rake angle, $\alpha_1$</td>
<td>Stem buckling threshold</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1: Parameters considered to potentially influence the performance of the DRD [45].
3. Research Rationale and Methodology

3.1.2 Operational and Substrate Parameters

Previous experiments have focused on the exploration of the operational and substrate parameters. The test bench described in Section 2.4.4 was initially used to perform drilling experiments up to depths of 25cm. Amongst those listed in Table 3.1, the test bench was used to vary the overhead force, the reciprocation frequency and amplitude, and the substrate type and density. These experiments compared the effects each parameter had on the absolute and relative depth achieved by the DRD to that of static penetration, and measured both the change in the forces experienced by the drill bit with depth and the effects on final depth, power and current consumed and initial velocity. This was able to demonstrate the DRD’s ability to penetrate deeper than static penetration. Though the goal of no net external force cannot be achieved, the DRD does lower the normal force required to penetrate regolith. Two Martian regolith simulants with distinctive properties were used in these experiments: SSC-1 and SSC-2, described in detail in Section 2.5.4, with the relative densities of each being determined by the preparation technique.

Later tests focused on the depths achievable by varying the overhead force, frequency and amplitude [42]. These demonstrated that increasing the frequency and amplitude results in a greater depth. Increasing any of these also increases the power requirement, with amplitude having the greatest effect. These experiments were performed using the same set-up, though with a barrel of regolith used as opposed to a bucket, allowing for a much larger drilling depth limit. Using this, the DRD was able to achieve a maximum depth of 450mm.

Figure 3.1: Diagram of the original geometrical parameters [45].
3.1.3 Drill Head Design Tests

While the operational and substrate parameters have been thoroughly examined, very little has been done with respect to the geometrical parameters. The DRD experiments performed in [45] used three drill heads, differing from each other by varying a single geometrical parameter. Any differences these caused were not recorded, either because they were not studied or were considered negligible.

As part of the MDH force tests, a number of drill heads were built and briefly tested in vibrated SSC-2. Four of these had different cylinder teeth rake angles, and another had a larger diameter. These were made with Acrylonitrile Butadiene Styrene (ABS), while another was also manufactured in steel. As with the other MDH tests, the penetration and traction forces were examined. These varied considerably for most slippage and rake angle values, with the exception of the high slippage case, in which the traction forces were consistently low, while the larger diameter and steel drill heads both showed greater penetration forces.

3.1.4 Investigation of the Drill Head Design

The previous experiments have shown that the DRD design experiences high levels of slippage and low traction forces. As a result, while DRD has been proven to be more effective than static penetration, the maximum depth it has reached is only roughly 450mm. This suggests that the teeth design of the DRD is not ideal for regolith. To improve the performance, the design of the drill head itself should be investigated.

Although different drill head designs have been created, the variations have generally been minimal. This research will create a wide range of drill heads, each having well-defined and significant variations of the geometrical parameters, complementing the previous work on the operational and substrate parameters. Experiments with these drill heads will be performed to determine the relationship each design has with regards to performance values such as final depth, penetration rate and power, with the aim of finding an optimal drill head design. The experiments will also attempt to show that the DRD is capable of drilling to greater depths than have currently been achieved.
3.2 Drilling in Icy Regolith

The majority of experiments performed throughout the research into DRD have used dry Mars simulants. A substrate property yet to be studied with regards to DRD performance is the water and/or ice content that may be present. The work performed here will act as a continuation of the investigation of substrate parameters by examining the properties of icy lunar regolith. The simulants used in previous DRD tests are summarised, and previous experiments performed to determine the properties of icy simulants are discussed. These will be used as a starting point from which a study of lunar highland simulants with varying water ice contents can be performed.

3.2.1 Summary of Substrates Used in DRD Testing

The first testing of a DRD design used plastic drill heads with varying rake angles and cutting speeds to measure the cutting forces required to cut through a condensed polystyrene workpiece [39]. A later study tested the drilling efficiency of a simplified metal prototype in three substrates with increasing densities: condensed chalk, lime mortar and none-fired clay [40, 41].

As part of the regolith simulant preparation tests performed for the first experiments with the DRD test bench, the properties of five simulants, SSC-1, SSC-2, ES-1, ES-2 and ES-3, were examined extensively [45], with the particle size distribution and shape, the density and humidity content for each determined. The densities and strengths of SSC-1 and SSC-2 with the various preparation methods described in Section 2.5.6 were also determined [45, 46]. For the DRD and MDH experiments, only the SSC-1 and SSC-2 simulants were used, prepared with both the poured and vibrated techniques, up to depths of 30cm. The first experiments with the DRD test bench revealed that the preparation technique had a greater effect on final depth than the choice of simulant. The forces experienced with depth were higher for the denser vibration techniques, and it was observed that the surface deformations during drilling were different for each technique [49].

3.2.2 Effect of Ice on Regolith Properties

Given the presence of water ice on numerous bodies in the solar system, there have been many experiments to determine the properties of icy regolith sim-
ulants. A study into the excavatability of lunar regolith examined the effects of different water ice concentrations, using samples prepared with water contents ranging from 0 - 11% by mass. Load-penetration tests determined the specific energy and specific penetration, allowing the strength and properties with respect to excavation to be examined. Low and medium strength samples with 0 - 1.5% water were easy to excavate, exhibiting behaviour similar to that of weak coal or shales. High strength (≈8.4%) and very high strength (≈10.6%) samples acted like moderate-strength and cemented limestones respectively, requiring significantly larger excavators [44].

Another series of experiments used JSC-1A mixed with water to have contents incrementally ranging from 0 - 8% by mass. Penetration tests using a percussive cone penetrometer were able to determine a clear correlation between penetration rate and ice content. The mechanics of penetrating icy regolith were proposed to be different to those for dry regolith, with the restriction of grain movement in frozen soils resulting in fractured ice being trapped, thus preventing the penetrometer from descending further [79]. A summary of other tests with icy lunar regolith simulants is given in [74].

Studies have also been made into the properties of icy JSC-1 Mars under simulated Martian conditions. When prepared by water vapour diffusion, it was found to have a thermal conductivity that increases linearly with water content [106], while a study into water ice nucleation characteristics demonstrated a significant temperature dependence, with the values measured also dependent on sample preparation [90].

Although a number of experiments have been performed with icy simulants, there has been no investigation of the properties of icy highland simulants of lunar polar regolith, such as the NU-LHT series. As the compositions of highland and mare regoliths are different from each other, as discussed in Section 2.5.2, it is possible that their properties when ice is present will differ. Additionally, the effect the presence of ice in lunar highlands and Martian regoliths has on drilling and sampling systems has yet to be tested.

3.2.3 Examination of the Properties of Icy Regolith

While previous research with the DRD has demonstrated the effects of many of the substrate parameters listed in Table 3.1, no work has been performed
to determine its performance were it to be used in regions where water or ice is expected. Similarly, the DRD has yet to be tested in lunar simulants. Additionally, the potential presence of ice at the lunar poles has led to the development of a lunar highlands simulant, though its properties with the presence of ice have yet to be studied.

This area of research will continue the investigation into substrate properties affecting the DRD by examining the effects of varying contents of water ice on the drilling performance. This will also form part of a broader investigation into the properties of the lunar highland simulant NU-LHT-2M. The aim of this work will be to present the first drilling tests in both icy and lunar regolith, and to provide a first step towards the characterisation of NU-LHT-2M. This will also involve the development of a standardised procedure for preparing icy regolith simulants. From this, further studies will be able to build upon and further the knowledge of the simulant’s physical and thermal properties.

3.3 Lateral Motion and Integrated Design

One of the major conclusions of the previous DRD research was that the presence of small lateral motions creates forces that play a much more significant role in the performance of the DRD than the traction forces generated by the backwards-facing teeth [45]. The work to be performed in this area will involve the addition and active control of lateral motions to the reciprocation motion. To do this, a new mechanism is required which is able to produce this complex motion. The design of the original internal actuation mechanism for reciprocating the drill heads is discussed, which will be used as a starting point from which a complex motion mechanism can be developed.

3.3.1 Importance of Lateral Forces

Lateral movements of the drill heads were initially observed in the first experimentation of the DRD in regolith [49]. It was seen that slight sideways movements of the drill bit occurred, caused by the regolith applying non-vertical forces due to the conical shape of the drill heads as they are pushed into it. This is shown in Figure 3.2.
The effects of these sideways movements were first discovered in the MDH experiments [50]. A single solid drill head was reciprocated under controlled speed, amplitude and slippage values using a hydraulic ram, with the penetration and traction forces measured using a force sensor test bench. A major conclusion from these experiments was that the traction force generated by the backwards-facing teeth is generally two orders of magnitude smaller than the force required to penetrate the regolith, explaining the high levels of slippage seen. Given that this traction value was so low, the added penetration obtained with DRD compared to static penetration cannot be explained by the additional penetration force provided by the traction generated by the teeth.

The major difference between the DRD and MDH is that the lateral movements observed for the former are absent in the latter, due to the axial symmetry of the MDH, coupled with a rigid test rig seemingly eliminating any sideways motion. It was proposed that the lateral movements of the DRD minimize the compression of the regolith in front of the drill head tip, allowing easier penetration. An analytical estimation calculated that the lateral forces generated by these sideways movements were at least 0.1 times the required penetration force, or more than an order of magnitude higher than the traction forces. As a result, it was concluded that the sideways movements are more important than the traction created by the backwards-facing teeth in DRD performance, and improve the drilling efficiency by anchoring the drill and creating extra tension in the receding half [50, 45]. Based upon these observations, demonstrating experimentally how and to what extent the controlled addition of lateral motion can improve the performance of DRD will be a major focus of this research.
3.3.2 Internal Actuation Mechanism

Currently the sideways movements of the DRD have been passively created and uncontrolled. To create consistent and measurable sideways movements, active control of the lateral motion is required. This cannot be achieved by external mechanisms such as the original test bench. Instead, a mechanism will be developed that can fit inside and actuate the drill heads.

Work performed in furthering the development of the DRD has involved advancing it from the current proof of concept design to a fully integrated prototype. The aim of this was to convert the actuation mechanism from the test bench shown in Section 2.4.4 into a compact design. Several trade-off studies resulted in the proposition of an integrated system, in which the actuation mechanism would be fitted inside the drill heads [33]. The mechanism chosen was a simple quad cam drive system, 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 reciprocation and removing any other radial motions [42]. A partial model of this system was built, shown in Figure 3.3 (a), which demonstrates the cam-drive system. An integrated system was designed, in which the actuation mechanism, motor and payload bays are incorporated into a single module, shown in Figure 3.3 (b). This would be deployed by a bistable composite mechanism, which would also provide a constant overhead force [42]. It must be noted that currently a full internal mechanism has not yet been built and integrated into the drill heads.

3.3.3 Design of a Complex Motion Internal Actuation Mechanism

Previous research has shown that lateral movements of the drill halves play a significant role in the performance of the DRD. However, these movements have so far only been created passively. To demonstrate the benefits of lateral movements, active control is required. The original internal actuation system design can be used as inspiration for the development of a new mechanism capable of producing reciprocation-only and combined lateral-vertical motions. An integrated system will be used, which will aim to show the additional depth reached through the use of controlled lateral movements, as well as record the penetration and traction forces experienced.
This research will provide the first investigation into complex motions and a comparison with the original reciprocation motion. The aim of this is to demonstrate how the controlled addition of lateral motions of the drill heads can be beneficial to the drilling performance of the DRD. This investigation will also involve the development of a complete internal actuation mechanism, and will demonstrate the first drilling operation using a fully integrated system. Though the mechanism will be designed for research purposes, this will provide another step towards creating a first system prototype.

3.4 Summary

In this chapter, three gaps in the knowledge of the DRD have been identified. The first continues the work performed in the evaluation of the operational and substrate parameters. Extensive research has been performed to determine their respective influences on the penetration performance of the DRD. However, the geometrical parameters that define the shape of the drill head have yet to be looked at in any great detail. A similar series of experiments will be performed to examine the importance of the drill head design parameters. This will further complete the investigation of the wide range of factors that must be considered in the design and operation of the DRD.
The second area will further explore the substrate parameters by testing the DRD in the lunar highland simulant NU-LHT-2M with varying water contents, providing the first testing of DRD in icy and lunar regolith. Additionally, the growing interest in the lunar south polar regions requires that the effects of water ice in highland simulants on its properties be understood. The changes in properties of the NU-LHT-2M with varying ice contents will thus be found and compared to the observations made with the DRD. This can then be used as a starting point for the further characterisation of this simulant in preparation for future instrumentation testing.

The final area of research will seek to experimentally confirm the observations made in previous experiments, in which lateral forces created by sideways movements of the drill head appear to have a significant bearing on the DRD’s performance. This will be achieved by designing a new mechanism that is able to create actively controlled lateral movements alongside the normal reciprocation. This will have the added benefit of furthering the work performed in designing an internal actuation mechanism, which at this point has yet to be built. The DRD can thus be evolved further, both in terms of the physical design and in creating and testing new drilling motions.

By addressing each of these areas of research, this thesis will have greatly advanced the understanding of the DRD, and the design will have taken significant steps towards the overall goal of becoming a viable drilling technique. The DRD will have been tested both to new depths and in lunar and icy simulants. New drilling motions will have been tested, which will lead to a greater understanding of the DRD mechanics and the proposition of techniques able to further improve the drilling performance. This will coincide with the first full development of an actuation mechanism able to sit within the drill heads, providing a first step towards the development of a true system prototype.
Chapter 4

Drill Head Design

This chapter describes the design of the drill heads used to examine the effects of varying the geometrical parameters on the performance of the DRD. These parameters are defined, and the drill head designs are presented. The experimental procedure is then outlined and the results are analysed, before the conclusions are given.

4.1 Redefinition of the Geometrical Parameters

As detailed in Section 3.1.1, the geometrical parameters define the shape of the drill head. In order to effectively examine the effect these parameters have on the performance, those used must be independent from each other, i.e. changing one parameter has no effect on the others. In the original design, shown in Figure 3.1, the cone teeth rake angle, $\alpha_1$, is dependent on the cone half-apex angle, $\alpha$, which itself is dependent on the cylinder and tooth radii. The shapes of the cone teeth are also different from those on the cylinder. To keep the shape consistent, the parameters are redefined, as shown in Figure 4.1. The cone half-apex angle is now defined as the angle of the cone only, while the width of the teeth, $R_t$, is now measured as the distance of the line normal from the face of the cone or cylinder to the tip of the tooth. The definitions of the cylinder radius, $R_{int}$, and tooth length, now symbolised by $L_t$, are kept the same. With these definitions, the teeth on the cone are now the same shape as those on the cylinder and do not affect the parameters that define the sizing of the cone.
From this new definition of the drill head geometry, five key parameters are identified, each of which are independent of the other. These are:

- Tooth width, $R_t$
- Tooth length, $L_t$
- Cylinder radius, $R_{int}$
- Rake angle, $\alpha_1$
- Cone half-apex angle, $\alpha$

The other parameters labelled in Figure 4.1 will be affected by changing the key parameters, such as the length of the cone face, $L_{cf}$, and the total number of teeth. These are considered relatively unimportant, and are accounted for by keeping the total length of the drill head, $L_{tot}$, constant. The upper and lower lengths of the teeth, $t_u$ and $t_l$, are defined by the tooth width, length and rake angle, while the drill stem attachment, $L_{att}$, is given an arbitrary length.

These parameters were also chosen due to their perceived effect on drilling performance. It is assumed that smaller $R_{int}$ and $\alpha$ values, creating a thinner, pointier drill, will increase drilling depth. Wide, small teeth with a greater $\alpha_1$ will result in a greater area of contact between the teeth and the substrate. It is predicted that this will cause the teeth to better grip the regolith, consequently improving the drilling performance by increasing the traction and reducing slippage.
4.2 Design of Experiment

In order to produce an efficient and feasible series of experiments, the correct experimental approach must be used. The $2^k$ factorial design is used in early experimental work [81], allowing a full investigation of the main effects and first-order interactions of each parameter whilst providing the smallest number of experiments necessary to do so.

Each of the five key parameters is given a low (-) and high (+) level. If a drill head design is made for each combination of parameter levels, a complete two-level factorial experiment would require $2^5$, or 32, drill heads. However, the time and resources required to make this number of drill heads is not feasible. If there are four or more parameters, it is often unnecessary to run all of the possible combinations. A $2^5$ experiment has 31 degrees of freedom, with five of these corresponding to the main effects of each parameter, ten corresponding to two-factor interactions and the remaining sixteen associated with three-factor and higher interactions. Generally, it can be assumed that the system is driven by the main effects and low-order interactions, and that the relevant information can be acquired using a resolution $V 2^{k-1}$ fractional factorial design. As a result, only half of the combinations need to be examined, resulting in a more manageable sixteen drill head designs. A disadvantage of this technique is that only two levels are measured, and as such a linearity in their effects is assumed, however for early experimental studies of new systems, this is considered a reasonable assumption [81]. Additionally, increasing the number of levels for each factor exponentially increases the number of combinations. To keep this number feasible, only two levels of five factors are used. The parameter level combinations this design of experiment results in are given in Table 4.1.

4.2.1 Drill Head Sizing

The low-level parameters chosen are designed to be generally similar to those used for the original drill head design. To increase the likelihood of observing notable differences in performance from these experiments, the high-level parameters are significantly larger. These values are chosen to be significantly far apart, though without representing the minimum and maximum values possible, allowing for drill heads with visibly different, but recognisably similar, shapes to be produced. There are several restrictions imposed on the
parameter sizes available. The cone face length, $L_{cf}$, must be a multiple of both the high and low $L_t$ values, restricting the possible combinations of $R_{int}$ and $\alpha$ values. Another requirement is that there must be at least two teeth on the cone for each drill head.

Given that manufacturing sixteen drill heads in steel would require significant time and resources, they are instead made with ABS plastic using a MakerBot\textsuperscript{TM} 3D printer. The total length of the drill heads are therefore limited by the dimensions of the printer. By taking the limit of approximately 230mm, and giving $L_{att}$ a value of 40mm based upon the original design, the maximum length of the drill head, $L_{tot}$, is 190mm. Finally, while it is not possible to have the same $L_{tot}$ for all drill heads, this value should be made as consistent as possible. From these restrictions the parameter levels were selected, and are given in Table 4.2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Drill Heads</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_t$ (mm)</td>
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<tr>
<td>$L_t$ (mm)</td>
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<tr>
<td>$R_{int}$ (mm)</td>
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<tr>
<td>$\alpha_1$ (°)</td>
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<tr>
<td>$\alpha$ (°)</td>
<td>+ - - + - + + - - + + - + +</td>
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</tbody>
</table>

Table 4.1: The parameter levels for each drill head for a $2^{5-1}$ fractional factorial experiment.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>- Level</th>
<th>+ Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_t$ (mm)</td>
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<td>9</td>
</tr>
<tr>
<td>$L_t$ (mm)</td>
<td>7</td>
<td>14</td>
</tr>
<tr>
<td>$R_{int}$ (mm)</td>
<td>7</td>
<td>14</td>
</tr>
<tr>
<td>$\alpha_1$ (°)</td>
<td>45</td>
<td>75</td>
</tr>
<tr>
<td>$\alpha$ (°)</td>
<td>9.59</td>
<td>14.48</td>
</tr>
</tbody>
</table>

Table 4.2: Low and high level parameters.
4. Drill Head Design

The parameter values for each drill head design are detailed in Table 4.3. The drills are shown in Figure 4.2, with the schematics shown in Figure 4.3. From these two figures, the differences in the designs created by each factor combination can be seen. Each drill head has a total length of 193 ± 1mm.

<table>
<thead>
<tr>
<th>Parameter</th>
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<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_t$ (mm)</td>
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<td>3</td>
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<td>$L_t$ (mm)</td>
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<td>$R_{int}$ (mm)</td>
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</tr>
<tr>
<td>$\alpha_1$ (°)</td>
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</tr>
<tr>
<td>$\alpha$ (°)</td>
<td>14.5</td>
<td>9.6</td>
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Table 4.3: The parameter sizes for each drill head.

Figure 4.2: Picture of the sixteen drill head designs.

4.2.2 Substrate Parameters

As the focus of these experiments is on the drill head design, the (OHF) and reciprocation frequency and amplitude will be kept constant. However, the properties of the regolith that the DRD may be required to drill into can vary considerably, potentially affecting the performance of the different drill head designs. The properties of the substrate are dependent on its type and preparation, as discussed in [46]. The substrates used in the previous DRD experiments are the SSC-1 and SSC-2, whose relative densities are
Figure 4.3: SolidEdge draft drawings of the sixteen drill head designs.

determined by using either the poured or vibrated preparation methods [49]. The properties of the regolith simulants with these preparation methods are given in Table 2.2.

While both regolith simulants will be used, they will only be prepared using the poured method, with the regolith being poured from a height of 40cm above the surface. This is partly due to the volume of sand that will be used, discussed in Section 4.3, which would require extremely expensive equipment to be vibrated successfully. Secondly, while changes seen in the force versus depth profiles due to density are consistent, the profiles for the substrate types are very different, as discussed in [49]. It is believed this variance in profile could cause the drill heads to behave differently.
4.2.3 Measured Outputs

In order to determine the efficiency and performance of the drill heads, three outputs will be recorded and analysed: depth profile, slippage and current. Depth profile will be the easiest indicator of drilling performance, as it will determine the vertical depth against time and final depth reached. This can then be used to calculate the drilling speed and slippage values.

As discussed in Section 2.4.4, slippage is caused by the backwards-facing teeth failing to grip the substrate enough to hold the receding drill half in place, which pulls upwards as a result. In this context, slippage is defined as the total amount of backwards movement of the receding half. No backwards movement would give a value of 0, while a fully receding drill head would give a value of 1, and would result in no further penetration. The levels of slippage seen so far have been very large, with the lowest average values observed being 0.9 [45]. Slippage, $s$, is calculated from the depth profile, using the equations:

\[ s = 1 - \frac{v_{\text{actual}}}{v_{\text{max}}} = 1 - \frac{\delta}{\Delta} \]  \hspace{1cm} (4.1)

where \[ v_{\text{actual}} = 2\delta f \] and \[ v_{\text{max}} = 2\Delta f \]  \hspace{1cm} (4.2)

$v_{\text{max}}$ is the drill progression speed if there is no slippage, found using the known reciprocation amplitude, equal to the distance the drill head progresses, $\Delta$, and the reciprocation frequency, $f$. $v_{\text{actual}}$ is the real speed of the drill, and can be found by differentiation of the depth profile. This can then be used to find the actual progression distance per reciprocation, $\delta$, and consequently the slippage.

These experiments will also examine how the motor current and drilling efficiency is affected by the drill head design and depth reached. The motor current can also be used to measure the forces on the drill heads using the torque-current constant, however this method, due to its indirect nature and the large variance in values seen previously [45], is not used here. Additionally, this will also be able to determine if the relatively small motor to be used, discussed in Section 4.3.2, will be able to cope with the current and power requirements.
4.3 Test Rig Modifications

This series of experiments was designed to use as much of the original test rig as possible, with the reciprocating mechanism, shown in Figure 4.4, and counter mass system remaining unchanged. This is attached to an aluminium plate, which itself is mounted via dry bearings at each corner onto Bosch™ profile rails. These allow the plate to slide up and down the rails with minimal friction. It is envisaged that the test rig could potentially be used on a rover for simulating planetary drilling missions. As a result, efforts have been made to reduce the weight of the system, such as by lightening the aluminium plate.

For these experiments, the regolith is filled to the brim of a drum of approximately 600mm diameter and 800mm height. The new maximum drilling depth was given as 760mm, allowing for a safety factor of 40mm between the drill head and the base of the barrel. In order to achieve this depth, a new drill stem was required. This section describes the modifications made to the test rig, including the selection of a new actuator and the data acquisition system used.

Figure 4.4: Picture of the reciprocation system, showing the double rocker pin and crank mechanism, attached to the lightened aluminium plate.
4.3.1 Drill Stem Redesign

The original drill stem consisted of the drill heads, a translation guide and a stem extension [45]. The translation guide locks the drill head halves together, preventing them from splitting apart while drilling, shown in Figure 4.5, with a T-shaped protrusion on one half able to slide freely in the other half’s corresponding groove. This system became subject to jamming in SSC-2, due to regolith entering the interlocking mechanism. In the tests used to drill up to 500mm, an industrial felt gasket was used to fill the gap between the two halves, reducing the friction of the reciprocation whilst also greatly reducing the amount of regolith entering the mechanism. However, general wear and tear through previous use has resulted in this method no longer being effective. Due to these jamming issues, it was decided that the drill stem should be redesigned to include an external translation guide.

![Figure 4.5: CAD model of the original translation guide, showing the T-shaped protrusion and groove.](image)

A number of drill extensions had been made for previous experiments utilising the original interlocking mechanism, however the largest was only able to give a total length (including the drill head) of 500mm. A new extension was therefore designed which allows the new maximum depth of 800mm to be reached, and can accommodate a new external interlocking mechanism.

The new design is shown in Figure 4.6. Stem half 1 has two indentations (1), into which fits an external sleeve each. The sleeves are sized to allow stem half 2 to fit through them, with a gap of 0.5mm enabling it to move up and down freely and with reduced friction. Though the sleeves protrude out from the stem halves by a maximum of 2.5mm, their small size and sparse positioning will likely have a negligible effect on the drilling performance. The interlocking mechanism can be seen in Figure 4.7.
Figure 4.6: CAD models of the parts making up the drill stem, showing each stem half, the interlocking sleeve, the test rig attachment and the fully assembled design.
Each stem half is 450mm long, so two of each were built. The top-end protrusions (2) match the dimensions of the drill head attachment, thus allowing both the other stem and the drill heads to be inserted into the grooves at the stem base (3). Finally, an extra attachment is required to connect the stem halves to the test rig. The stems’ diameters were limited to the cylinder radius of the smallest drill heads, as a larger stem that extends beyond the teeth may have an adverse affect on performance. As a result, the stems have dimensions of 5 x 10mm, giving a maximum diameter of \(\sim 14\)mm. Figure 4.6 also shows the assembled design with a single stem pair and attached drill heads, while the assembled test rig, including the counter mass system, is shown in Figure 4.8.

### 4.3.2 Actuator

The original Parvalux Direct Current (DC) PM11 MF motor was considered unsuitable for use as part of a rover test bed, due to its large size, mass of over 2kg and an operating range used of 0 - 90V. This was replaced with a Maxon 118776 motor. Though no longer in the Maxon catalogue, it is very similar to the 273752 RE35 60W model, with a maximum input voltage of 36V, a speed constant of 491rpmV\(^{-1}\), a maximum continuous current limit of 4A and a nominal torque of 77.7mNm. This was coupled with a Maxon GP42C gearbox, which has a reduction ratio of 43:1. The combined motor gearbox has dimensions of 141mm length and 42mm maximum diameter, a total weight of 800g and a maximum torque of 2.4Nm. More details of the motor and gearbox are provided in Appendix A. The motor is attached to the back of the reciprocating mechanism, as shown in Figure 4.9.
4.3.3 Data Acquisition System

To measure the outputs discussed in Section 4.2.3, the circuit current, drill position and time elapsed must be recorded. To do this, two Arduino Unos were used. These provide very low-cost and simple micro-controllers which can take hundreds of readings per second, although the time steps are not fixed, and vary according to the complexity of the circuit. Originally, a single Arduino was to be used to measure all outputs simultaneously, however doing so appeared to result in a grounding issue that rendered the data too inaccurate. As such, separate Arduinos operated at the same time were used to measure the distance and current respectively.

The experiments performed in [42] used a Spectra Symbol 500mm Soft-Pot membrane potentiometer stuck to one of the supporting rails. An arm attachment is added to the plate, which uses a roller to press into the potentiometer, shown in Figure 4.10, creating a variable voltage signal as the test rig descends. The same method is used here, with another potentiometer added to give a displacement range of 1m. The SoftPot’s pins can be easily attached to the Arduino, where the voltage signals given can then be converted into distance measurements.
To measure the current of the circuit with an Arduino, either a dedicated hall sensor or DC shunt resistor can be used. DC shunts are considered to be the most accurate, cheapest and easiest to use option for low current applications. A low value resistor is placed in series after the motor, whose voltage drop is measured by the Arduino and used with the constant voltage of the power supply to find the current. The resistor value is a compromise between voltage drop and data resolution. Assuming the current ranges from 0 to the maximum 4A, the voltage through an example resistor of 1Ω, and consequently the voltage lost to the motor, would range from 0 to 4V. The power is also an issue, with a maximum of 16W passing through the resistor. Given that the voltage is related to the motor’s rpm, the voltage drop needs to be as small as possible to minimise the drop in reciprocation frequency.
Typical shunts have values of 0.01Ω, or 10mVA⁻¹, however such small shunts will cause issues with data resolution. An Arduino has 1024 digital values, and is able to read between 0 and 5V, giving approximately 2 values per 10mV. For a 10mVA⁻¹ resistor, this equates to 2 units per amp, or 0.5A per unit. Given the motor current limit of 4A, this resolution is far too poor to be useful. A 0.1Ω resistor was chosen, as this provides the best compromise, with a data resolution of 0.05A per unit and a maximum voltage drop of 0.4V. A circuit diagram of the full data acquisition system is given in Appendix B. The Arduino has a resolution of 0.5mm, and produces around 100 - 200 readings a second.

To confirm that the voltage readings of the Arduino were accurate, they were compared to those given by an oscilloscope. It was seen that, although the readings recorded by both instruments covered a similar range, the Arduino values were consistently smaller by 20mV, with this error remaining at the same magnitude for various voltage and current settings. This error was thus assumed to be caused by losses through the wires, soldered points, etc. and was accounted for. Oscilloscope and Arduino values measured for the same period of time can be seen in Figure 4.11. Given the large amount of noise seen, filtering was added to smooth out the voltage measurements and resultant current values, the effects of which can be seen in Figure 4.12.

Figure 4.11: Graph of the voltage measurements recorded by an oscilloscope and the Arduino during the same time period.
4. Drill Head Design

4.4 Experiment Procedure

Each experiment followed the same procedure, given in Appendix C, with the typical time for each experiment being 1.5 - 2 hours. Due to the build up of dust generated from pouring the regoliths, infrequent cleaning of the mechanisms was required to avoid increased friction and jamming.

4.4.1 Control of Variables

The operational parameters of OHF and reciprocation amplitude, $a$, and frequency, $f$, will be kept constant at values similar to those used in [42]. Here, the OHF was set at values of 25, 45 and 55N, the $a$ at 0.5, 1.5, 2 and 5mm, and the $f$ was set at 1, 2 and 3Hz. The $a$ for these experiments was fixed at $\pm$3mm, i.e. the drill head will travel a distance of 3mm from its middle position.

While the DRD is theoretically a self-propelling drill, in practice this is not the case, with the wood wasp itself using its abdomen to exert an OHF onto the ovipositor when drilling [117]. Instead, the DRD can be viewed as a system able to drill with reduced overhead force requirements compared to traditional techniques. The previous DRD experiments in regolith used a counter-mass system with the test rig described in Section 4.3 to control

Figure 4.12: Graph of the voltage measurements recorded by the Arduino with and without filtering.
the total OHF acting on the drill, and demonstrated how increasing the OHF results in a greater depth \cite{49, 42}. This approach is also used in these experiments, with the OHF set at 30N without the drill stem attached. This creates a constant artificial error in the data being measured, with the depth achieved being driven by the OHF as well as the drill design. However, this is required to ensure that all sixteen drill heads penetrate a significant distance into the regolith. By doing this, the effects of each parameter can be more accurately measured and any trends can be more easily discovered. Slight variations of $\pm 2\text{N}$ were seen when the test rig was held at different positions. These are likely caused by imperfections in the rig or rails creating slight friction differences, and were considered small enough to not cause any appreciable alterations to the drilling operation.

The $f$ is kept constant by using a TTi TSX3510P continuous DC power supply unit to provide the motor’s nominal voltage of 15V, which provides a frequency of approximately $2\frac{1}{3}\text{Hz}$. The current was allowed to range from the 0.8A required when the fully assembled test rig was run freely, to the motor-defined maximum of 4A, giving a power range of 12 - 60W. In this set-up, the voltage is fixed, which keeps the reciprocating frequency constant. The current is allowed to change depending on the resistance, resulting in a fluctuating power supply, which will allow an insight into how the power demands of each drill changes under the constant operational conditions set out here. The power supply is stopped only when the current reaches the maximum limit as determined by the motor.

4.4.2 Summary of Experiment Plan and Aims

From the design of experiment used, there are sixteen drill heads which will be examined. These will each be used to drill into poured SSC-1 and SSC-2 regolith simulants. At least two runs will be performed for each combination, resulting in a minimum of 64 experiments, in which the vertical drilling depth and motor current will be recorded.

The major aim of this series of experiments is to determine if the geometrical parameters that define the design of the drill head have an influence on the drilling performance. A secondary aim is to achieve the deepest drilling performed by the DRD to date. The analysis of the results will show the depth and power profiles caused by the drill head designs in the two substrates.
Given the large number of parameters that define a substrate’s properties, it is not possible to create an empirical model which determines the performance in any substrate. As such, the results can be used to complement the previous research, with the aim of determining as best as possible notable relationships between the drill head design, current and depth, as well as establishing if there are any patterns caused by the different substrates used.

4.5 Analysis of Results

Though the initial intention was to perform two experiments per drill head-regolith combination, it was quickly noticed that the drill stem was undergoing bending in some runs. This bending would affect the results, and is discussed in Section 4.6. Factors such as the long, flexible drill stem, difficulties in judging a perfectly vertical entry angle into the regolith and the structural weakness in the drill heads’ stem attachment meant consistently performing runs with no bending was extremely difficult. As such, the experiments were categorised into four levels of success. Ideal experiments experienced negligible to no bending, while a number of experiments showed slight bending, generally no more than five degrees, and was often not immediately obvious. Both of these were considered successful. Significant bending, in which the stem could be seen to be bending during the experiment, often resulted in damaged or permanently bent drill heads. Failed experiments were caused by the drill head snapping, requiring the broken drills to be reprinted, or the motor jamming before a result could be taken. To account for this, it was required that at least one experiment for each drill head-regolith combination must show minimal to no bending. The resultant 92 experiments, along with details of their levels of success, are presented in Appendix D.

4.5.1 Typical Depth Profiles

For all results discussed herein, the term maximum depth is used to describe the greatest possible depth as determined by the size of the regolith barrel, given in Section 4.3 as 760mm. The term final depth is given to the depths lower than 760mm at the point where a drill is no longer penetrating, or is doing so at an extremely slow rate. The experiments gave rise to two typical depth against time curves. The first of which, demonstrated in Figure 4.13 (a), shows the drill steadily progressing until it reaches the 760mm limit, at
which point the drilling was stopped. In the second, shown in Figure 4.13 (b), the depth against time curve follows an inverse exponential trajectory, until the drill stops progressing and reaches a natural final depth. In both curves, the sharp increase in depth at the start of each experiment is the initial penetration caused by the momentum gained by releasing the test rig, in which the drill head is dropped into the regolith. For the figures showing individual depth profiles, the legends are presented as DH\textsubscript{x}SSC\textsubscript{y}R\textsubscript{z}, which gives the drill head and regolith used, and the run that is being shown.

### 4.5.2 Depth Achieved

The individual depth and time values of the two experiments for each drill head-regolith combination that presented minimal to no bending and their averages are presented in Figure 4.14. Here, it can be seen that eight and four drill heads reached the maximum depth in SSC-1 and SSC-2 respectively.

Each successful run created approximately the same depth profile shape, as demonstrated in Figure 4.15. Runs 3 - 5 reached different final depths at different times, but the profile shapes are still largely similar. As such, the profile of run 5 can be scaled up to match the profiles of runs 3 or 4, and vice versa. It can be assumed that the profiles of runs 1 and 2, which reached the maximum depth, would follow the same pattern if given the required room. Taking this assumption, the profiles and final depths of all drills which reached the maximum depth were estimated. Given that the data...
Figure 4.14: Graphs of the average depth and time values for all drill heads in SSC-1 (a) and SSC-2 (b), with the values for each successful test given as scatter points.
points in Figure 4.14 fall within 0 - 8% of the average values, the estimated final depths will be given an uncertainty value of 8%. These final depth estimates are given in Table 4.4.

![Graph of five selected depth profiles](image)

**Figure 4.15:** Graph of five selected depth profiles. Lines 3 - 5 show the typical profile seen when reaching a final depth, while lines 1 - 2 show an incomplete profile due to the maximum depth being reached. The glitches in the data are created by brief unavoidable errors in the potentiometer readings.

<table>
<thead>
<tr>
<th>Drill Head</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>5</th>
<th>7</th>
<th>9</th>
<th>11</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSC-1 Depth (mm)</td>
<td>1855</td>
<td>857</td>
<td>2209</td>
<td>1125</td>
<td>989</td>
<td>2045</td>
<td>1715</td>
<td>802</td>
</tr>
<tr>
<td>SSC-2 Depth (mm)</td>
<td>964</td>
<td>-</td>
<td>1038</td>
<td>-</td>
<td>-</td>
<td>1284</td>
<td>1024</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4.4: Estimated final depths of the drill heads in SSC-1 and SSC-2, with an uncertainty value of 8%.

### 4.5.3 Analysis of Depth Results

The $2^{k-1}$ design allows the identification of the most important geometrical parameters with regards to depth reached, by calculating the percentage contributions of the main effects and first-order interactions for SSC-1 and SSC-2. The main effect is the change in response produced by changing the level of one geometrical parameter, ignoring the effects of all other parameters. A first-order interaction occurs when the effect of one parameter is
dependent on the level of another. For example, $R_t L_t$ refers to the difference in the effects of $R_t$ at the two $L_t$ levels. The greater this difference, the greater the magnitude of the interaction effect [81].

To calculate the factors’ contributions, Table 4.1 is expanded to include the first-order interactions. The signs of the first-order interactions’ for each drill head are found by multiplying the signs of the relevant columns. For example, the sign of $R_t L_t$ is found by multiplying the signs of $R_t$ and $L_t$. The average values for each drill head found in Figure 4.14 and Table 4.4 are then substituted in, with some examples shown in Table 4.5. The percentage contributions for each parameter, $p$, can then be calculated using Equation (4.3), and the results are presented in Figure 4.16.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Drill Heads</th>
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<td>16</td>
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<td>$R_t$</td>
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<td>+(857)</td>
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<td></td>
<td>-(802)</td>
</tr>
<tr>
<td></td>
<td>+(247.5)</td>
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<tr>
<td>$L_t$</td>
<td>-(1855)</td>
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<td>-(857)</td>
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<td></td>
<td>+(802)</td>
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<td></td>
<td>+(247.5)</td>
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<td>$\alpha$</td>
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<td>+(802)</td>
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<tr>
<td></td>
<td>+(247.5)</td>
</tr>
</tbody>
</table>

Table 4.5: Table of some of the main effect and first-order interactions.

\[
\text{Percentage Contribution}_p = 100 \times \frac{(\text{Sum of Depths for Row } p)^2}{2^k - 1} \tag{4.3}
\]

Generally the results are similar for both simulants. By far the most significant variables are $R_t$, $R_{int}$ and $R_t R_{int}$. This suggests that, while $R_t$ and $R_{int}$ are important on their own, their combined effect is also significant. This can be clearly seen in Figure 4.14 (b), which shows only the four thinnest drills reaching the maximum depth. Variable E is also seen to have a small effect, while the other variables’ effects are relatively insignificant. It can be assumed that, for these simulants, the length and angle of the teeth have little to no effect on the performance of the DRD, while the most critical factors are the radii of the teeth and the cylinder, with the shape of the cone also having a small effect.
4. dw Und Head Deign

4.5.4 Influence of Drill Radius and Cone Shape

For SSC-2, the importance of the effects of \( R_t \) and \( R_{int} \) suggests a nonlinear relationship with depth is likely. By considering \( R_t \) and \( R_{int} \) as similar factors, and combining these into a single parameter that defines the total radius of the drill head, \( R_{tot} \), this gives a parameter with high, low and two medium levels. The relationship between the \( R_{tot} \) values and depth can be seen in Figure 4.17. The trendline created from these results suggests an inverse power relationship, with the final depth, \( D_f \), decreasing dramatically with increasing \( R_{tot} \). This is represented by Equation (4.4), where \( c \) and \( k \) are constants.

\[
D_f = cR_{tot}^{-k} \tag{4.4}
\]

The relationship between the depth and cone angle can be found by separating the results given in Figure 4.17 into two groups that correspond to the high and low level cone half-apex angle values. This allows two additional trendlines to be formed, one for each data group, as shown in Figure 4.18.

Taking the equations that define the three trendlines, it can be seen that the cone half-apex angle affects \( c \) in Equation (4.4), while the change in \( k \) is negligible. This gives a final relationship for SSC-2 which approximates \( D_f \) relative to \( R_{tot} \) and \( \alpha \), and is represented in Equation (4.5).
It must be noted that there are limitations which have to be placed upon this equation. For example, whilst it covers drills with an $R_{\text{tot}}$ between 10 and 23mm and an $\alpha$ between 10 and 15°, drills with parameters outside these ranges must be extrapolated. Also, neither $R_{\text{tot}}$ nor $\alpha$ can be equal to zero, and $\alpha$ cannot be larger than 90°. Given the inverse power relationship found for $R_{\text{tot}}$, depth estimates dramatically increase as $R_{\text{tot}}$ tends to zero. Similarly, the linear relationship for $\alpha$ results in negative depth values beyond 35°. As such, it should be assumed that the relationship given in Equation (4.5) will no longer apply for drill heads with parameters that are close to these values.

The relationships between $R_{\text{tot}}$, $\alpha$ and $D_f$ follow a similar pattern in SSC-1, as shown in Figure 4.19 and described in Equation (4.6). In this case, a very small change in $k$ is also seen, though this can be attributed to estimation inaccuracies, and does not create a significant change in results.

\[
D_f = 8500(35 - \alpha)R_{\text{tot}}^{-2.27} \quad D_f \propto \frac{c\alpha}{R_{\text{tot}}^{k}}
\] (4.5)

\[
D_f = 11300(21 + \alpha)R_{\text{tot}}^{-2.25} \quad D_f \propto \frac{c\alpha}{R_{\text{tot}}^{k}}
\] (4.6)
The similarity of the profiles suggests that there is a pattern with regards to the geometrical parameters and depth. The constant $c$ is dependent on both the cone half-apex angle and the drilled substrate. The total drill radius and depth have an inverse power relationship of constant value, $k$, between 2.2 and 2.3. Given that $k \approx 2$, $D_f$ can be related to the cross-sectional area of the drill, given by $\pi R_{tot}^2$. It can therefore be concluded that the cross-sectional area of the drill is the critical factor related to drill performance, with the cone half-apex angle having a minor influence. Given the number of substrate parameters, an empirical model for all substrates cannot realistically be constructed. However, the results shown indicate that regolith influences the final depth, but has little to no effect on the depth profile for the geometrical parameters.

### 4.5.5 Trends of the Cone and Teeth Shape

The main purpose of these experiments was to determine the main factors that influence the DRD performance, which has been shown to be $R_{tot}$. Given its huge significance, it is possible that any secondary small trends with regards to the other geometrical parameters may have been lost, appearing merely as noise when compared to the effect of $R_{tot}$. While not a focus
here, the influence of the cone and teeth shapes may be the subject of other research. As such, a brief qualitative analysis was performed which examined the effects of $L_t$, $\alpha_1$ and $\alpha$. To do this, the eight drill heads which had the mid-range $R_{tot}$ of 16 and 17mm were separately considered. The percentage contributions of these three parameters and their first-order interactions were found, as shown in Figure 4.20.

This graph once more shows that $\alpha$ provides a contribution to the performance of DRD. It can also be seen that $\alpha_1$ produces a small contribution, which was not seen in Figure 4.16. This also shows that $L_t$ has no impact whatsoever on drilling performance, while the first-order interactions also have near negligible effects.

### 4.5.6 Slippage

The majority of slippage profiles follow that shown in Figure 4.21 in which, after the period of initial penetration where slippage is briefly below zero before rising to a value between 0 and 1, slippage steadily increases until the drill reaches its final depth. At this point, slippage is equal to 1, and the drill is unable to progress any further. The slippage curve follows the same curve as the depth profile.
Main Variables and First-Order Interactions

Figure 4.20: Graph of the percentage contributions of $L_t$, $\alpha_1$, $\alpha$ and their first-order interactions.

In the case of the four thinnest drills in SSC-1, the slippage remains below zero for some time after the initial penetration, as shown in Figure 4.22. Here, the drill is progressing beyond its own capabilities, and is aided by the natural sinking of the drill through the regolith, caused by a combination of the momentum gathered from the initial penetration, the low density of the regolith and the overhead force of the test rig. The most critical factor is the regolith density, as this negative slippage is not seen for the same drills in the denser SSC-2. While this can be considered to be an error in the measurements, as the penetration of the DRD is being augmented by outside factors during this negative slippage, it also demonstrates how the DRD can
be helped to briefly perform beyond its capabilities. The progression of the slippage curve continues as per the other drills, increasing steadily until the drill reaches the maximum depth. Beyond 25s, the slippage becomes positive, and the penetration from that point on is caused by the drilling motion only. It must be noted that the spike in slippage at 15s was due to a fault in the membrane potentiometer, which briefly created false distance measurements.

![Slippage profile graph](image)

Figure 4.22: Graph of the slippage profile of drill head 1, run 2, in SSC-1.

### 4.5.7 Analysis of the Power Consumption

The current measurements typically produced a profile such as that shown in Figure 4.23. The initial current, i.e. that required to run the test rig mechanisms, was approximately 0.8A. During the experiments, the current tended to increase at the same rate as depth, with a sharp increase during the initial penetration, before slowing and retaining a steady maximum value as it reaches its final depth.

Given that the voltage throughout the experiments remained constant at 15V, by taking only the drills that did not reach the maximum depth, the relationship between the final depth and the average power consumption measured at this depth could be found. From Figure 4.24, it can be seen that there is a linear relationship between power and depth for both regolith simulants. The nature of the external interlocking mechanism led to variations in current readings for the same drill, as the regolith presents a jamming risk. This was particularly noticeable in SSC-1, due to the particles’ larger...
size often creating much larger and variable readings, despite being the less dense material. As such, the SSC-1 results are less reliable, however there is still a clear relationship between depth and power. Had there been no increase in current caused by the friction in the interlocking system, the power deviation and increase with depth would have been much smaller. Using the initial current and voltage of 0.8A and 15V respectively to give 12W as the \( x \)-intercept, the relationships between depth and power can be seen to be quite similar, with the standard deviation and the mmW\(^{-1}\) gradient being larger for SSC-1.

Figure 4.24: Graphs showing the relationships between the final depths and average power measured in SSC-1 (a) and SSC-2 (b).
4. Drill Head Design

4.5.8 Specific Energy

Specific Energy (SE), as discussed in Section 2.2.1, is a good representation of drilling efficiency, taking into account drilling power, rate of penetration and drilling area, and determines the energy required to drill the substrate. However, the $p_r$ decreases dramatically as the drill tends towards its final depth. As such, for all drills that reached a final depth, the depth and time values were taken at the point where the depth profile begins to level out, in the range of 90 - 95% of the final depth. As an example, the values taken from the profile in Figure 4.13 (b) are 276mm and 125s. For the drills which reached the maximum depth, the SEs required to reach the 760mm limit were calculated. The SEs for the final and maximum depth runs were calculated using Equation (2.1) and are given in Figures 4.25 (a) and (b) respectively.

![Figure 4.25](image)

Figure 4.25: Graphs showing the calculated specific energy values for all drill heads in SSC-1 and SSC-2 for the final depths (a) and maximum depths (b), with the values for each test given as the scatter points.

Though these values are estimates, some observations can be made. The SE’s for the final depths follow a very similar pattern to the time taken values given in Figure 4.14, suggesting a correlation between the two. This is supported by the results for the maximum depths, as the SSC-2 runs, which took longer to reach the maximum depth, have larger SE values. SE is also likely to have a correlation with the final depth reached, given the relationship between power and depth discussed in Section 4.5.7, and is supported by the four largest drill heads having the lowest final depth and SE values.
4.6 Bending of the Drill Stem

By far the most common difficulty faced with performing consistent experiments was avoiding bending of the drill stem and/or drill heads. The extent to which the drill stem had bent could only be determined once the majority of the regolith had been removed from the barrel after the experiment, as shown in Figure 4.26.

Figure 4.26: Comparison of the drill stem when resting vertically, and after it has bent during an experiment.

While slight bending of the drill stem did not affect results, with depth profiles indiscernible from the straight runs, significant bending led to completely different depth profiles, with an increase in final depth and/or a reduction in time taken to reach the maximum depth. Often the penetration profiles of the straight and bent runs would be broadly similar until a certain point, as shown in the example given in Figure 4.27. Here, the curves are the same up until a depth of 500mm, after which the straight run’s penetration rate would slow and eventually halt. The bent stem however would continue progressing at a fairly continuous rate.
4. Drill Head Design

Figure 4.27: Depth profiles of drill head 4 in SSC-1 with a straight (a) and bent (b) drill stem. The drop in depth between 100 - 150s in (a) was caused by another error in the penetrometer readings.

4.6.1 Proposition of Compression Mechanics

It is theorised from the behaviour evidenced by these results, that lateral motions caused by the diagonal direction of the drilling are the cause of these increases in drilling depth. A possible explanation for this is the direction the regolith is being compacted, as shown in Figure 4.28. The principle behind the DRD is the gripping of the backwards-facing teeth into the regolith, which holds the receding half in place and subsequently provides an extra compression force for the penetrating half. However, this relies on the regolith not shearing and remaining in place. Another factor may be the pressure of the surrounding regolith acting on the drill heads. This pressure creates a resistive force against the motion of the drill from all sides and increases with depth. It is possible that the power-depth relationship seen in Section 4.5.7 is due to the additional power required to overcome this increasing resistance created by the pressure as the drill descends.

In vertical drilling, the receding drill half attempts to push the engaged regolith upwards. Resistance to this is largely created by the regolith positioned directly above the engaged regolith, which exerts a pressure on to the drill head. However, as this volume of regolith is fairly small and already sheared, the overall resistance this offers to prevent the movement of the engaged regolith is very small, and as a consequence the drill head recedes
easily upwards. Some resistance may also be provided by the pressure of the surrounding regolith compressing the engaged regolith, however as the movement of the drill is normal to the direction of this force, the effect of this pressure will likely be very small.

Figure 4.28: Proposed compression mechanisms when drilling straight (a) and at an angle (b).

When drilling at an angle, the regolith is being pushed both upwards and horizontally. The vertical resistance is now larger, as there is a greater volume of regolith directly above the drill heads, both sheared and untouched, resulting in a larger pressure exerted that resists the drill’s upwards movement. Pushing the engaged regolith horizontally into the surrounding regolith is also much more difficult. The pressure of this regolith acts against the horizontal movement of the drill head. Given the much larger volume and untouched nature of the surrounding regolith, this creates a significant resistance force which, acting alongside the larger vertical resistance, makes it much more difficult for the receding drill head to push the engaged regolith back. This therefore creates a larger tensile force, resulting in less slippage and allowing the drill to penetrate further.
4. Drill Head Design

Though the extent of how much the drill stem bending was able to improve the drilling performance could not be recorded, due to the almost random nature of its occurrence and magnitude, and because it often coincided with the drill heads breaking, these results indicate that diagonal drilling is beneficial to the performance of the DRD. The compression mechanics proposed here are likely similar to those caused by the lateral forces discussed in Section 3.3.1. A brief investigation into the benefits of controlled diagonal drilling compared to vertical drilling is conducted in Section 6.10.

4.7 Summary

In this chapter, the exploration of the parameters governing the operation and design of the DRD has been completed, by performing a full investigation into the influence of the parameters that define the drill head geometry. It has been demonstrated that the overall radius is by far the most important factor in achievable drilling depth, while the teeth shape and spacing have very little effect. These experiments have also provided the first testing of the DRD down to a depth of 760mm.

The original geometrical parameters were redefined, allowing five independent key parameters to be identified. These were each given two distinct levels which, coupled with a fractional factorial design of experiment, resulted in sixteen unique drill head designs. The operational parameters were kept constant at values similar to those used in previous experiments, while the substrates used were the SSC-1 and SSC-2 Mars regolith simulants. To allow drilling experiments at greater depths than those previously achieved, the test rig was modified and the drill stem was redesigned. The vertical distance and motor current values were measured for each experiment. From these, the drilling depth, slippage and efficiency values could be obtained. The final depths of a number of drill heads that reached the test rig’s maximum depth of 760mm were estimated, with several reaching well beyond one metre.

The most critical factors for drilling performance with respect to depth achieved were found to be the radii of the backwards-facing teeth and the drill head cylinder. The total drill radius was shown to have an inverse power relationship with final depth. The cone half-apex angle also has a small neg-
ative linear relationship with depth. However, the length and rake angle of the teeth were found to have a negligible effect on performance. The drilled substrate was found to affect the final depth achieved, with the depth naturally being smaller in the denser SSC-2, but did not affect the aforementioned relationships between depth, total radius and cone half-apex angle. Such was the importance of the total radius, that the thinnest drill heads experienced negative slippage for some time after the initial penetration. It was also found that the motor current, and by extension the power, increased linearly with depth, with this increase being more pronounced in SSC-2. The specific energy of each drill was found to be similar to the time taken to reach the final depths, and was also believed to have a correlation with depth.

Many of the experiments experienced varying amounts of drill stem bending, resulting in the drill following a curved path. Those that experienced significant bending had depth profiles notably different from those that followed a vertical trajectory, and showed an increase in drilling depth and/or speed. This led to the consideration of the mechanics of diagonal drilling. Here, it was proposed that large horizontal resistive forces from the surrounding regolith, created by the horizontal movement of the receding drill head, are able to create a larger overall tensile force, allowing the drill to penetrate further. These observations provide further evidence of the importance of lateral movements in the performance of the DRD. To confirm this, active control of the lateral movements, and experiments performed with the test rig at a known, fixed angle, are examined in the following Chapter.
Chapter 5

Characterisation of Icy Regolith Simulants

This chapter presents an investigation into the properties of icy regolith simulants. This begins with a brief demonstration of the effects of ice content in a selected simulant mimicking the regolith found in the lunar polar regions on the drilling capabilities of the DRD. From this, the properties of the lunar simulant with different ice contents was then investigated, which also forms part of the work for the development and testing of a sampling mechanism. Firstly, a dedicated preparation procedure that is able to create icy simulants with repeatable and controllable water contents is selected. This leads into the testing of the lunar simulant, with its strength and resistance properties with varying water contents examined.

5.1 Drilling in Icy Lunar Regolith

As stated in Section 3.2, one substrate parameter that has yet to be tested with regards to the performance of the DRD is the potential ice content that may be encountered, particularly in the south polar regions on the Moon. As has been discussed in Section 3.2.2, the properties of icy regolith will change with increasing volumes of ice present. The first testing of the DRD in both icy and lunar regolith here will contribute not only to furthering the understanding of the DRD’s behaviour under different substrate parameters, but can also be used to begin an investigation into the properties of the highland regolith believed to exist at the lunar south poles.
Given the presence of water on Mars, there is also a need to investigate the effect of ice in Martian regolith. The unique phenomenon of soil induration and cementation, and how this may affect the operation of instruments that interact with the regolith, is of particular interest, and an investigation into the effects of cementation on sampling systems was also performed. As this is an additional study into the properties of icy regolith, and does not relate to the DRD, this work is not presented here, but is detailed in Appendix E. This research provided new insights into the cementation of Martian regolith, and the conclusions and novelties are also listed in Chapter 8.

5.1.1 Lunar Highland Simulant

To perform these experiments, the correct simulant must be used. The identification of the properties of regolith simulants is critical for the testing of systems designed to interact with the soil. This is the case for the Lunar Generic Regolith Acquisition/Sampling Paw (L-GRASP), a sampling device currently being developed by the companies SELEX and OHB System on behalf of ESA, designed for taking samples from a lunar polar site [97]. Using lunar mare simulants such as JSC-1A for hardware testing of instruments expected to encounter highland regolith could lead to significant errors, resulting in mechanisms that are unable to function in the polar environment.

The L-GRASP study identified the NU-LHT-2M simulant detailed in Section 2.5.2 as the best available dry analogue to mimic the chemical and mechanical properties of the lunar polar regolith [32]. This was therefore chosen as the simulant to be used for these experiments, and will from this point be referred to as the Lunar Highland Simulant (LHS).

5.1.2 Point of Saturation

Although estimates have been made from orbiter observations, the lack of quantitative information that exists concerning the exact extent and distribution of ice in the lunar polar regolith means that everything from fully or over-saturated (ice lenses) to strongly under-saturated or completely dry regolith may be possible. As such, the ability of a drill to penetrate regolith with water ice contents within this entire range will need to be demonstrated. The DRD will therefore be tested in LHS with water contents ranging from dry to nearing saturation.
To do this, an initial investigation was undertaken to approximately identify the saturation point of the LHS. This also allowed the properties of the regolith with increasing water contents to be qualitatively examined. Six samples of dry LHS were mixed with water in increasing increments of 6ml in containers of $1.34 \times 10^{-3} \text{m}^3$ volume. The water mass contents of the samples were obtained by heating a small portion (5 - 20g) in a high precision moisture analysis scale, shown in Figure 5.1. This measures the weight loss due to evaporation of the moisture as the sample is heated as a function of time, providing a measurement of the sample’s water content as a mass percentage. Though it gives percentages to three decimal places, the values measured should be considered as representative of the sampling area, as the water content distribution is likely to not be homogeneous. The samples were frozen overnight in a deep freezer at $-20^\circ \text{C}$. The penetration resistance was qualitatively determined by pushing a pencil with a 5mm diameter and conical tip into the samples, as shown in Figure 5.2, with the observations given in Table 5.1.

Figure 5.1: Picture of the moisture analysis scale used for measuring the samples’ water mass content percentages.

These observations demonstrate that the penetration becomes increasingly difficult as more water is added. Since the 24ml and 30ml frozen samples were clearly cohesive and behaved like a single body, these were assumed to be water saturated. This was confirmed by thawing the samples, after which a very thin and a much thicker layer of water could be seen on top of the
5. Characterisation of Icy Regolith Simulants

### Figure 5.2: The six LHS frozen samples after being penetrated by a pencil.

<table>
<thead>
<tr>
<th>Volume of Water (ml)</th>
<th>Water Mass %</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (dry)</td>
<td>0.2</td>
<td>Extremely soft, easy penetration</td>
</tr>
<tr>
<td>6</td>
<td>4.6</td>
<td>Small clumps, fairly easy penetration</td>
</tr>
<tr>
<td>12</td>
<td>9.0</td>
<td>Small clumps, very difficult to penetrate to the base</td>
</tr>
<tr>
<td>18</td>
<td>12.8</td>
<td>Small clumps, only penetrates a few mm down</td>
</tr>
<tr>
<td>24</td>
<td>17.3</td>
<td>One solid, lumpy piece, unable to penetrate</td>
</tr>
<tr>
<td>30</td>
<td>20.3</td>
<td>One solid, smooth piece, unable to penetrate</td>
</tr>
</tbody>
</table>

Table 5.1: Observations made when testing the hardness of the LHS samples.

24ml and 30ml samples respectively. The samples also had a mud-like consistency, with water draining as they were handled [17]. As this was not the case for the 18ml sample, the saturation point of the LHS can be assumed to occur at a water mass content between 13% and 17%. These observations also indicate that the frozen LHS experiences a rapid change in properties, going from soft to very hard, when the water mass content is in the range of 5 - 9%, which is examined further in Section 5.3.

#### 5.1.3 Experimental Set-Up

To test the DRD, the same test rig set-up used in Chapter 4 was utilised. As these experiments were designed to solely focus on the effects of the presence of ice in the regolith, the geometrical and operational parameters were kept constant. As a result, only one drill head was required. Due to the very small amount of LHS provided for the L-GRASP study that could be used for these experiments, only $7.36 \times 10^{-3} \text{m}^3$ was available which, in a bucket
5. Characterisation of Icy Regolith Simulants

of 25cm diameter, provides a depth of only 15cm. In order to account for the initial penetration caused by dropping the test rig, and to have enough substrate to drill through to clearly demonstrate the drilling speeds for each experiment, it was determined that a depth of at least 25cm was required. As such, a new container was made, shown in Figure 5.3. This has sides of 15cm length, which was believed to be large enough with respect to the drill heads to avoid any significant boundary effects, resulting in a depth of 32.7cm for this volume of LHS. The DH10 drill was chosen, due to its mid-range $R_{tot}$ helping to avoid exacerbating any potential boundary effects, while its low penetration rate in dry regolith should allow any subtle changes to be more noticeable than with a faster drill. Ideally, the DRD’s drilling capabilities in dry LHS would be compared to those in SSC-1 and SSC-2. However the small depth of the LHS, coupled with the penetration rate in dry LHS being too rapid to measure accurately, make such a comparison infeasible. It can be noted that the LHS has a minimum dry density of 1367kgm$^{-3}$ [127], which is similar to the 1383kgm$^{-3}$ minimum density of SSC-1 [102]. As the poured technique produces relative densities of around 10% [46], it can be assumed that the density of the LHS here is similar to that of poured SSC-1.

The LHS is tested in four states: dry, frozen, wet and icy. Initially the dry LHS is poured into the container and drilled into at room temperature. This is repeated, and afterwards the regolith is re-poured and stored in a freezer overnight. The frozen regolith is drilled into, before being left in the open and allowed to gradually reheat throughout the day. Water was then added to the sample and mixed thoroughly. The total volume of LHS weighed 6013g, so a volume of 300ml was added to create a water mass content of 5%. The procedure was repeated, with the wet regolith poured and drilled into twice at room temperature, before being frozen overnight, after which the icy regolith was drilled into. This is repeated with incrementally added water, producing mass contents of 7.5, 10 and 12.5%. As more water is added, clear coagulation of the regolith can be seen, as demonstrated in Figure 5.4, with the clumps increasing in size and frequency as the water content increases.

5.1.4 Results

The time taken for the drill to penetrate the sample for each water content and temperature is given in Figure 5.5. While a sample 30cm deep was initially used for the dry tests, the addition of water and the pouring and
freezing of the regolith resulted in volume changes [25], with the smallest sample being 25cm deep. As a result, the times given are for when the drill reaches 25cm in each sample. It should be noted that the dry results are not presented, as the drill penetrated too quickly for accurate measurements to be taken.

The results show that the time taken to penetrate the wet regolith remains fairly constant, with only a very small increase of a few seconds seen overall between the 5% and 12.5% samples, suggesting that room-temperature water content has very little effect on drilling time. The 5% icy time is roughly the same as the corresponding wet time. However, it takes a noticeably longer time to drill to the final depth as the ice content increases. There is also a clear critical point between 10% and 12.5%, at which point the frozen drilling time increases dramatically. These increases in drilling time appear to correlate with the observations made in Table 5.1. There is a clear change in the penetration properties between the 6ml and 12ml samples, with
penetration becoming more difficult, which is reflected in the increasing times for the 5 - 10% icy regolith. Further exploration of the penetration resistance is detailed in Section 5.3.1. Additionally, the very steep increase in time for the 12.5% icy regolith is likely due to the saturation point being approached. The 18ml sample, which has a similar water mass percentage, could only be penetrated a few millimetres, and it was not possible to penetrate samples with higher water contents. From this, it can be assumed that 12.5% is the limit at which penetration can be achieved. Another observation made is that for the 12.5% icy run, the penetration has almost stopped, with any further penetration likely being minimal. This depth is shallower even than the 232mm depth of the DH10 in SSC-2.
An additional observation made was the boreholes created by the drill in the room temperature and frozen samples, shown in Figure 5.6. The drill creates a very regular, circular hole in the room temperature sample, whereas the hole is much more irregular in the frozen sample, with a very wide hole at the surface that gradually gets smaller as it nears the drill.

Figure 5.6: Pictures of the holes drilled into wet (a) and icy (b) LHS.

This section has provided a first examination of the effects of ice and water content on drilling performance. Due to the limited availability of the LHS, no testing to deeper depths can be performed. Despite this, two notable observations in the difference between the effects of water and ice content on the DRD performance have been made. The changes in the LHS’s properties caused by the addition of water ice will be further investigated, resulting in the first testing of the properties of an icy lunar highland simulant. However, in order to accurately ascertain the properties of icy regoliths, an accurate method for introducing water evenly throughout the sample must be used. The mixing technique used so far, while suitable for the relatively large quantities used for these drilling experiments, is very approximate, and unlikely to produce samples with homogeneous and repeatable water contents. For more precise testing of an icy regolith’s properties, a preparation procedure must be used which is able to consistently produce samples with homogeneous water contents at the desired degree of saturation.
5. Characterisation of Icy Regolith Simulants

5.2 Simulant Preparation Procedures

The importance of creating standardised regolith preparation procedures has previously been highlighted with respect to the regolith’s density and mechanical properties. Doing so allows the testing of instruments in regolith with known and consistent mechanical properties, from which system performances can be compared more accurately [46]. In a similar vein, the preparation of icy simulants will have an effect on the distribution and extent of water content, thus potentially creating simulants with notably different properties when frozen. Currently there appears to be no standardised procedure for developing icy simulants. Many of the experiments performed with icy simulants discussed in Section 3.2.2 do not give details of the preparation method used [44, 79], while those that do demonstrate a clear range of different techniques [22, 90, 106, 74].

As part of the investigation of the properties of frozen LHS, a number of preparation procedures will be examined. These will aim to add a controlled volume of water to the regolith simulant under ambient conditions, after which the wetted sample will be frozen, creating the desired icy regolith. The procedures will be evaluated on their ability to create an LHS sample with reproducible water contents ranging from dry to saturated. The target water mass content is 13%, and the regolith should be as uniformly wetted as possible to create a homogeneous sample. The procedure must also be able to produce, within a reasonable time scale, icy simulants with a size and mass large enough for the testing of sampling devices such as L-GRASP. It is envisaged that, by varying the basic non-volatile constituents, the developed procedure can be used for other planetary materials, such as the ice-containing near-surface soils on Mars.

Alongside the LHS, two other sample materials have been used to provide comparisons where necessary. One is the JSC-1A lunar analogue which, although not suitable for mimicking the polar regions, has established characteristics that mean it can be used as a comparison lunar simulant. The other material is the well-characterised fine-grained quartz sand, Schwarzl UK4, selected due to its easy availability in large quantities. This has also been used in a previous study as a substitute for the JSC-1 Mars material [104], and has a grain size distribution in the range of 0.1 - 1mm [128]. The water contents of the three dry simulants, measured before each experiment, fell
within the range of 0.1 - 0.4%. The work presented in this section was performed with Dr. Norbert Kömle at the Planetary Surfaces Laboratory of the Space Research Institute, Austrian Academy of Sciences, in Graz, Austria.

5.2.1 Initial Procedures

Two preparation procedures were originally considered, with the aim of wetting the sample with water vapour in notably different ways. For each, the sample is held in a steel skeleton cage with a 7.5cm radius and 16cm height, consisting of several equidistant rings, as shown in Figure 5.7. The inner surface of the cage was covered with a semi-permeable fleece, used to hold the simulant in place whilst still allowing diffusion of the water vapour into the sample.

![Figure 5.7: Picture of the sample cage with its rings labelled.](image)

**Water Disperser into Vacuum Chamber**

This procedure attempted to introduce vapour through the use of a Wasser-rauch Ventilator water disperser, shown in Figure 5.8 (a), which produces fine water droplets a few micrometres in size that can be fed via a feed-through tube. A secondary aim of this set-up was to offer the possibility of establishing lunar conditions to the sample at a desired stage of the wetting process. The sample cage was held within a stainless steel container closed by a lid, shown in Figure 5.8 (b). This was encircled by copper tubing, through which a connection can be made to a cooling circuit. This was placed within
a vacuum chamber, seen in Figure 5.9 (c), in which lunar atmospheric conditions can be established. Whilst this is possible, only ambient conditions were required for the purposes of these experiments, and as such neither the vacuum nor the cooling systems were used.

![Figure 5.8: Pictures of the water disperser and feed-through tube (a), and the sample cage held within the steel container, encircled by the copper cooling tube (b).](image)

The feed-through tube is fed into an inlet of the vacuum chamber, seen in Figure 5.9 (d), where it is then split into two smaller tubes, which are connected to the base and lid of the steel container respectively. This allows vapour to flow into the sample from two directions, creating a greater distribution.

Three experiments were performed, in which the UK4 sand was filled to Ring 3 of the sample cage. In the first experiment, in which the water disperser was run for 90 minutes, it was seen that only the top 5 - 10mm of the sample was wet and sticky, with the rest being dry. The latter two experiments were run for 15 and 20 hours respectively, however once again no significant wetting was observed. Upon inspection, this was seen to be caused by blockages within the two small water tubes. The small cross-sectional areas of $5.0 \times 10^{-5} \text{m}^2$ at the connection points, seen in Figure 5.9 (d), would become blocked by a combination of sand particles and water droplets, preventing the vapour flow from reaching the simulant. The water mass contents of samples taken at different depths of the simulant were measured for the first and third experiments, with the results given in Table 5.2.
Figure 5.9: Pictures of the vacuum chamber (c) and the full set-up of the Water Disperser into Vacuum Chamber experiments (d), with the steel container with the lid attached placed inside the vacuum chamber, and the small water disperser tubes fixed to inlets on the container lid and base.

<table>
<thead>
<tr>
<th>Sample Depth</th>
<th>Surface</th>
<th>2cm Depth</th>
<th>Middle</th>
<th>Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp. 1 Water Mass %</td>
<td>2.1</td>
<td>-</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Exp. 3 Water Mass %</td>
<td>0.9</td>
<td>0.8</td>
<td>0.9</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 5.2: Water mass contents of samples taken from the Water Disperser into Vacuum Chamber experiments.

**Hot Water Vapour**

The second procedure used a cooking pot, with water filled to a depth of 3cm. The sample cage, again filled with regolith to Ring 1, was placed on supports inside the pot, allowing the base of the cage to rest just above the surface of the water. A lid, with a small hole to allow steam to escape and avoid a pressure build-up, was placed over the top of the pot. This was positioned on a heating plate, and the water was gently boiled for three hours. Figure 5.10 shows the set-up, including the semi-permeable fleece, which for these experiments also covered the top surface of the regolith, to avoid additional wetting through condensing water droplets falling from the lid. The procedure was performed with each of the regolith simulants.
After each experiment, two samples were taken from the surface; one from the centre and one from near the boundary. Additional pairs of samples were taken at depths corresponding to just above each ring on the cage, and a final pair was taken at the base. Each sample’s water mass percentage was measured, with the results given in Figure 5.11. To determine the average water content, the wetted LHS sample was mixed and refilled in the cage to create a homogeneous sample. Water content measurements were again taken along the centreline from the surface to the base.

These results show that the method is fairly effective at wetting the UK4 and JSC-1A simulants, while the LHS absorbs notably less water vapour. There is a clear relationship between water content and sample depth, showing that the water diffuses from the base to the surface. The centre and boundary measurements are fairly similar, with the centre values tending to be slightly larger. As expected, the water contents of the samples taken from the mixed LHS were roughly equal, however the average values of just under 2%, and even the largest unmixed value of $\sim 5\%$, were much lower than the desired near-saturation target of 13%. As such, this method was also considered unsuitable.

### 5.2.2 Pressurised Hot Water Vapour

Whilst the Hot Water Vapour method did not produce the desired extent of wetting, it was believed that the vapour diffusion could be greatly improved by replacing the cooking pot with a WMF pressure cooking pot, which allows
Figure 5.11: Graph of the water mass percentage values for the Hot Water Vapour experiments. The depth corresponds to the point at which the sample was taken, from the surface (0cm), each ring (3 - 15cm) and the base (16cm).

a much larger vapour pressure to be held inside the pot during the experiment. By holding more water vapour inside the pot, this is expected to increase the rate of diffusion of water into the sample. Due to the smaller size of the new pot, a smaller sample cage, shown in Figure 5.12 (a), with a 5.5cm radius and 12cm height, and consisting of a thin steel shell with holes interspersed around it, had to be used. The simulant was filled to the brim, and the same set-up and procedure as given in Section 5.2.1 was used, demonstrated in Figure 5.12 (b). All three simulants were used, with the UK4 sand being used twice, and each wetted sample was mixed afterwards.

After three hours of boiling, the pressure pot was allowed to de-pressurise for 20 minutes (75 minutes in the second UK4 experiment), by letting the steam slowly escape from the pot, before being opened. Once again, samples were taken at the centre and boundary, this time at depths corresponding to the cage’s 1st, 3rd, 5th and 7th rows of holes, as well as the surface and base, with the results given in Figure 5.13.

Despite the increased water vapour presence, the JSC-1A water content values with depth are broadly similar to those in Figure 5.10, while the UK4
values are considerably lower. However, the LHS values are much higher near the surface than the previous experiments, with a much gentler increase in water content with depth, creating a sample with a much more homogeneous degree of wetting. Though the $\sim 7\%$ water content of the mixed sample is still lower than the target of 13%, this is a considerable improvement, with the potential for longer experiments being able to achieve this goal. Additionally, the differences seen for the three simulants with these two procedures suggests that the effectiveness of the preparation procedure can vary depending on the simulant used.

### 5.2.3 Open Water Disperser

The Water Disperser in Vacuum Chamber method was believed to have potential, though design constraints created from the inclusion of the vacuum chamber and cooling system resulted in the blockages in the vapour tubes. To address this, a simplified version was created, shown in Figure 5.14, in which only the sample cage and water disperser were used. The feed-through tube was attached directly to the sample cage, inserted into a hole in the semi-permeable membrane, which again covered the entire substrate. The single tube allows for a large and consistent cross-sectional area of $2.5 \times 10^{-4} \text{m}^2$, with no bottlenecks that could result in blockages.
Initially, two approaches for this procedure were examined. In the first, the cage was filled with regolith up to Ring 4. This was wetted for one hour, before another layer was added, filling the cage to Ring 3, and was subsequently wetted for another hour. This was repeated once more, with the cage filled to Ring 2. This was performed with the UK4 and LHS, referred to as Exp. 1 and 2 respectively. For the second method (Exp. 3), the cage was filled with LHS to Ring 2 in one go, and the simulant was wetted uninterrupted for three hours. Measurements for each were taken at depths corresponding to the surface and each ring, after which the samples were mixed and re-measured, with the results given in Figure 5.15.

The results indicate that, even without mixing, the method of intermittently adding layers is capable of producing a very high and fairly homogeneous water content nearing saturation. The single large layer also provides high water contents, though there is a noticeable decrease with depth, yet despite this the mixed values are nearly as high as the layered method. Given that the water mass values for these experiments are consistently above 10%, this technique is by far the most effective for producing samples close to saturation. In Exp. 3, some small regions at the boundary of the base were
noticeably drier than the surrounding simulant, having a water mass of only 4.5%. This fairly rapid change from wet to dry suggests that the diffusion front of the water had yet to reach these areas at this time. It can thus be proposed that the three hours of wetting used here is the minimum time required to sufficiently wet the vast majority of the sample volume.

5.2.4 Control of the Water Content

Given the ability of the Open Water Disperser procedure to produce samples nearing saturation, additional experiments were performed to examine how the water mass content and extent of diffusion are altered with varying vapour flow conditions. To do this, the single-layer method used in Exp. 3 was selected. The fourth experiment used an extra tube with a cross-sectional area of $1.1 \times 10^{-4} \text{m}^2$ attached to the end of the feed-through tube. The fifth experiment halved the vapour flow by using a tube splitter. One end was left open to allow vapour to escape into the atmosphere, while the other end was attached to the tube used in the fourth experiment, sending vapour to the sample. The sixth experiment used the original larger tube, and reduced the wetting time to 1.5 hours.

The results of these experiments are given in Figure 5.16, and can be compared with the results of Exp. 3. The results of Exp. 4 show that the extent of wetting is very consistent and even greater with the smaller vapour tube. This could be due to the volumetric flow rate remaining the
same, given that the same volume of water was used for each experiment. As such, the smaller tube area results in a greater flow velocity, creating a more concentrated flow of vapour that is able to diffuse more efficiently into the sample, with less vapour escaping into the atmosphere. Experiments 5 and 6 both show a rapid decrease in water mass contents, with the LHS becoming completely dry approximately halfway down. As halving either the total vapour flow or the time taken results in only the upper half of the LHS being wetted, this is consistent with the observation made in Section 5.2.3. As such, it can be stated that the set-up in Exp. 3, with three hours of full vapour flow, is able to sufficiently wet the simulant to near-saturation.

A final test was performed to examine the effects of compaction on vapour diffusion. Using the same set-up as Exp. 3, the sample cage was subjected to shaking and hammer shocks while the simulant was slowly poured into it. After three hours of wetting, the results of which are given in Table 5.3, it can be seen that the water contents between Rings 2 and 3 are comparable to that of Exp. 3. However, below this the water content decreases dramatically, with the bottom 1cm of regolith being nearly completely dry. This indicates that increased density makes diffusion of water into the sim-

Figure 5.15: Graph of the water mass percentages for the Open Water Disperser procedure. The points correspond to the surface at Ring 2 (0cm) and Rings 3, 4 and 5 (3 - 9cm).
Figure 5.16: Graph of the water mass percentages for the follow-up experiments using the Open Water Disperser procedure.

These experiments have demonstrated the potential of the Open Water Disperser method as a preparation procedure for creating regolith simulants with a water content nearing saturation. This procedure can be modified to allow it to be placed in a vacuum chamber, from which the sample may be wetted and cooled in simulated lunar or Martian atmospheric conditions. The experiments investigating the control of the water flow have also shown how the degree of saturation can be controlled by adapting the sample size,
compaction, wetting time and vapour flow conditions. Although not investigated further here, these tests can be used as a first step from which a more detailed analysis of the operating conditions can be made. From this, it will be possible to produce a standardised procedure from which the desired water content can be added to a specified sample. An icy regolith simulant can then be produced that can be used for experiments and instrumentation testing.

5.3 Properties of Frozen LHS

With a suitable procedure for preparing icy regolith simulants established, it is possible to use this to begin the first investigation of the properties of icy lunar highland regolith simulants. This study involves a first characterisation of the penetration resistance, compressive strength and shear strength of the LHS with varying degrees of saturation, with comparisons to samples of the UK4 sand made where necessary. This work was performed in cooperation with the Geotechnical Laboratory of the Institute of Soil Mechanics and Foundation Engineering at Graz University of Technology, with the experiments detailed in Sections 5.3.2 and 5.3.3 kindly performed by Otto Leibniz and Odalys Morales-Calderon.

5.3.1 Penetration Resistance

These tests will follow on from the observations made in Section 5.1.2, in which the LHS appeared to undergo a rapid change in penetration resistance when the water mass increased from 5% to 9%. This is examined in greater detail, with the penetration profile of the LHS with different water contents within this range measured, with the aim of determining the resistance changes with water content, depth and position in the sample. Given the desired water mass range, the LHS produced in the compaction experiment in Section 5.2.4, which had an average water content of 7 - 8%, was used. The penetration resistance was measured with a hand-held Field-ScoutSC9000 penetrometer, seen in Figure 5.17 (a), which has a conical tip of 1.27cm (0.5in) and a full opening angle of 28°. The penetrometer was gently pushed into the simulant and recorded the resistance experienced as it reached intermittent depths. To allow a full examination of the changes in strength across the whole sample, measurements were taken first in the
centre of the sample, then at points close to the boundary, as shown in Figure 5.17 (b). After this, the sample was left in an open container at room temperature and allowed to dry for a day, before the water mass content was redetermined, in this case as being 4 - 5%. The sample was refrozen overnight and the penetrometer experiments were performed again. This was repeated once more, with penetration tests performed in the dried sample with a water content of 3 - 4%.

Figure 5.17: Pictures of the penetrometer (a) and a reading taken near the boundary of the frozen LHS (b).

Figure 5.18 gives the penetration resistance profiles for each of the samples. Since these tests were performed with a hand-held penetrometer, inaccuracies created due to uneven rates of penetration are inevitable, and as such these profiles should be taken as guidelines as opposed to precise values. Additionally, given that the first penetration through the centre disturbs and partially breaks the sample, this may potentially have an effect on the results of the subsequent boundary measurements.

These results support the observations made in Section 5.1.2, with a very clear decrease in penetration resistance as the water mass content decreases, while there is a notable increase in penetration resistance with depth. The 7 - 8% sample shows a very high resistance throughout, reaching a maximum resistance of over 3MPa after a depth of 5cm. This trend was also seen with the 4 - 5% sample, though the top 3cm was very easy to penetrate, with the resistance increasing only below this soft layer, reaching a maximum of
∼3MPa at a depth of 8cm, comparable to that of the 7 - 8% sample. The resistance in the 3 - 4% sample was much smaller, with a considerably gentler increase and reaching a maximum of only 1MPa beyond 5cm.

Additional observations include the oscillation of some of the curves, however this is an expected phenomenon due to the alternating phases between elastic deformation and the breakage of the solid material when a certain limit is exceeded. The central penetration resistance of the 7 - 8% sample was much larger than the boundary measurements, whereas the boundary resistance in the other two samples tended to be slightly higher. This sharp increase in the central resistance may also be a result of the simulant’s transition from soft to hard, with the central strength now increasing beyond the boundary strength. These results show that the frozen LHS experiences
a sharp change in penetration resistance at a critical water mass content of $5 \pm 1\%$. Samples with water contents below 3% are soft, with a similar strength to dry powder. Above this point the strengthening starts, and hard samples with strengths of several MPa are found beyond 5%.

### 5.3.2 Uniaxial Compression

Supplementary to the penetration resistance tests, the strength properties of the LHS with varying water contents will be examined. Understanding the strength of the regolith will be useful for instruments such as L-GRASP that will interact with samples and may be required break apart or crush them. This also provides a further characterisation of the properties of icy LHS. A series of experiments examined the compressive strength of the frozen simulants using standard uniaxial compression tests. Three samples of loose LHS with a density of $1550\text{kgm}^{-3}$ and water contents of 3, 6 and 12% were created. Three samples were also created with loose and compacted UK4 sand each, with densities of 1400 and 1700$\text{kgm}^{-3}$ respectively, to allow a comparison of both the simulants’ strengths and the effects of density. Each sample was mixed to produce a high degree of homogeneity, before being poured into cylindrical containers of 7cm diameter and 14cm height, consisting of three removable segments. Once the density of the sample was determined, it was frozen for several days in a $-20^\circ\text{C}$ environment. After this, the segments were removed, with the sample now consolidated, as seen in Figure 5.19.

![Figure 5.19: Picture of the consolidated frozen UK4 sample.](image)
The sample was then placed on a compression stand and confined by a cylindrical lid that rests on top without applying any compression force, shown in Figure 5.20 (a). The sample was then squeezed between the two confinements by a slow upward motion of the table, while the lid was held in place. The axial resistance force of the sample against this constant motion was normalised to a pressure value by dividing it by the sample’s cross-sectional area. This was measured against the deformation of the sample, defined as the percentage change in its axial height compared to the original height. The test was ended after the sample began to fail mechanically, at which point crevasses typically formed and propagated from the upper or lower edge of the sample, as seen in Figure 5.20 (b). At this point, the maximum axial stress had been reached, and afterwards the sample began to crumble and the stress decreased. The uniaxial compression strength was defined as the maximum compressive stress reached during a test run.

Two tests with each sample were performed, with the results for the LHS given in Figure 5.21. Here, the results are presented as the coloured curves, with the averages for each water mass content derived and given as the black lines. The maximum compression strengths of the average curves are also displayed. It can be seen that as the sample is squeezed between the two
5. Characterisation of Icy Regolith Simulants

confinements, and is thus increasingly deformed, the uniaxial stress exerted by the sample along the cylindrical axis continuously increases. As the sample begins to reach its maximum stress, the rate of increase with deformation begins to slow. The point at which the sample fails mechanically and begins to crack can be seen as the point in which the strength rapidly decreases whilst the deformation continues increasing. The corresponding graphs for the loose and compacted UK4, provided by the University of Graz, are given in Appendix I.

![Graph of uniaxial compression strength with deformation of the LHS with different water contents.](image)

Figure 5.21: Graph of the uniaxial compression strength with deformation of the LHS with different water contents. The test results and averages for each are given as the coloured and black lines respectively.

For all three samples, it can be seen that an increasing water mass content results in both a greater maximum compressive strength and a larger deformation of the sample before failure occurs. These results demonstrate the additional cohesiveness and structural integrity created by the addition of ice in the regolith, with more ice creating a significantly stronger sample. It should be noted that there is a large variation between several pairs of results, in particular for all 12% water content tests and the 6% results for the LHS. Because of this, the averages obtained cannot be considered truly accurate, but this does not affect the conclusions that have been made.
The maximum compressive strengths can be compared in Figure 5.22. Here, the test results are presented as the coloured marker points, with the averages for each simulant given as the black points on the corresponding lines. This graph shows that the compressive strength of the UK4 increases both with water content and density, with the results of the compacted UK4 comparable to that of the loose LHS. Additionally, whilst the strengths of the UK4 samples show a fairly linear increase with water content, the LHS appears to exhibit a more nonlinear trend, with the increase between 3 - 6% much larger than that between 6 - 12%. This could indicate that the compression strength is reaching a constant level for the given conditions as the water content approaches saturation.

5.3.3 Shear Strength

To complement these results, a series of shear strength tests were performed with loose LHS, loose UK4 and compacted UK4. Here, the simulant is held in two rectangular boxes, as shown in Figure 5.23. Under a defined vertical confining, or normal, stress, the two boxes are slid apart laterally in opposite
directions, until the sample fails at a measured shear stress. The same three water mass percentages are used for the LHS, with only the 6% and 12% for the loose UK4 and the 12% for the compacted UK4 used to provide a comparison, with each performed under normal stresses of 100, 200 and 300kPa.

![Figure 5.23: Picture of the shear test set-up using the LHS.](image)

The results of these tests are presented in Figure 5.24. As can be seen, the LHS results do not change with water mass content. This can also be seen, though to a lesser extent, with the two loose UK4 simulants, in which only the 300kPa tests are noticeably different. The shear strength of the LHS is also slightly larger than that of the UK4, becoming more pronounced with the increasing normal stress, given the slightly steeper gradients of the LHS samples. The greatest difference is seen in the compacted UK4, whose shear strength is much larger for the 100kPa normal stress, but the gradient of increasing shear with normal stress is much gentler, resulting in the shear strength of the 300kPa test being lower than that of the 6% UK4. This suggests that compacting the regolith can significantly increase the shear stress, though this effect is negated when larger normal stresses are applied.

The results in this section reinforce the observations made in Section 5.1. Both have demonstrated that there is a tipping-point value of 5±1% in which the icy regolith changes from soft to hard. This corresponds to the point at which the drilling time in icy regolith begins to increase from the respective room temperature wet regolith, though at this point there is no serious impact on drilling performance. While no examination of the properties of the LHS
was made with water content nearing the point of saturation, it can again be assumed that another phase of significant hardening, in which the regolith becomes a single consolidated piece, occurs between 10 - 12.5%, hence the dramatic increase in drilling time.

Ideally, testing would continue to further examine various other characteristics of the icy LHS beyond the requirements of the L-GRASP study. However this was not possible, due to the limited time in Graz and the already small amount of LHS available being greatly reduced by these series of experiments. Despite this, these tests have provided a first characterisation of icy NU-LHT-2M, and a first step towards the understanding and development of icy polar simulants suitable for future instrumentation testing.

### 5.4 Summary

The work performed in this chapter continues the examination of the parameters affecting DRD performance, by focusing on the effects of water and ice content on drilling. This has included the first testing of the DRD in both a lunar and icy regolith simulant, with the effects of water and ice content on the drilling time demonstrated, and resulted in the first examination of
5. Characterisation of Icy Regolith Simulants

the effects of ice content on the properties of the lunar highland simulant NU-LHT-2M. To do this, a preparation procedure able to add a controlled amount of water to the regolith was selected. The penetration resistance and strength properties of icy simulants were then examined.

Drilling tests with the DRD were performed in LHS with water and ice contents ranging from dry to near saturation, qualitatively estimated to be between 13 - 17%. These tests together showed that ice contents above 5% begins to slowly affect drilling performance, until a critical point between 10 - 12.5%, when the drilling time increases dramatically. These results correlate with initial penetration tests, which showed a clear change in properties between 5 - 9% and coagulation of the saturated sample.

In order to accurately measure the properties of icy simulants, a number of preparation procedures were tested. The open water disperser method was shown to be able to produce LHS samples with water contents nearing saturation, while modifying the set-up accordingly would allow the degree of saturation to be controlled. This represents a potential standardised procedure for producing icy simulants with the desired water content.

Cone penetration tests revealed that a sharp increase in the penetration resistance of the LHS occurs when the sample has a water content of 5 ± 1%. This reinforces the drilling observations, with the change in regolith properties here corresponding to the increased drilling time in icy regolith. Uniaxial compression tests of the LHS and UK4 also showed the compression strength and degree of deformation before failure to increase with water content. Finally, shear tests of these samples showed that shear strength did not seem to be affected by water content, with only the compacted UK4 showing noticeably different results. These results, as part of the study into highland simulants to be used for the testing of L-GRASP, can be considered a first step towards the understanding of the effects of ice on highland regoliths.
Chapter 6

Integrated Complex Motion Mechanism

The importance of lateral forces in the drilling performance of the DRD, discussed in Section 3.3.1, coupled with the increased depth achieved with diagonal drilling, observed in Section 4.6, have provided evidence that the addition of lateral motions can improve the performance of the DRD. This chapter presents the design of an integrated mechanism that is able to investigate the benefits of complex motions compared to the original reciprocation-only motion. First, the study into potential mechanism designs will be presented. The chosen design will then be described, along with the available motions it is able to create. The experiments to be performed will then be discussed, before the results are presented.

6.1 Dual Mechanism Concept Designs

This area of research has two objectives:

1. The exploration of the effects of controlled lateral motions combined with the original reciprocation motion

2. The development and demonstration of an integrated internal actuation mechanism

The former involves the study of two key factors. The first is how the magnitude of the penetration and traction forces experienced by the drill
head are affected by the different drilling motions. Secondly, the depths achieved by these motions will be recorded. This requires the development of an actuation mechanism that is capable of producing vertical-only and combined lateral-vertical reciprocation. These motions are hereby referred to as *simple* and *complex* respectively from this point. The mechanism will be inserted into two hollow drill head halves and powered by a motor. It must be noted that, as this mechanism is being designed for the purposes of researching the effects of lateral motion, a fully integrated system prototype is not the goal of this work. As such, only the mechanism will be enclosed within the drill heads, as opposed to the system shown in Figure 3.3 (b).

Before this integrated actuation mechanism (IAM) can be designed and tested, a number of concept designs were created. A critical requirement of these concepts is the motion they provide. Ideally, the drill head halves will undergo a cycle in which they are pushed horizontally outwards before or during being pulled upwards, and are pulled inwards before or during penetration. This will maximise the lateral force, and by extension the overall tensile force, by pushing the drill half into the surrounding regolith before it is retracted. It will also minimise the penetration force required by reducing the volume of regolith being penetrated into, as shown in Figure 6.1.

To this end, a number of options were explored. Five suitable concept designs were selected, and basic models of these mechanisms, were created. Brief descriptions of the rejected concepts can be found in Appendix F. Each concept has a figure showing the SolidEdge model and a schematic of the mechanism and drill head motions.

### 6.1.1 90° Cam and Gearing

This concept, shown in Figure 6.2, is based upon the DRD004 concept design introduced in [33], built in [42] and discussed in Section 3.3.2. The general design remains the same for creating the simple motion. The complex motion is achieved by rotating the mechanism 90° around the motor shaft. The cams are attached to the drill heads via a rod, whose position and orientation remains fixed. As the cams rotate, this pushes the rod and subsequently the drill heads in a circular motion. The new position of the rods will require a modified drive rail.
6. Integrated Complex Motion Mechanism

6.1.2 Shaft Base Third Cam

This also uses the same mechanism to create the simple motion. To facilitate the linear motion, a third cam wheel is fitted perpendicular to the base of the motor shaft. This will use similar principles to the cam system to connect the rod to the drill heads, creating a linear motion that will push/pull both drill heads simultaneously. By cutting grooves into the drill head-drive rail connection points, the combined linear movements of the drive rails can be converted into a smooth circular motion. A key aspect of this design is that the vertical and horizontal motions are independent from each other; in

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**Figure 6.1**: Diagram of the simple and complex motion cycles, demonstrating a comparison of the volumes of regolith drilled into by each penetrating half ($V_P$), the total volume of penetrated regolith ($V_{PT}$) and the volume of regolith engaged by the receding teeth ($V_E$).
other words, the amplitude of the vertical reciprocation, $a_v$, can be changed without this affecting the set horizontal amplitude, $a_h$. Another benefit of this independent system is that, depending on the set-up of the cam wheels and connecting rods, the mechanism can create a circular or diagonal motion.

Ideally, the third cam would be connected to both drill heads using a rod for each, as opposed to the single connection shown in Figure 6.3. However, the piston-like motion of the cam rod is not sinusoidal, as shown in Figure 6.4, meaning that the lateral movements of two cam rods placed in opposing
directions would not be equal. As a result, this would cause the drill heads to overlap by a small distance.

Figure 6.4: Graph showing the horizontal displacements of the drill heads when operated by opposing connecting rods on the same cam wheel. As can be seen, the drill heads do not share an equal trajectory.

6.1.3 Tilted Cam

Once again, this uses the original DRD$_{004}$ mechanism to provide the simple motion. The complex motion is achieved by using angular mitre gears, replacing the normal $90^\circ$ bevel gears. This allows the drive rails to reciprocate as normal in a diagonal direction. Although the possible angles are limited by the very narrow range of angular bevel gears available, there are no other changes to the mechanism required.

Figure 6.5: SolidEdge model of the Tilted Cam concept and sketch of the mechanism and drill head motions.
6.1.4 Tilted Cam With Linear Actuator

This concept utilises the same tilted cam mechanism, though the motor used is a linear actuator, creating a reciprocating motion of the motor shaft. A second adjacent shaft is connected via a gear to create two reciprocating motor shafts. These drive another gear each, which are connected to the drive rails. The angle and position of the drive rails can be modified, allowing for reciprocating and diagonal drilling.

![SolidEdge model of the Tilted Cam With Linear Actuator concept and sketch of the mechanism and drill head motions.](image)

It should be noted that linear actuators cannot be used with the cam and gearing systems described for the other concepts. A linear motor would reciprocate the cams as opposed to continuously rotating them, and the motion produced would only be ideal for half of the reciprocation cycle.

6.1.5 Quadruple Cam

This concept is a combination of the first two concepts. The original cam-drive system is used for the simple motion. For the complex motion, two additional cams are added, positioned 90° around the motor shaft. The corresponding drive rails are held horizontally and connected to both drill heads. This results in two drive rails simultaneously reciprocating the drill heads horizontally independently to the two vertically reciprocating rails. As with the second concept, the horizontal and vertical motions are independent from each other, and both circular and diagonal motions can be created.
6.2 Concept Trade-Off Study

Based upon these initial models, the five concepts were subjected to a trade-off study to determine their overall suitability. There are numerous trade-off methods, and for a concept design study such as this, in which the preliminary designs do not represent accurate models, the linear combination method is suitable [26], with a scoring system defined by Equation (6.1).

\[
Rank = \sum_{i=1}^{n} w_i x_i
\]  

(6.1)

Each performance criterion, or figure of merit, \(i\), is given an importance rating, or weight, \(w\), between one and five. These are then normalised so that the sum of the weights is one. The concepts’ ability to satisfy each criterion is given a rating value, \(x\), between zero and ten. This can then be used to find the concepts’ overall scores, or \(Rank\).

6.2.1 Trade-Off Criteria

The criteria and respective weights chosen are partly inspired by those used in the actuation mechanism [33] and L-GRASP sampling system trade-off studies [99]. These are:
6. Integrated Complex Motion Mechanism

1. Total Number of Individual Parts

This is determined by the total number of parts required to build the IAM as shown in Figures 6.2 - 6.7. This acts as a guide to the design’s complexity, and does not include the motor, motor shaft, drill heads, sealing, bolts/screws or structures required to hold the parts in place. The number of parts are summed and normalised to a value from one (many parts) to ten (very few parts), found using Equation (6.2). **Weight: 2.5.**

\[ x_i = 10 \left( 1 - \frac{\text{Sum of concept } i \text{ parts}}{\text{Sum of all concept parts}} \right) \] (6.2)

2. Ease of Implementation

This is determined by the ease with which the mechanism can be assembled from the ground up, including the intricacy of the implementation required for the gears and/or linkages. This also includes the ease with which the simple and complex motions can be modified and set up. **Weight: 3.**

3. Coupling of the Vertical and Lateral Motions

To maximise the range of motions the IAM can produce, the vertical and lateral amplitudes must be able to be independently changed. Mechanisms allowing this are given a score of three. If an amplitude cannot be changed without altering the other, the motions are defined as coupled, and the mechanism is given a score of two. If the amplitudes are coupled and dependent on multiple factors, the mechanism is given a score of one. The scores given are then normalised to a range of 1 - 10. To fully study the effects of adding lateral movements, the creation and testing of multiple motions is crucial, and as such this criterion has the highest priority. **Weight: 5.**

4. Ease of Changing Between Simple and Complex Motions

This is determined by what changes are required, including additional parts, orientation changes and the amount of disassembly needed, to alternate between the simple and complex motions. **Weight: 2.**
5. Overall Drill Diameter

This is an estimate of the minimum inner diameter of the drill heads required to accommodate the IAM. As the concepts shown in Figures 6.2 - 6.7 were created with parts larger than they would be in a final design, the rating values are determined by their relative dimensions. **Weight: 3.**

6. Even Distribution of Force to the Drill Heads

To minimise the buckling effects and the friction on the mechanism-drill head connections, and to maximise the overall efficiency of the IAM, 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.**

6.2.2 Results

The results of the trade-off study are given in Table 6.1. It is clear that the tilted cam designs performed very poorly. This is largely due to the vertical and lateral amplitudes being both coupled together and determined by the orientations of the cams and drive rails. Fitting the mechanisms accurately at an angle was also considered to be a significant difficulty.

<table>
<thead>
<tr>
<th>Performance Criteria, $i$</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>Rank</th>
</tr>
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<tbody>
<tr>
<td>Concepts</td>
<td>Value</td>
<td>Normal</td>
<td>Value</td>
<td>Normal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>90° C &amp; G</td>
<td>7</td>
<td>8.83</td>
<td>9</td>
<td>2</td>
<td>6.67</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>SB 3rd Cam</td>
<td>12</td>
<td>7.83</td>
<td>6</td>
<td>3</td>
<td>10</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>Tilted Cam</td>
<td>9</td>
<td>8.5</td>
<td>4</td>
<td>1</td>
<td>3.33</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>TCWLA</td>
<td>11</td>
<td>8.17</td>
<td>5</td>
<td>1</td>
<td>3.33</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Quad Cam</td>
<td>20</td>
<td>6.67</td>
<td>5</td>
<td>3</td>
<td>10</td>
<td>7</td>
<td>5</td>
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<tr>
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<td><strong>Total</strong></td>
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<tr>
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<td>0.25</td>
<td>0.1</td>
<td>0.15</td>
<td>0.225</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 6.1: Performance criteria scores and rankings of the IAM concept designs
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 disadvantages of coupling the motions and providing a poor distribution of force. The Shaft Base Third Cam and Quadruple Cam designs were largely similar, with both able to produce independent variation of the vertical and lateral motions. Due to the Quadruple Cam’s extra cam wheel, it is a more complex design and so scored lower in a number of categories. However, the two additional cams are able to provide a much greater force distribution along the length and width of the drill head via multiple drive rails and 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. This new mechanism will be known as the Dual Complex Motion Mechanism (DCMM).

6.3 Dual Complex Motion Mechanism Construction

To achieve the goals stated in Section 6.1, the DCMM must be designed to allow the recording of both of the forces experienced by the drill head and the depth to which it can drill. To achieve the former, a force sensor must be integrated into the mechanism. The latter can once again be found by using a SoftPot membrane potentiometer. A major consideration which drove the design of the Quadruple Cam was the overall size. While length was not strictly constrained, the drill diameter had to be kept as small as possible. Given the complicated design and number of parts involved in the SolidEdge design, the desired diameter of the completed drill was 46mm, equal to the largest drill diameter in Section 4.2.1, with an upper limit of 56mm. This section describes the design and construction of the DCMM, with further details of the parts and assembly given in Appendix G.

It must be emphasised that, for the purposes of these experiments, the DCMM to be built is solely designed for the testing of the motions available with the Quadruple Cam design. This inevitably results in a design that is not representative of a system prototype. While focus is given to the
integration of the DCMM inside the drill heads, this is not required for
the motor, and as such the drill will once again be deployed using a test
rig. Potential designs for fully integrated system prototypes, inspired by the
conclusions and designs detailed in this chapter, are discussed in Section 7.3.

6.3.1 Drive Rail Design

The gearing and drive rails are shown in Figure 6.8. Early in the design
phase, it was seen that having the four cams together as shown in the original
concept was impossible. To resolve this, the gearing for the vertical and
horizontal drive rails were separated, resulting in two transfer boxes through
which the motor shaft runs, as shown in (a). These consist of three RS
SBM08/16 bevel gears; one is fixed onto the motor shaft, and the other
two are positioned at 90°. Inserted into these gears are the cam wheels.
These are in turn slotted into the central structure of the mechanism using
Simply Bearings F67022RS rubber sealed ball bearings, shown in (b). This
structure also consists of the linear guides for the drive rails. Each wheel is
then connected to their respective drive rails via a connecting rod (c). Each
cam has three screw holes, allowing amplitudes of 1, 2.75 and 4.5mm to be
selected. The central structure, bevel gears, ball bearings and drive rails were
designed as a compromise between keeping the DCMM as small as possible,
the positioning and guidance of the drive rails and maintaining the overall
strength of the system.

6.3.2 Outer Shell and Force Sensor

The mechanism is fixed to the drill heads by two hollow outer shell structures,
as shown in Figure 6.9 (a). These are attached to the drive rails via a number
of connection points, which consist of precision slide bars linked to the drive
rails and shells by supports. Whilst the four rails produce linear motions,
the combination of these causes the outer shell to move in a complex motion.
To allow this, the connection points between the drive rails and outer shells
include a precision slide bar linked to the drive rail, seen in (b), which is
allowed to slide freely in supports attached to the shell. In the case of the
lateral drives, the slide bar pushes the supports, and subsequently the shells,
horizontally. The freedom of movement in the support allows it to freely
slide up and down. Friction caused by this interaction, and consequently the
risk of the mechanism jamming, is reduced by having multiple connections
Figure 6.8: Pictures of (a) the bevel gear transfer boxes, (b) the central holding structure of the DCMM and (c) the reciprocating and lateral drive rails.

per drive. The movement of the rails and bars is shown in (d). Each shell is attached to one of the vertical and both of the horizontal drive rails. The force sensor is attached between one of the vertical drive rails and the precision slide rail connections, shown in (c). This is discussed in greater detail in Section 6.4.

6.3.3 Drill Heads and Test Rig

The radius of the DCMM, including the outer shell, is 23mm, equal to the radius of the largest drill heads in Chapter 4. To avoid the drill heads becoming excessively large, the dimensions of the teeth were kept relatively small, with an $R_t$ of 4mm and an $L_t$ of 7mm, giving an $R_{tot}$ of 27mm. The mid-point of the drill head length was determined as the middle of the lateral drive rails. Using this, and taking the top of the drill head to be just below the force sensor, gave an $L_{tot}$ of 230mm. The cone length was made as large as possible, with an $\alpha$ of 15.9°. The drill heads are made of three ABS parts fixed together, shown in Figure 6.10 (a), with cylindrical extrudes on the top of the cone that slot into the base of the outer shell, and screw holes near the top.
Figure 6.9: Pictures of the outer shell structure (a), the precision slide bar connections (b), the force sensor (c) and a schematic showing the movement of the rails and bars.

The motor is the same one used in the experiments detailed in Chapter 4, and is attached to the DCMM via the central shaft and fixed to a wooden test rig plate, shown in Figure 6.10 (b). The mechanism is prevented from rotating with the motor shaft by an additional holding part, which wraps around the top of the central structure, threads through the outer shell and is fixed on to the plate. This part was made of plastic (later parts, seen in Figure 6.9, were a combination of plastic and wood) to create a point of failure in the system that would break, should a fault occur, before any of the mechanism’s parts could be damaged. The completed mechanism, with the drill heads attached, is shown in Figure 6.10 (c).

6.4 Force Sensor

One of the aims of these experiments is to examine the forces experienced by the drill as it penetrates with and without the addition of controlled lateral movements. The current conclusion of previous experiments [50] is that the lateral forces created by the sideways movements are much larger than the traction forces. It is believed that increasing the sideways movements will help the backwards-facing teeth dig further into the regolith, creating
greater lateral and traction forces, resulting in a larger available penetration force. Ideally, separate sensors would be used to measure the penetration, traction and lateral forces experienced by each drill head. However, due to cost and sizing constraints, a single tension-compression load cell will be used, placed within one drill head, which will measure the vertical penetration and traction forces. Given that identical drill heads will be used, with only a small difference in the vertical drive rail designs, it can be assumed that the forces experienced by both drill heads will be very similar.

6.4.1 Selection

Due to the mechanism’s unique set-up, and the numerous factors that would require consideration, accurately estimating the force range that would be experienced is extremely difficult. As such, the forces measured in the previous experiments were used as a conservative estimate. The area of regolith penetrated by a single DCMM half is approximately the same as the 18mm radius MDH, which experienced ~2kN in vibrated SSC-2 at a depth of 200mm [45]. While the conditions for the DCMM tests differ from the MDH, and are likely to produce different results, a 2kN minimum range was considered suitable for measuring the DCMM forces. The traction forces measured in the MDH tests often ranged in the order of Newtons, and as such the force sensor would need to have a resolution within this range.
Tension-compression load cells are able to measure both forces, and miniature designs have been created for use in constricted spaces. They can be installed in numerous ways, with common examples being the button, donut and inline types. Given the relatively unstable nature of the DCMM, due to its constant movement, the button and donut cells are unsuitable. Finally, as this will be installed within the mechanism, the cell must be as small as possible. The LCM Systems 2.5kN DCE Tension Compression load cell was chosen, which has a diameter of 20mm, a resolution of 0.002kN, positive and negative outputs to differentiate between tension and compression respectively, and male threads for inline installation.

6.4.2 Placement and Operation

To utilise the force sensor properly, it must be placed between one of the vertical drive rails and its corresponding shell, allowing the forces experienced by the rail and shell to be transmitted through the sensor. A requirement for the load cell is that forces must be applied axially. To this end, the sensor is placed between the drive rail and slide rail supports, resulting in the sensor reciprocating with the drive rail. A drawback of this is, given that the drill head will be moving laterally, it will hit the sensor as it pulls inwards. To avoid this, the drill head height is limited to that of the sensor’s position, as can be seen in Figure 6.10. The drive rail with the force sensor does not have a slide rail connection between itself and the shell base. As a result, all forces experienced between the drive rail and outer shell are transmitted through the sensor. With this set-up, a tensile force is created between the upwards resistance created by the regolith against the drill head’s penetration and the downward motion of the drive rail. Conversely, the upwards movement of the drive rail during retraction and the resistance to the ascent of the drill head caused by the teeth gripping the regolith creates a compression force.

6.4.3 Amplification and Calibration

The DCE load cell produces an output in the range of 1.5mV/V. This range is much too small to be measured accurately by data acquisition systems. Typically, force sensors use an amplifier to amplify the signal to a readable range. Ideally, a sensor with an integrated electronics package would be used, but the limited range of integrated inline sensors, and the additional size required for the electronics, resulted in this option not being considered. A
custom-built model based upon the SGAU Universal Strain Gauge Amplifier from Industrologic is used here. This is connected to an Arduino, creating a circuit similar to that used for a simple potentiometer, though an external power supply is needed to provide the 9V required for the voltage swing to span the entire 0 - 5V range of the Arduino. Due to a small current caused by the amplifier’s resistors, the output signal is limited to 4.24V. The amplifier uses a 1kΩ trimmer potentiometer to determine the resting, or central, point of the sensor readings. This is adjusted to produce a resting voltage of 2.12V, giving a maximum range of 2.12V each for the tension and compression values. The resolution of the readings is limited by the Arduino, with the 512 data points for the full 2.5kN range providing a resolution of 4.88N. This was improved by reducing the readable force range, by changing the gain resistor. By hanging fixed weights of known values from the sensor and noting the corresponding reading changes, a 120Ω resistor was selected, providing a force range of approximately 848N. The amplifier and Arduino circuit is shown in Figure 6.11, with a full circuit diagram given in Appendix H.

![Figure 6.11: Picture of the force sensor amplifier and Arduino data acquisition circuit and the connections used for the ThinPot potentiometer.](image)

Before being used, the force sensor was calibrated in order to confirm the linearity of the measurements and the conversion rate from the voltage values recorded by the Arduino to the forces experienced. Masses of known weights were hung from and placed on top of the sensor to produce tension and compression forces respectively. The changes in voltage from the resting value were recorded and are shown in Figure 6.12, with the tension values registering as positive forces and the compression values as negative. The graph shows a linear increase for all values as expected, with a gradient of 3.05mV per Newton. The resolution of the readings was 1.6N, which is consistent with the load cell’s stated resolution of 0.002kN.
6.5 Motions Available

The main benefit of the Quadruple Cam design is that the $a_v$ can be altered without affecting the $a_h$. Each cam wheel has three amplitudes, giving a total of nine possible amplitude combinations. An additional benefit of the uncoupled amplitudes is that, by changing the position of the cam wheels and rods, as shown in Appendix G.2, different motions can be created.

6.5.1 Circular Burrowing

The displacements of the drill heads created by the Quadruple Cam is the same as that discussed in Section 6.1.2, i.e. non-sinusoidal. Combining the same horizontal and vertical amplitudes together creates a slightly squashed circular burrowing (CB) motion, as seen in Figure 6.13 (a). Here, the lines trace the paths travelled by the drill heads around a central point when observed from the angle in Figure 6.10 (c). Decreasing both amplitudes naturally results in a smaller circular motion. By reducing only $a_v$ whilst keeping $a_h$ constant, or vice versa, the motion of the drill heads becomes more elliptical, as shown in Figure 6.13 (b). In both graphs, it can also be seen that the path travelled becomes more regular as the amplitude decreases.

6.5.2 Diagonal Burrowing

Although diagonal burrowing (DB) can be achieved by changing the starting position of the cams, the non-sinusoidal motion of the rods makes this
difficult. For example, one set-up created the diagonal motion for one drill head, but a curved motion for the other, while another resulted in the drill heads splitting apart slightly during the middle of the cycle. By changing the position of one of the vertical rods, a diagonal motion could be achieved with both drill heads, in which the horizontal and vertical displacements combine together to create an inclined line of travel, with the paths created shown in Figure 6.14 (a). As with the CB, the paths travelled can be altered by changing one or both amplitudes. However, when changing a single amplitude, for example $a_h$ as shown in Figure 6.14 (b), there is a small change in the paths. Once there is a difference in the amplitudes, the path begins to curve slightly on the right-hand side of the graph, and the point at which $a_v = 0$ for both drill heads is no longer at $a_h = 0$. This becomes more pronounced as the difference in amplitudes increases. Given that these curves are very slight, and do not affect the overall displacements of the drill heads, it is believed that this will have a negligible effect on performance.

6.5.3 Reciprocation-Only

The DCMM can also produce the original DRD motion, by removing the horizontal cam wheel connecting rods and fixing the horizontal drive rails
Figure 6.14: Graphs showing the diagonal path travelled by the drill heads with (a) an $a_v$ and $a_h$ of 4.5mm, and (b) under different $a_v$ values with a constant $a_h$ of 4.5mm.

in place by screwing them into the hold support. Three amplitudes are available, and the results obtained from these will be used as the base values from which the performance of the complex motions can be measured.

### 6.6 Experimental Plan and Aims

From the three amplitudes provided by the cam wheels, and the ability to produce reciprocation-only, circular or diagonal drilling, the DCMM can produce a total of 21 different motions, summarised in Table 6.2. Each of these will be tested twice in the SSC-1 regolith. Only the poured technique will be used for this series of experiments to reduce the number of tests performed, though the vibrated technique is used for a small series of tests detailed in Section 6.9. Given that there is no sealing of the DCMM, and due to imperfections in the ABS drill heads, it is possible that some regolith may be able to enter the mechanism, potentially creating a jamming issue. This would worsen significantly with the SSC-2, given its smaller particles. Additionally, the estimated depth reached by the drill using Equation 4.5 for reciprocation-only drilling with a 3mm amplitude is 92mm in SSC-2 and 251mm in SSC-1. It should be noted that this value is a very approximate estimate, as the
6. Integrated Complex Motion Mechanism

Operational and geometrical parameters for this set-up are different to those used in Chapter 4. As the lowest lateral drive rail connection is roughly 130mm above the drill tip, the lateral motion seen in the submerged part of the drill will likely be greatly reduced or eliminated entirely. In order to involve the lateral mechanism as much as possible, and due to the increased risk of jamming of SSC-2, this regolith is not used.

<table>
<thead>
<tr>
<th>DRD</th>
<th>Circular Burrowing</th>
<th>Diagonal Burrowing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 0</td>
<td>1 - 1</td>
<td>1 - 2.75</td>
</tr>
<tr>
<td>2.75</td>
<td>0</td>
<td>2.75 - 1</td>
</tr>
<tr>
<td>4.5</td>
<td>0</td>
<td>4.5 - 1</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>4.5 - 2.75</td>
</tr>
<tr>
<td></td>
<td>2.75</td>
<td>4.5 - 4.5</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>4.5 - 4.5</td>
</tr>
</tbody>
</table>

Table 6.2: Summary of the motions available for the DCMM (presented as vertical amplitude - horizontal amplitude).

The full test rig set-up includes a box 28cm deep that is filled with SSC-1 using the poured technique. A roller attachment is added to the wooden plate, which presses into a 300mm ThinPot membrane potentiometer to record the distance. This is connected to the same Arduino used to record the force sensor data. The reciprocation frequency was lowered to 1Hz, as it was felt that a slower motion would reduce any potential damage caused to the DCMM if a fault were to develop. The motor and Arduino are connected to separate TTi TSX3510P continuous DC power supply units. With all mechanisms attached, and an additional 500g mass added, the OHF of the test rig was \(\sim 48\)N. As with the choice of regolith simulant, this OHF, which is larger than that used in Chapter 4, is also needed to ensure that the drill heads dig deep enough for the effects of the mechanism to be fully utilised. Given that these experiments focus on the effects of the motions and amplitudes of the drill heads, the frequency and OHF operational parameters will be kept constant; this will also allow the number of experiments to be kept to a reasonable number. The full system is shown in Figure 6.15.

As the DCMM is a complex system, with numerous potential points of failure, sources of friction and small parts that could easily be worn down, it is highly likely that faults could develop, causing significant damage that would result in costly delays. Particular points of weakness are the connections between the rods and cam wheels/drive rails. Priority was therefore
given to increasing the longevity of the mechanism, in order to complete as many experiments as possible. The reciprocation-only tests were performed first. The results from these were then used to analyse the forces measured. After this, the complex motions were performed. All vertical amplitudes are performed with \( a_h = 1 \text{mm} \) with both the CB and DB, before using \( a_h = 2.75 \text{mm} \) and finally \( a_h = 4.5 \text{mm} \). Each experiment undergoes a test run, in which the test rig is held in place with the drill heads positioned above the regolith, and the mechanism is shown to be able to run freely with a reasonably smooth motion, with both sensors recording the initial forces and depth. After this, the rig is held with the drill heads just above the regolith surface. The rig is then dropped, and the drill is operated for up to 100s. This was long enough to determine the final drilling depths, whilst also being short enough to not place undue stress on the mechanism’s components. For the rest of this chapter, the motions are referred to as \( xVybH \); for example 4.5V1H represents \( a_v = 4.5 \text{mm} \) and \( a_h = 1 \text{mm} \).

There are three aims for these experiments. The first is to demonstrate a fully functioning actuation mechanism integrated within the drill heads, producing simple and complex motions. The second is to examine the vertical tension and compression forces experienced by the DCMM, and to identify
how they change during a reciprocation cycle. Finally, the benefits of the addition of controlled lateral movements to the vertical motion will be examined, by comparing the depths achieved by the simple and complex motions.

6.6.1 Results of the First Simple Motion Tests

The first experiments performed with the simple motion were largely used to provide a first demonstration of the DCMM. Slight changes to the DCMM set-up were made for the later experiments, which resulted in a more stable drilling direction and smoother motion. While this caused changes to the depth and force values, the profiles, in particular those of the forces experienced, can be analysed here. Two runs were performed with the 4.5mm \( a_v \), with the initial test force profile and the combined force-depth drilling profile for one of these runs given in Figure 6.16. It is reiterated here that the compression values given during retraction of the drill head are negative and the tension values given from penetration are positive.

![Figure 6.16: Graphs of the force profile for a test run (a) and the combined force-depth profile for a run of the 4.5V0H set-up (b).](image)

As can be seen, there is a very consistent force profile, with consistent spikes in the compression and tension values. During the drilling, in which the starting point can be determined by the depth profile, both forces increase with depth. Both profiles follow a similar path to those observed for the drills in Section 4.5 that reached a final depth; i.e. after the rapid initial penetration caused by the dropping of the test rig, the increase in depth/force
slows and eventually ceases. The experiments were performed twice again for the other vertical amplitudes, with a force-depth drilling profile for each given in Figure 6.17. None of these motions are able to achieve the estimated depth in SSC-1 of 251mm predicted by Equation 4.5. However, both the $R_{tot}$ and $\alpha$ of these drill heads are larger than the parameter ranges examined previously, and as such the equation may not apply here. Additionally the amplitude, frequency and OHF parameters, which each have a bearing on final depth, are different to those used in Chapter 4. Because of these factors, the reduced depth seen is expected. Both the forces experienced and depth reached decrease with smaller amplitudes. While this is to be expected, with similar results found in Section 4.5, an interesting point for the 1V0H set-up is that, during the initial penetration, the compression value decreases to zero, and remains this way for $\sim$25s before increasing to a stable value.

![Figure 6.17: Force-depth profiles for the 2.75V0H (a) and 1V0H (b) set-ups.](image)

**6.7 Analysis of the Force Measurements**

The analysis presented here focuses on the results obtained in Section 6.6.1. To confirm the validity of the force measurements and the correct operation of the force sensor, two free-run experiments are performed with the 2.75V0H set-up. As with the test runs, here the drill and test rig are held in place while the drill is in motion. As such, there is no OHF acting on the drill or interaction with the regolith. The first is a normal test run, though without the drill heads attached. For the second, a 1kg mass is hung from the shell
top part attached to the force sensor, which can be seen in Appendix G.1, creating a fixed additional compression force of 10N. From the graphs shown in Figure 6.18 it can be seen that, when the weight is added, the force profile is shifted down by approximately 10N. This confirms that the extra 10N compression created by this mass is being applied to the sensor, and that the forces are being measured correctly.

Another point to consider is how the force profile relates to that of the reciprocation. Determining this will allow an understanding of how the forces are being produced throughout a single reciprocation cycle. Also, up to this point, the starting position of the drill heads has not been recorded, and it is possible that this affects the force profile. To investigate this, the DCMM is started at four known positions relating to the drill head containing the sensor: (a) at maximum retraction, (b) at the mid-point from retraction to penetration where the drill heads are level, (c) at maximum penetration and (d) the mid-point from penetration to retraction with level drill heads. Three slow cycles were performed, with the force profiles given in Figure 6.19.

From these graphs, it can be seen that the initial force is given by the starting position. The profile from this point is the same for each cycle, with the sensor experiencing compression during the top half of the cycle, peaking at the maximum retraction, and undergoing tension during the bottom half, with the largest value seen at the maximum penetration. This shows that a force is acting on the DCMM before the motion has started, with the magnitude determined by the starting position. This suggests that much of the force exerted on the sensor is created by resistance from the internal friction of the mechanism, increasing as the drill head moves away from the mid-point, or neutral, position. This is explored further in Section 6.7.3.

6.7.1 Current Measurements
To further demonstrate this point, an oscilloscope is used to see how the current changes during the reciprocation cycle under various operating conditions. The current provided by the motor changes according to the motion of the drill and increases when it begins drilling, as previously shown in Section 4.5.7. The motor current is related to the torque, and by extension force, provided. The voltage is recorded across a 0.1Ω shunt resistor, placed in series in the motor circuit as described in Section 4.3.3.
Figure 6.18: Graphs of the force profiles for the free-runs with nothing (a) and a 1kg mass (b) attached.

Figure 6.19: Graphs of the force profiles at different starting positions.
The current variation seen in the normal reciprocation cycle was recorded with the DCMM free running at a frequency of just under 1Hz, with only the shell top segment of the outer shell attached. From Figure 6.20 (a), a small variation in current can be seen per cycle. For comparison, a 3kg was hung from the shell top and the motion run again. A large increase in current during the retraction is seen in Figure 6.20 (b), while the current during penetration remains fairly unchanged. This is expected, as more force, and thus current, is required to pull the additional mass upwards.

![Graphs of the measured oscilloscope and averaged current values for the DCMM with nothing (a) and a 3kg mass (b) attached.](image)

**Figure 6.20:** Graphs of the measured oscilloscope and averaged current values for the DCMM with nothing (a) and a 3kg mass (b) attached.

### 6.7.2 Force and Depth Comparison

The increases in the tension and compression forces were compared to the final depths reached for each experiment, given in Figure 6.21. The values are grouped into the tension or compression values achieved for each $a_h$. In all cases, it can be seen that both forces increase with depth reached, with the tension-penetration forces larger than the retraction-compression forces. Several 1T values are clear outliers, with the four deepest runs experiencing much lower forces than other motions that reached similar depths. By discounting these, it can be seen that the tension and compression trendlines are fairly similar, suggesting that the forces increase equally with increasing depth. It is likely that much of the difference between these trendlines, and the cause for the negative compression values, is due to the 50N overhead force produced by the test rig. The reaction of the regolith to the OHF acts...
through the drill heads and pushes them upwards, and consequently pulls at the force sensor. Assuming the regolith reaction is spread evenly between the two drill heads, a constant tension force of $\sim 25N$ is being applied to the sensor. This explains the negative compression values seen, as the small compression caused by the retracting drill head is smaller than the tension created by the test rig. By translating the tension and compression trendlines down and up by 25N respectively, the two set of forces become very similar. This can be seen to be demonstrating the transfer of forces acting within the DRD system, with the traction force of the receding half being converted to a similar digging force in the penetrating half.

Figure 6.21: Graph showing the relationship between the final tension, compression and depths achieved for each experiment. This includes the trendlines before (black) and after (red) the test rig OHF is taken into account.

It must be noted that, due to the scattering of the results seen, the forces measured here are likely not especially accurate, though they are suitable enough for the observations that have been made here. Additionally, the combination of the lateral movements and the complexity of the mechanism is likely to result in changes in internal friction in the complex motions that cannot be examined as easily as the simple motions, and as such large discrepancies in the force measurements are likely. As a result, it is not possible to make any further accurate analyses beyond the generalisations discussed.
6. Integrated Complex Motion Mechanism

6.7.3 Analysis of the Forces Acting on the Sensor

Further analysis of the forces acting on the sensor is explored here. Two force equations can be created: one for free motion and one for drilling, given in Equations 6.3 and 6.4 respectively. These are simplified equations that describe the sum of the two forces discussed in Section 6.4.2 that act on the sensor to create the compression or tension: the pushing/pulling force of the actuation mechanism provided by the motor, \( F'_{\text{motor}} \), and the resistance to the movement caused by the internal friction, \( F_{\text{int}} \). The total force acting on the sensor, \( F_{\text{comp/tens}} \), will either be a compression or tension, depending on the drill’s position in the reciprocation cycle. During drilling, an additional force is created by the resistance of the regolith, \( F_{\text{res}} \), whether it be against the drill head’s penetration or the gripping of the backwards-facing teeth during retraction. As well as this, the current increases when drilling. Given that the motor’s current and force are related, as discussed in Section 4.2.3, the force provided by the motor and actuation mechanism during drilling, \( F_{\text{motor}} \), increases from that produced in free motion.

Freeload: \((\pm)F_{\text{comp/tens}} = F'_{\text{motor}} + F_{\text{int}} \) (6.3)

Drilling: \((\pm)F_{\text{comp/tens}} = F_{\text{motor}} + F_{\text{int}} + F_{\text{res}} \) (6.4)

A brief analysis will be performed to determine the contribution each force makes to the total sensor reading. This will begin with examining the forces during free motion, i.e. with the drill suspended above the regolith with no external forces acting on it. As \( F_{\text{int}} \) can vary significantly from one drilling test to another, as discussed in Section 6.7.2, the contributions of \( F'_{\text{motor}} \), which can be easily accounted for, must be calculated first. By comparing the motor forces, with the friction excluded, against the total measured forces, the contribution of the internal friction to \( F_{\text{comp/tens}} \) can be measured. To do this, the basic reciprocating system will be modelled as a slider-crank mechanism, with the cam wheel acting as a camshaft, and the drive rail, force sensor, outer shell and drill head acting together as the piston, as shown in Figure 6.22.

The slider-crank mechanism is used to find the total net force acting on the piston in an internal combustion engine, \( F_p \), using Equation (6.5), which creates a torque that acts to turn the crankshaft. The forces acting on the
piston are the external force due to gas pressure, $F_e$, inertial force, $F_i$, and the friction, $F_r$. For a vertical piston, the weight of the reciprocating parts, $F_w$, contributes to the overall effort when the piston is moving downwards, and opposes it on the upstroke [16].

$$F_p = F_e + F_i \pm F_w - F_r$$  \hspace{1cm} (6.5)

This system differs from the combustion engine model, as it is now the crankshaft that is producing a force to push the piston, $F_c$. This force must overcome the sum of the forces that are now acting against the reciprocation of the piston. Additionally, there is no external force acting on the DCMM when run freely, and so $F_e = 0$. Given these differences, which are shown in Figure 6.23, Equation (6.5) was modified to allow the calculation of the total force required by the crankshaft to reciprocate the piston.

$$F_c = F_r \pm F_w - F_i$$  \hspace{1cm} (6.6)

The weight of the mechanism adds to the overall force to be overcome on the upstroke and reduces it on the downstroke. The inertial force, given by D’Alembert’s principle [119] and shown in the direction of motion, results from a body’s resistance to any change in its velocity proportional to its
mass, \( m \), and acceleration. This is given as a function of the displacement of the piston downwards from its highest position.

\[
F_i = -m\omega^2 R \left( \cos \theta + \frac{R \cos 2\theta}{L} \right)
\]  

(6.7)

Only the inertial force created by the reciprocating mechanism is considered. Although the rod and cam wheel each have their own inertial forces and weights, their respective masses are much smaller than the components of the ‘piston’, and as such their forces are considered negligible.

The sum of \( F_i \) and \( F_w \) equates to the force required by the motor to move the mechanism when friction is neglected. A reciprocation amplitude of 4.5mm and an angular frequency, \( \omega \), of \(~5\text{rads}^{-1}\) was used to find the inertia needed for large operational parameters. By calculating these, the total force to be overcome when friction is neglected over one reciprocation cycle can be found, where it can be seen in Figure 6.24 that the inertial force is very small compared to the other forces.

The change from negative to positive values for the total force at 180° is due to the transition from the downstroke to the upstroke of the piston, at which point the weight changes from reducing to adding to the total force required. Here, it can be seen that the effect of the weight results in a difference of approximately 3.2N between the downstroke and upstroke. This
change in force can also be seen in the free-run force profiles in Figure 6.19, in which the maximum compression force during the upstroke is \(~7\text{N}\), while the tension force during the downstroke is \(~4\text{N}\). For these tests, it can be assumed that this is also caused by the change in effect of the weight from downstroke to upstroke, creating a difference of \(\pm1.6\text{N}\) around a consistent maximum internal friction force of approximately \(5.5\text{N}\).

The torque required to overcome this force, \(T_c\), can also be found using the distance \(OM\), which is obtained by extending the rod length \(CB\) to point \(M\), which lies on the line perpendicular to \(OC\), as shown in Figure 6.22.

\[
T = F \cdot OM = FR \frac{\sin(\theta + \phi)}{\cos \phi}
\]  
(6.8)

This can be compared to the torques required to overcome the forces measured from a free run with a fully assembled DCMM, \(T_m\). The forces measured over one reciprocation cycle are converted into torques using Equation (6.8). From this, the torques required with and without friction can be compared in Figure 6.25.

The negative torque seen for the calculated results is due to the negative force that needs to be overcome during the penetration, caused by the weight
of the system aiding the motion. A negative torque is therefore required to slow the system to keep the reciprocation frequency constant. Throughout the cycle, the measured torque is much larger than the calculated torque needed to overcome the inertial force and weight. This further demonstrates the importance of the friction in the DCMM.

From this analysis, it can be concluded that the DCMM’s internal friction is responsible for the majority of the forces measured. It is not possible to further analyse the forces when drilling, as the change in forces measured cannot be separated out into the changes seen in $F_{\text{motor}}$, caused by the increase in current, and the additions caused by $F_{\text{res}}$. However, by assuming that the internal friction force cycle remains constant when the mechanism is also drilling, the increase in forces seen during drilling can be attributed to the additional penetration or traction forces created by the regolith interaction.

### 6.7.4 Friction Experimental Analysis

The internal friction of the DCMM can be further explored by determining the current profiles of different parts of the mechanism. This was done with the DCMM in four stages of completion: (1) with only the transfer box and cam wheels, (2) with the sensor and drive rail, (3) with the outer shell and (4) with the drill head. The current plots of each are shown in Figure 6.26.
Figure 6.26: The oscilloscope and averaged current readings for the DCMM at various stages of completion.

The current readings for both (1) and (2) are very similar, showing a consistent current of \( \sim 0.52 \text{A} \), suggesting that the friction of the drive rails is negligible. It is clear that, while there are slight variations in the current readings in (3), suggesting some friction is present when the outer shell is attached, the vast majority of the current oscillation, and subsequently the friction, occurs when the drill head is attached. This increase in current is reflected by the values measured by the force sensor for (3) and (4), shown in Figure 6.27, with the forces being much larger when the drill head is attached.

The results of these measurements have demonstrated the significance of the friction forces in the drill head, including how they are affected by the reciprocation amplitude, the position of the drill head and the components of the DCMM, and their overall contribution to the total freeload force. Ideally,
friction force would be negligible, though naturally given the sheer number of parts and moving components, there will always be friction in the system. This is very dependent on the set-up of the DCMM, with numerous factors, such as the tightness of the screws, the alignment of the slide rails, etc. potentially having a great effect on the total friction force. As such, the freeload forces measured for the runs not shown in Figures 6.16 and 6.17 varied considerably. Friction will also increase if the DCMM is not properly maintained, as regolith particles that enter the system could potentially reside in the guide rails and slide holds. This issue increased with depth achieved, resulting in the DCMM needing to be cleaned after several uses of the 2.75V motions and after each 4.5V experiment, though the risk of jamming was negligible for the 1V motions. Doing this reduced both the friction force and the risk of the mechanism jamming.

6.8 Complex Motion Experiment Results

The results from this section will focus on the depths achieved by the different motions. Due to factors discussed in Section 6.10, the reciprocation-only experiments were redone. All motions detailed in Section 6.5 were performed, except for the 4.5V4.5H motions. Severe difficulties in maintaining the drill to allow it to run smoothly with the $a_h$ at 4.5mm, and the strain put on
the DCMM when $a_v = 4.5\text{mm}$, created a significant risk that the mechanism could suffer a serious failure. The omission of these motions does not affect the conclusions that can be taken from the results.

### 6.8.1 Final Depths

The simplest results that can be measured are the final depths achieved by each of the drilling motions. This is taken as the depth measured at 100s, minus the starting position of the drill as it is held just above the surface of the regolith. The results of these experiments are given in Figure 6.28. In this graph, the averages of the depths reached for each motion are represented as the bars, while the individual results are given as the scatter points. To provide further detail, Figure 6.29 separates the CB and DB values.

![Graph of average final depths](image)

Figure 6.28: Bar graph of the average final depths reached by each motion, with the scatter points showing the depths reached by each individual run.

The most important conclusion that can be made from Figure 6.28 is that the simple motions have the lowest final depths for all $a_v$ values. Additionally, in all cases except the 1V4.5H, the depth increases as the $a_h$ value increases. If this result is considered to be an anomaly, then there is a clear upwards trend with regards to the depth and the extent of the lateral motions.
From Figure 6.29, it can be seen that the very low 1V4.5H DB values were responsible for the 1V4.5H average final depth being smaller than the 1V2.75H depth in Figure 6.28. If this is ignored, another trend that can be seen is that the DB motions tend to reach slightly greater depths than their equivalent CB motions.

The significance of these trends can be examined by looking at the percentage increase in depth each complex motion produces from the simple motion. From Figure 6.30, it can be seen that the greatest increase occurs for the 1mm $a_v$, ranging from 5 - 25%. The maximum percentage increases for the 2.75mm and 4.5mm $a_v$ motions are more or less equal, suggesting a limit to the total percentage increase that can be achieved. The results for the 4.5V1H CB motion are smaller than the respective simple motion, hence the negative increase, though this can also be considered to be an anomaly.

Alternatively, the actual depth gains each complex motion achieves is presented in Figure 6.31. As opposed to the percentage gains, here it can be seen that, while the values for the DB where $a_h = 2.75$ and 4.5mm vary considerably, the other $a_h$ depths tend to be broadly similar for each $a_v$ value. These results suggest that the gains created by the lateral motion are constant for varying $a_v$ and increase respectively with $a_h$.

### 6.8.2 Drilling Depths

Another measurement that can be made is the actual depth achieved by the drilling motion. By excluding the initial penetration caused by the release of the test rig, the drilling depth can be attained, which gives a truer indication as to the drilling capabilities of the motions. The depth reached by the initial penetration was estimated by dropping the drill into the regolith as normal, though without the motor running, and the depth was recorded. This was performed five times, providing an average depth of 88.9mm. The depths of these tests varied from 84.5 - 98.5mm, giving a standard deviation of 6.514, which suggests that the initial penetration can vary slightly. While this cannot be measured accurately for each individual result, the low variation of the penetration depths should not have any significant effect on the results.

The results in Figure 6.32 further demonstrate the importance of the $a_v$, with the 1mm motions producing a very low drilling depth range of
Figure 6.29: Bar graph showing the average and individual final depths reached by the reciprocation-only, CB and DB motions.

Figure 6.30: Bar graph showing the percentage gains of the CB and DB final depths from the simple motion depths. The legend used in Figure 6.29 is also used here.
Figure 6.31: Bar graph of the actual depth gain of the CB and DB drilling depths from the simple motion depths. The legend used in Figure 6.29 is also used here.

10 - 35mm, while the 4.5mm motions are able to drill to depths of 65 - 95mm. More significant are the results presented in Figure 6.33, in which the percentage increases of the drilling depths for $a_v = 1$mm range from 60 - 270%, while the maximum increases for $a_v = 2.75$ and 4mm are both approximately 50%. Whilst the actual depth gains are broadly similar for each $a_v$, it is clear that the addition of lateral movements creates the greatest benefit for the low $a_v$ motions.

6.8.3 Examination of the Burrowing Mechanics

The depth results found here can be used to examine the burrowing mechanics first discussed in Section 6.1. The addition of sideways movements increases the drilling performance by both improving the gripping of the regolith and reducing the penetration requirement.

However, an observation made during the runs with the larger $a_h$ values was the significant reduction of the lateral movements of the drill heads when the drilling was established. Given that the strength of the surrounding re-
Figure 6.32: Bar graph showing the average and individual drilling depths reached by the reciprocation-only, CB and DB motions.

Figure 6.33: Bar graph showing the percentage gains of the CB and DB drilling depths from the simple motion depths. The legend used in Figure 6.32 is also used here.
golith can be considered to be much larger than the horizontal force provided by the mechanism, the drill is not able to push into the regolith. Instead, the regolith’s reaction force pushes the mechanism back. As such, it is proposed that the ideal drill head movement shown in Figure 6.1 is split in two, with a partial movement of the drill head into the regolith, and a partial reaction which pushes the DCMM back. This split motion is shown in Figure 6.34 (c), and is compared to the simple (a) and ideal complex (b) motions.

Despite this revision of the burrowing mechanics, the principle remains largely the same, though the effect is smaller than would have been experienced in the ideal motion. In this case, the force applied by the mechanism compresses the surrounding regolith which, coupled with the slight movement of the drill heads to further engage more of the regolith, creates a greater traction force, resulting in the increase in penetration. To further improve the performance, by creating a motion closer to the ideal, a stronger internal mechanism is required that is able to resist the regolith reaction force, allowing the drill head to dig further into the surrounding substrate. This will further compress the regolith, creating an even greater traction force that will enable the drill to penetrate further.
6.9 Compressed Regolith

To complement the results obtained from these experiments, two additional series of tests will be performed. The first of these is drilling in compressed regolith. For the experiments performed so far with the DCMM, the poured technique has been used for preparing the regolith. Here, the regolith will be vibrated to a number of specified relative densities, after which experiments will be performed with both the simple and complex motions. The aim of these tests will be to determine how effective the complex motion is in denser regolith.

6.9.1 Relative Densities

Relative density is measured as the percentage between the minimum and maximum possible densities that the regolith state is currently in. SSC-1 has a minimum density, \( \rho_{\text{min}} \), of 1383kgm\(^{-3}\) and a maximum density, \( \rho_{\text{max}} \), of 1794kgm\(^{-3}\) [102]. The relative density of regolith is dependent on the preparation technique. Dedicated experiments using the American Society for Testing and Materials (ASTM) standards have shown the poured and vibrated techniques to produce very distinctive mean relative densities of 15\% and 71\% respectively for SSC-1 [46]. Relative density of regolith also increases with depth [28]. As such, by using regolith compacted to greater densities, experiments can be performed in regolith with simulated properties equal to depths greater than can be reached by the current DCMM.

Experiments were performed in SSC-1 at three relative density levels. SSC-1 was filled to the brim of a bucket of known volume and mass. The total mass was measured, and from this the density, \( \rho \), was calculated. The relative density, \( D_r \), was then found using Equation (6.9).

\[
D_r = \frac{\rho - \rho_{\text{min}}}{\rho_{\text{max}} - \rho_{\text{min}}} \times 100\%
\]  

The bucket and regolith were then vibrated using a Fritsch Analysette 03.502 sieve shaker, shown in Figure 6.35, for approximately one minute. The difference in regolith volume was measured, and from this the new relative density was calculated. The regolith was vibrated again for five minutes, with the volume and density measured once more. This process was repeated, with the values found given in Table 6.3.
6. Integrated Complex Motion Mechanism

Figure 6.35: Picture of the sieve shaker and SSC-1 to be compressed.

<table>
<thead>
<tr>
<th></th>
<th>Poured</th>
<th></th>
<th>Vibrated 1</th>
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<th>Vibrated 2</th>
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<td>2</td>
</tr>
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<td>20.00</td>
<td>19.52</td>
<td>20.00</td>
<td>19.52</td>
<td>20.00</td>
</tr>
<tr>
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<td>0.0131</td>
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<td>0.0121</td>
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<td>28.57</td>
<td>58.29</td>
<td>59.21</td>
<td>70.61</td>
<td>70.00</td>
</tr>
</tbody>
</table>

Table 6.3: Volume and density measurements of the SSC-1 when compressed with a sieve shaker.

Given the approximate nature of this preparation method, the densities achieved by using the ASTM standards could not be recreated. However, this method allowed the creation of three distinct densities: the poured density of ~30%, and the vibrated densities of 60% and 70%. Trial and error was used to determine the approximate volumes and shaking times required to create these densities. A brief series of experiments will be performed, in which the 2.75V0H and 2.75V2.75H CB motions will be tested twice in each density.

6.9.2 Results

The results of these tests are presented in Figure 6.36. As is to be expected, the denser regolith results in lower depths achieved. However, while the complex motion is once again shown to drill deeper than the simple motion in the poured density of 30%, this gain is negated in the larger densities.
These observations provide evidence to back up the mechanics proposed in Section 6.8.3, with the denser regolith producing a greater reaction force, further reducing the lateral movements achievable by the DCMM. As a result, the teeth cannot engage further into the regolith, and do not provide any additional tensile forces. This is likely exacerbated by the very shallow depths achieved by the drill. The horizontal drive rail connections to the outer shell lie \( \sim 115 \text{mm} \) above the cone tip, and as such are still above the regolith surface at the final depths achieved in the 60% and 70% SSC-1. As such, the horizontal forces applied by the mechanism never act within the regolith. The combination of these two factors may explain why the complex motions do not provide any benefit here. This again highlights the importance of the strength of the internal mechanism, as its ability to produce complex motions that are able to both act against and push into the surrounding regolith is key to its performance.

![Graph of the depths achieved by a reciprocation-only and CB set-up in different relative densities of the SSC-1.](image)

Figure 6.36: Graph of the depths achieved by a reciprocation-only and CB set-up in different relative densities of the SSC-1.

### 6.10 Drilling at an Angle

One of the key observations made in Section 4.6 was that the final depth achieved increased when the drill stem bent significantly, causing the drill head to travel in a diagonal direction. This phenomenon was also seen in the main experiments with the DCMM. In the first simple motion runs, and in
the CB runs with $a_h$ set at 1mm, the DCMM would drill at a slight angle. This was due to a poor connection between the plate and the DCMM holding part, allowing the drill to bend slightly. After the original hold broke, a new part was made that allowed for a much stronger connection and prevented any bending. These tests were redone, and once more it was seen that the DCMM, when drilling at an angle, reached a greater depth than the repeated tests when it drilled vertically. This is shown in Figure 6.37.

![Graphs of the force-depth profiles for the 2.75V1H CB set-up when drilling at a slight angle (a) and vertically (b).](a)

Figure 6.37: Graphs of the force-depth profiles for the 2.75V1H CB set-up when drilling at a slight angle (a) and vertically (b).

To examine this in controlled conditions, the test rig was tilted at a 15° angle, as shown in Figure 6.38. For these experiments, all $a_v$ values for the simple motion and 2.75mm $a_h$ CB were used. Due to the additional friction in the rails caused by the angle reducing the vertical overhead force, a 1kg mass was added, making the OHF approximately equal to the previous experiments.

### 6.10.1 Results

It should be noted that, at this stage in the experiments, the DCMM was very worn at the rod hold connection points, resulting in a small amount of room for the screws to move about in. This creates lower amplitudes, and is particularly noticeable when $a_h$ and $a_v$ are set at 1mm, as the amplitudes are effectively reduced to zero. Tape used to wrap around the rod screws and reduce the gaps would tend to work for a very limited time, often becoming ineffective during the second run. The reduced amplitudes from this general...
wear may have reduced the depths seen during these experiments. Also, due to the high level of maintenance and the increasing number of failures and unsuccessful runs, the second 4.5V2.75H run was not performed. The first run failed after 50s, with the final depth estimated from the profiles of the runs using this set-up. Despite these problems, enough data has been gathered to make a number of observations.

Given that the ThinPot used to measure the distances is also tilted along with the test rig, the depth values recorded are converted to vertical depths. These, along with the corresponding depths found in the original experiments in Section 6.8, are given in Figure 6.39. From this, it can be clearly seen that, in all cases, drilling at an angle results in a greater final depth. This confirms the observations made in Section 4.6 and those in the initial DCMM experiments, which is that drilling at an angle increases the performance of the DRD and DCMM.

6.10.2 Proposed Mechanics of Diagonal Drilling

Information regarding non-vertical drilling, or directional drilling, of regolith is scarce. Directional drilling of rocks is often used for the purpose of reaching targets otherwise inaccessible by conventional vertical drilling, while hor-
Figure 6.39: Graph comparing the depths achieved with the 2.75V0H and 2.75V2.75H CB motions when drilling vertically and at an angle of 15°.

Horizontal drilling is often used for laying piping and cables [92]. Studies into directional drilling have generally focused on the deviation of vertical penetration caused by the geology and properties of the rocks being drilled into, and how such deviations can be accounted for and controlled [10]. Studies of drilling diagonally into regolith have so far been limited to inclined cone penetration tests, which largely examined the effects of inclination on tip resistance [63].

The elastic behaviour of soils can be determined by the relationship between the effective horizontal and vertical stresses, $\sigma'_h$ and $\sigma'_v$. Changes in the soil properties, such as volume and shear strength, are governed by the effective stresses. The vertical stress of a soil element is determined by the weight of the soil above it. This compresses the element vertically, but is prevented from expanding outwards by the horizontal stress [115]. The ratio of these stresses, known as the coefficient of Earth pressure at rest, $K_0$, is defined by the soil’s internal angle of friction, $\phi'$, given in Equation (6.10).

$$K_0 = \frac{\sigma'_h}{\sigma'_v} \quad \text{where} \quad K_0 = 1 - \sin(\phi') \quad (6.10)$$
This equation is a suitable approximation for normally consolidated materials allowed to settle naturally under gravity, and gives a range of 0.31 - 0.67 for clays and soils [115]. Materials that have undergone some compression, through ageing or preshearing, will likely have an in-situ $K_0$ greater than that given in Equation (6.10), though this value will still be lower than 1. Whilst $K_0$ can be higher than 1, this is only achieved with significant compression of the soil from vibration and compaction methods, and as such the equations governing these conditions are not applicable for the diagonal drilling experiments performed here.

A potential explanation for the increased depth experienced by diagonal drilling is that, given the typical range of values of $K_0$, $\sigma'_h$ is smaller than $\sigma'_v$, and as such, compressing the regolith in a horizontal direction is easier than doing so in a vertical direction. Diagonal drilling involves penetration in both directions, and by taking both into account, the net effective stress will be lower than for purely vertical drilling at the same depth, as demonstrated in Figure 6.40.

![Figure 6.40: Diagram of the proposed effective stresses acting upon the vertical and diagonal drill.](image)

Given that effective stress is not the only factor in determining penetration performance, with variables such as deformation patterns not being considered here, this does not present the entire reasoning for the increased depth achieved when drilling at an angle. However, this can be seen as a simplified first explanation of the benefits of drilling at an angle. It is also possible that separate factors caused by the set-up have contributed to this increased depth. However, as increased depths have now been observed both
here and in the bent drill stem of the previous test rig, this lends more credence to the benefits of diagonal drilling. As these tests have been brief, further testing would provide an opportunity for the mechanics and benefits of this technique to be confirmed and studied in greater detail.

6.11 Summary

This chapter has investigated the effects of new drilling techniques, by implementing controlled sideways movements of the drill heads into the traditional reciprocation motion. This has been achieved by designing an actuation mechanism that is able to actively control the sideways and vertical reciprocation movements, and which can be fitted within the drill heads. This has allowed the first testing of an internally integrated actuation mechanism, as well as the creation and testing of two new burrowing motions never before used in a drill. These tests allowed an analysis of the forces acting within the mechanism during drilling, and a comparison of the depths achieved with a range of drilling motions. Additional experiments also examined the effects of drilling in compacted regolith and at an angle.

Five concept designs able to create the required simple and complex motions were subjected to a trade-off study. The Quadruple Cam design, based upon the original reciprocation actuation mechanism, was chosen. The different motions that could be created, made possible due to the independent vertical and horizontal reciprocation of its drive rails, and the wide distribution of force, outweighed its complexity and large size. With three amplitudes available for each drive rail, the completed DCMM was able to produce three reciprocation drilling, nine circular burrowing and nine diagonal burrowing motions. The completed mechanism included the fitting of a force sensor able to measure the penetration and traction forces experienced during drilling. The completed mechanism was fitted within two drill heads, with an $R_{tot}$ of 27mm and length of 230mm. The mechanism and motor were attached to a test rig, from which the depths achieved were recorded.

The profiles of the penetration and traction forces were measured during free-running and drilling operations. Tests with the simple motion showed that the profile shape was consistent regardless of starting position, weight of the mechanism and reciprocation amplitude. An analytical analysis of the
forces acting on the mechanism determined that the majority of the free-run forces were created by the internal friction, which was found to be largely created by the addition of the drill heads. It could be seen that both forces increased with depth reached, however the imprecise nature of the system, and the likely changes in friction during drilling that cannot be measured, prevented any further detailed analysis.

The depths achieved by each motion were examined in terms of final depth, actual drilling depth and percentage gain from the simple motion. From these it could be seen that, for virtually all cases, the complex motions were able to achieve greater depths than their corresponding simple motions with the same $a_v$. For each $a_v$, the depth increases with larger $a_h$ values for all but one cases, and as such the depth gain from the simple motion also increases with the $a_h$. Interestingly, the values seen for the different $a_h$ amplitudes tend to remain fairly constant for each $a_v$, suggesting that the actual depth gains of the complex motions are only affected by the size of the horizontal amplitudes.

The mechanics of these burrowing motions were then proposed. The addition of sideways movements allows the drill heads to dig further into the regolith, improving the gripping capabilities of the teeth. While observing the experiments, it could be seen that the drill heads were not achieving the larger lateral amplitudes. This was proposed to be due to the reaction force of the regolith to this motion partially pushing back the DCMM within the drill. Despite this, the lateral movements achieved were enough to compress and engage the regolith, increasing the traction force and allowing greater penetration. This was backed up by the depths obtained in additional experiments performed in SSC-1 with different relative densities, where the gain of the lateral motions decreased with increasing relative density.

Additional tests were performed with the test rig tilted at an angle, designed to provide a controlled confirmation of the observations seen with the bending drill stem. These experiments, performed at a 15° angle, achieved greater depths than those performed vertically, confirming that drilling at an angle allows the DRD to penetrate further. This led to an additional investigation into the mechanics of diagonal drilling, in which it was theorised that the smaller horizontal effective stress of the regolith results in a lower net effective stress, making penetration easier.
Chapter 7

Recommendations for Future Work

The research performed in this thesis has advanced the understanding of the DRD, and has provided a number of new avenues for further research or system development, which are presented in this chapter. In terms of research, the benefits of lateral motions and diagonal drilling has opened up a new area of unexplored drilling motions, and the data obtained from the previous experiments can be used for the creation of numerical models. The evolution of the DCMM has also opened up the possibility of the creation of a true system prototype, while sampling mechanisms can also be considered. The effects of ice in regolith can be investigated in both ways, whether it be in the further characterisation of NU-LHT-2M or the testing of instrumentation.

7.1 Understanding the Lateral Motion

The benefits of lateral motion have been confirmed in Chapter 6, with both the controlled sideways movements added to the traditional reciprocating motion and the diagonal drilling increasing the drilling depth. Explanations for these improvements have been offered in Sections 6.8.3 and 6.10.2 respectively. The burrowing and diagonal drilling designs have a lot of potential for improving the performance of both DRD and other traditional drilling techniques, therefore fully understanding the mechanics that resulted in these greater depths should be a priority for future research. Ideas are presented here for experimental set-ups that may be able to achieve these goals.
Given the complexity of the DCMM, a true investigation of lateral motions and the forces experienced in regolith would likely not be possible. The reduced lateral motion of the drill heads caused by the reaction of the regolith against the sideways movements, for example, would have to be accounted for and overcome. As such, a new system that is able to produce these movements correctly, whilst also providing accurate measurements of the forces experienced, would be required.

Such a system could involve the use of a specialised half-cylinder, onto which a cone is attached to the base, to create a DRD drill head half. The cone protrudes out from the base of the cylinder by a defined distance, $R_p$, representing the radius of a single tooth. Throughout the length of the cylinder, blades can be attached to simulate teeth. With this, a different number of ‘teeth’ of different radii can be used, as shown in Figure 7.1.

Figure 7.1: Concept design of the half cylinder, with the cone and blades attached, and various numbers and sizes of teeth used.

From this, the cylinder can be modified to create a wide range of parameters, paralleling the drill heads designed in Chapter 4. The bladed cylinder is attached to a rig that is able to produce separate, controllable lateral and vertical reciprocations via two hydraulic rams. A rough schematic of this design is shown in Figure 7.2. The rig connects to the bladed cylinder via two poles, and is slotted via a plate into an opening in a regolith container. Strategically-placed load cells would allow the forces to be measured. As an example, the cylinder can be pushed into the regolith horizontally, before
being lifted up, each at a predetermined amplitude. The penetration, lateral and traction forces can be measured separately, and any patterns that emerge for different amplitudes, blade size or number, etc. can be established.

Figure 7.2: Schematic and CAD model of the proposed test rig set-up using the bladed half-cylinder.

The benefits of diagonal drilling can be examined by using cone penetration tests to determine the penetration forces experienced at different angles and depths. A study of the regoliths’ properties, such as the internal angle of friction, cohesion, density and particle size, may be able to determine the factors that favour diagonal drilling, and to what extent. Additionally, tests performed with a protruding cone, as shown in Figure 7.3, can be used in a similar set-up to the MDH experiments. The traction and penetration forces can be measured, again with varying levels of slippage, amplitude and velocity, but also with different angles. The cone shape can also be changed to increase the forces seen, which may also reveal interesting patterns.

7.2 Numerical Modelling

As discussed in Section 2.4.4, the interaction of the drill and regolith has been briefly examined using DEM simulations with large particles numbers. While it was possible to use million-plus particle simulations, the MDH penetration simulations were not able to produce forces similar to those found experimentally [50]. Initially, continuing this aspect of the research into the
Figure 7.3: Diagram of a force sensor test rig with a protruding cone MDH, which can be set at different angles.

DRD performance was considered, with the aim of creating a model that accurately simulates the drilling under set operational conditions. From this, the DRD could be modified, and it would be possible to make analyses of factors such as drill head design.

This approach was ultimately rejected for several reasons. As the thesis aimed to focus on improving the efficiency of the DRD, much of the emphasis was placed on creating as many new designs and motions as possible, to provide a broad investigation into the factors affecting DRD performance. An experimental approach allowed the immediate creation and testing of these parameters, as well as evolving the DRD with the creation of a first integrated research prototype. On the other hand, modelling simple DRD penetration would require significant work in creating an accurate model, which would then have to be verified with experimental data. This would greatly limit the work performed on testing new designs of the DRD. It was concluded that the right direction would be to continue the experimental evaluation of the DRD by mechanically testing new designs.

As further experimental data has been obtained, it would now be an opportune time for a focused study on DRD performance using numerical modelling and simulations. DEM simulations using GPUs, in particular the CUDA architecture developed by NVIDIA, have been used for a number
of large-particle problems, such as multi-body collision analysis [64], charge
distribution in mills [53] and particulate systems [37]. By using this hardware
to build upon the previous simulations performed with the MDH [45], and
using the data provided by the experiments performed up to this point, it
will be possible to create a model that is able to accurately simulate the
motions and forces of the DRD. Modifications to the operational, substrate
and geometrical parameters, as well as the drilling motions, can thus be
accurately represented. This can then lead to the investigation of new designs
that are either too expensive or too numerous to test experimentally.

7.3 System Prototypes

One of the major achievements of this work has been the creation of a func-
tioning actuation mechanism, that produces the motions achieved by the
original test benches and has been internally integrated within the drill heads.
For the purposes of the experiments performed in Chapter 6, the mechanism
and motor were attached to the sliding plate, with a holding part required to
stop the mechanism rotating around the motor shaft. In a non-experimental
demonstration of the drill, changes were made to the original design. Here,
the holding part was modified, with two ABS parts attached to the top of
the central structure and the motor respectively, connected together by steel
rods. This results in the motor itself holding the mechanism in place. The
force sensor was also removed, allowing the two drill halves to be more or
less identical. This modified design is shown in Figure 7.4.

The DCMM cannot be labelled as a true system prototype, as the motor,
while positioned above the mechanism, has yet to also be integrated within
the drill heads. More crucially, the aims of the experiments required the
testing of as many motions as possible. As a result, the concept trade-off
study described in Section 6.2, which resulted in the Quadruple Cam design
being chosen, placed much more emphasis on this, with less importance given
to traditional system prototype trade-off criteria, such as size and complexity.
As such, the DCMM can be more accurately labelled as an integrated research
prototype. The next stage of DRD development should involve the creation of
a true system prototype. While a prototype for the reciprocation-only motion
has already been discussed and designed to an extent [33], new designs should
consider including lateral motions.
Figure 7.4: Picture showing the evolution of the DRD, with the wood wasp ovipositor mechanism, the original drill head designs, the initial reciprocating mechanism and the integrated research prototype.

The overall drilling system, shown in Figure 3.3 (b), in which the motor and payload bays are contained within separate closed modules above the actuation mechanism, can remain the same. The deployment mechanism chosen for this system was a bistable composite made by Rolatube, shown in Figure 7.5. The building of this, with the design not needing any changes from the original concept, would allow tests and demonstrations of the entire system.

7.3.1 Alternative Designs

As discussed previously, a true system prototype of the actuation mechanism would likely be significantly different to that used in this research. Likely to be the most critical design factor is the overall diameter. As found in Chapter 4, the diameter of the drill is by far the most significant geometrical
7. Recommendations for Future Work

Figure 7.5: Model of the overhead force and deployment mechanism for the DRD system, and a picture of the Rolatube bistable composite [42, 33].

parameter for increasing drilling depth. The complexity of the Quadruple Cam inevitably led to a very large drill head, resulting in depths no greater than 20cm being reached. The chosen mechanism would also need to be much simpler to reduce the risk of jamming or failures and allow easy operation in an extraterrestrial environment.

Some alternative concept designs for a system prototype are presented here. For these, it is assumed that the desired amplitudes for both the vertical and lateral motions have been predetermined. The first uses a modified version of the 90° Cam and Gearing concept detailed in Section 6.1.1, in which the original reciprocating cam-drive system described in [42] is rotated 90° around the motor shaft. Whereas just one pair of cam wheels was shown in the trade-off study, an additional pair, attached via bevel gears affixed to a separate shaft, allows for two connection points to the drive rails, as shown in Figure 7.6. This concept was noted for its relative simplicity, creating circular burrowing with very little modification beyond the original design required.

The use of complex motions such as circular or diagonal burrowing may lead to difficulties in the full system design. For example, gaps in the drill head caused by the lateral motion will need special sealing. Another avenue of design may be to increase the volume of engaged regolith without the
need for lateral motions. An example of how this may be achieved is with a series of blades that are able to slide out of slots in the drill head as it moves upwards, and retract inwards as it descends. Pushing blades into the regolith would require much less force than the entire drill head, and would result in a large gripping surface with little reaction resistance, while also creating a smooth cone and cylinder surface to allow for easier penetration. The blade, shown in Figure 7.7, can be reciprocated using a gear that can be attached to the motor shaft. Difficulties would naturally occur as more blades are added, with care needed to avoid collisions with the normal reciprocation drive rails.
Another concept uses four drill heads as opposed to two, with each powered by the $90^\circ$ Cam and Gearing mechanism, as shown in Figure 7.8. Here, each pair of drill heads follows the same identical motion, with pair 1 moving upwards and in, while pair 2 moves downwards and out. By ensuring the hollow quarters have a sufficient outer thickness, no gaps are caused by this motion. This concept is designed to negate the reaction force of the regolith that pushes back against the drill heads. With two quarters pushing outwards in opposing directions, the reaction forces are cancelled out, and as a result the drill heads can only be pushed further into the regolith, while the internal mechanism remains in place. This would create significantly greater traction that can then be used to assist the two penetrating quarters. Although this technique could theoretically be extremely effective, construction would be very difficult, with the need for four drive rails contained within a very restricted space, as well as an actuation mechanism that is strong enough to overcome the regolith reaction forces.

![Figure 7.8: Diagram of the quarter drill adaptation of the 90° Cam and Gearing mechanism, showing the movement of each quarter.](image)

7.4 Sampling Subsystems

The ability of a drill to acquire and deliver samples significantly adds to its value as a subsurface drilling method. The majority of proposed subsurface exploration missions both past and present have included the use of a sam-
pluing subsystem within the drill. Incorporating a sampling mechanism into the DRD design was an initial goal of this thesis. However, it was felt that such a study, though beneficial for the DRD evolution, would not provide a significant research contribution. The focus was consequently shifted to examining the properties of the regolith materials, in particular those at the lunar poles and the cemented Martian soils, that the DRD may encounter.

The next stage of DRD development should involve the design of a sampling subsystem. A brief review of the samples that can be collected, and the mechanisms used to do so, is given in Appendix J. Whilst the mechanisms used in drilling systems such as ExoMars and the Beagle 2 mole can be used for inspiration, the unique motion of the DRD will likely require new solutions. The sampler would also have to take into consideration the other mechanisms held within the drill head that are producing the drilling motion, especially if a complex motion is being used.

7.4.1 Sampling Concept Mechanisms

So far, the only sampling mechanism that has been proposed for the DRD is the angled bristles method discussed in Section 2.4.3. Though this method has not been taken beyond an initial concept design, with factors such as sample storage, delivery and shutters for the cavity not taken into consideration, this presents a very passive method that can be used during normal drilling operation.

The simplest method used for taking powdered cuttings, in which a hollow segment is opened to allow cuttings to be obtained during drilling [123], can be modified for use in the drill heads. The teeth themselves can be used as cavity entrances, as shown in Figure 7.9. Here, the upper side of the tooth consists of a separate layer wrapped within the drill head. This can then be retracted upwards by a separate mechanism, opening up the entrance to a cavity into which the sample can fall. Multiple cavities per drill head can be used, and it may also be possible for the cavities to be opened at different times, allowing samples to be collected at different depths, after which the cavity can be closed. Once the drilling is completed, the samples can be removed by tilting the drill upside down and reopening the teeth.
Taking cored samples may also be possible, by taking inspiration from the sampling devices used for ExoMars and Rosetta. The shutter and cavity system used for ExoMars [120] could be modified for the DRD, as shown in Figure 7.10. In this set-up, the tip of the cone is separated from the rest of the cone, and does not have any teeth. As with the teeth cavity, this is attached to a retractable layer, which pulls the tip upwards along the inside of the upper cone surface, seen in Figure 7.10 (b). After this, the coring chamber can be pushed down by another separate mechanism, putting it level with the opening (c). The drilling can continue as normal, and the sample will be collected in the chamber. The process can then be reversed to break off and contain the sample. An additional mechanism would then be required to push out the sample.

Figure 7.9: Sampling mechanism using hollow teeth cavities.

Figure 7.10: Coring mechanism using a removable cone tip.
Alternatively, the coring cavity can be pushed through a slot in the cone, allowing the sampling tube to extend out, similar to the operation and design used for the Rosetta SD2 drill [31]. After the tube is dropped, a coring action is created by a separate hammering system, held under the DRD mechanism. The SD2 sample discharge procedure can also be modified for use in the DRD.

7.5 Properties of Icy Regoliths

The work in this thesis has demonstrated the effects of ice and water content on drilling performance and has examined the phenomenon of cementation of Martian regolith on sampling instruments. The tests with the DRD in icy regolith have been brief, given the limited volume of lunar regolith available. As such, it was not possible to make a comparison between its performance in NU-LHT-2M and other regoliths. Future work could involve a full testing campaign of the DRD in numerous substrates. For those mimicking regions where water may be present, this should also include testing with varying icy contents. The effects of the presence of ice, such as cementation, may result in mechanisms being tested experiencing unanticipated behaviours.

The work performed with the icy NU-LHT-2M has provided a first characterisation of its properties with varying water contents. A more detailed examination of its properties, and in particular a comparison of the effects of ice on it and other lunar simulants, such as JSC-1A, is required. This will then enable instruments designed to work in these regions, such as L-GRASP, to be tested in conditions that accurately simulate the environment they will encounter. Similarly, the effects of the physical properties of duricrusts and cemented Martian regolith have demonstrated the need for instruments designed to handle the soil to be tested in the expected conditions.

7.6 Summary

This aim of this chapter was to identify the areas in which the work performed on the DRD can be continued beyond the research detailed in this thesis. A number of potential areas were identified, including continuing the research into the DRD performance, furthering the progress of the DRD towards a system prototype and extending the study of icy regoliths.
The first research area is a response to the benefits of lateral motion experimentally confirmed in Chapter 6. A bladed cylinder and specialised test rig design was proposed, in which the forces experienced with various motions and teeth options could be accurately measured. The second proposal suggested that numerical modelling could now be used with the obtained experimental data to create an accurate model of the DRD motion, enabling accurate simulations of drilling with various parameters and motions.

The design of the DCMM was modified to allow it to be operated in a closed system without the need for a plate. It was concluded that the DCMM should be referred to as a research prototype, as a true system prototype would be designed with factors such as size and complexity taking priority. As such, the design of the DRD can be furthered by considering system prototypes that also incorporate lateral motion mechanisms. Proposed designs include using the 90° Cam and Gearing concept to produce circular motions, an alternative concept using a rotating blade system, designed to increase the volume of engaged regolith without the need for lateral movements, and a quarter drill design for countering the regolith reaction forces. Finally, the importance of including a sampling subsystem for the value of a drilling mechanism was highlighted. Two concepts able to retrieve samples with the DRD were proposed. These were a simple sample cavity within hollow teeth that is able to collect regolith cuttings, and a coring mechanism that can be deployed once the tip of the cone is retracted. The testing of icy regoliths can also be furthered in a number of directions, including further testing of the DRD and continued characterisation of icy regolith properties for use in future instrumentation testing.
Chapter 8

Conclusions

This chapter summarises the work performed in this thesis and presents the final conclusions. The major novelties and contributions achieved are highlighted, and the publications presenting this work are listed.

8.1 Chapter Summaries

The Literature Review highlighted the value of drilling systems as part of planetary exploration missions, and provided a summary of the missions past and present that have penetrated extraterrestrial surfaces. The challenges associated with planetary drilling were presented, with the difficulties resulting from the different media that can be drilled into and environmental factors, such as the temperature and low pressure/vacuum, explained. The conventional drilling techniques available and used in planetary missions were analysed, and their respective benefits and drawbacks were detailed. Non-conventional techniques able to produce a lightweight, low power drilling system were examined, with an emphasis on biologically-inspired solutions. The Dual-Reciprocating Drill (DRD), inspired by the ovipositor of the wood wasp, was introduced, and its evolution from the initial concept and the experiments performed with the different designs were detailed. Finally, the lunar and Martian regolith simulants used in the testing of instruments was reviewed. This highlighted the effects of location, density and water content on the regoliths’ properties, placing emphasis on the current state of the characterisation of regoliths designed for areas where water is believed to be present.
The Research Rationale and Philosophy identified the three gaps in the knowledge of the DRD that would be explored in this thesis. The first was presented as a continuation of the investigation of the parameters defining the DRD operation, by focusing on the geometrical parameters that shape the drill head design. Secondly, the effects of the water ice content of a lunar highland simulant on drilling performance would be examined. This would be coupled with a study into how the degree of ice content would affect the regolith’s properties. The final area would attempt to experimentally confirm the observations made previously, which showed the importance of lateral forces created by sideways movements. This would also be used to further the design of the DRD from a test rig to an internally actuated system.

The Drill Head Design defined five independent geometrical parameters, each of which were assigned two levels, from which sixteen drill heads were created. The original test rig was modified to allow experiments up to depths of 760mm with constant operational parameters in SSC-1 and SSC-2. The motor current and drilling depth were measured for each experiment. Analysis of the depth profiles showed that the total radius of the drill head had by far the most influence on drilling depth, with the cone half-apex angle providing a lesser effect. Such was the radii’s significance, the thinnest drills experienced negative slippage, and were estimated to be able to reach depths of up to 2m in SSC-1. The length and rake angle of the teeth were found to have a negligible bearing on performance. The tests also demonstrated relationships between depth and current, power and specific energy. The long, flexible drill stem was seen to experience bending in a large number of experiments. Significant bending, causing a diagonal drilling path, resulted in depth profiles notably different from those that drilled vertically. A large horizontal resistive force of the surrounding regolith was proposed to create a greater tensile force, thus allowing the drill to progress further, providing more evidence as to the importance of lateral movements of the drill heads.

The Characterisation of Icy Regolith Simulants investigated the effects of water and ice content on both the DRD performance and the properties of regoliths. This continues the exploration of the parameters affecting DRD performance, with the first experimentation of DRD in icy and lunar regolith. Using the NU-LHT-2M lunar highland simulant with water and ice contents ranging from dry to fully saturated, the time taken to drill the icy compared to the wet sample slowly increased as water content increased be-
yond 5%, before hugely increasing between 10 - 12.5%. The cause of this was further investigated in the first characterisation of the icy NU-LHT-2M. To do so, a preparation procedure able to add repeatable and controllable water contents from dry to fully saturated was required, with the open water disperser technique selected, and has the potential to be used as a standardised procedure for future icy regolith preparation. Cone penetration experiments revealed that a sharp increase in penetration resistance occurs at $5 \pm 1\%$, explaining the increase in the time taken to drill in icy regolith, while uniaxial compression and shear strength tests examined the relationships between compression strength, deformation and water content.

The Integrated Complex Motion Mechanism examined the effects of actively controlled lateral motions implemented into the typical reciprocation. To achieve this, the motion of the DRD was transferred from the test rig to an actuation mechanism designed to fit within the drill heads. Five concepts able to achieve the desired motions were considered, with a trade-off study resulting in the selection of the Quadruple Cam mechanism. Two new complex drilling motions, named circular and diagonal burrowing, could be produced along with the simple reciprocation, with a total of 21 amplitude combinations possible. The completed mechanism was connected to a motor, and both were attached to a new test rig. The forces experienced were recorded by a sensor integrated into the mechanism, and an analysis of these measurements revealed the significance of the internal friction. The depths of each motion were recorded, from which it was found that the complex motions were able to achieve greater depths than the simple motions, with the depth gain increasing with the horizontal amplitude used. It was proposed that the sideways movements of the drill heads, despite being reduced by the reaction force of the surrounding regolith, allowed the teeth to dig into, compress and further engage the regolith, creating the greater traction that resulted in the increased penetration. Experiments performed in regolith with varying relative densities backed up the suggestion that the increased depth was related to the amount of lateral motion achievable. Finally, experiments performed with the test rig tilted at an angle confirmed the observations made with the bent drill stem, with the diagonal drilling resulting in greater depths, leading to an examination of the effective stresses in the soil.

The Recommendations for Future Work explored various ways in which the work performed on the DRD can be continued, and split this into re-
search and system development. The research areas include a continuation of the examination of the lateral movements, with a focus on the forces created by different motions and drill designs, and the building of a numerical model able to accurately simulate the drilling motion of the DRD based on the experimental results obtained thus far. The system development areas include the creation of a true system prototype able to produce the complex motions and the implementation of a sampling system, with two potential design concepts given for both.

8.2 Final Conclusions

There are numerous conclusions that have been made from this work, with those that are considered the most important listed here.

- The DRD is a biologically-inspired drilling technique, which aims to become a viable alternative method for drilling in planetary bodies, with a lower mass than the traditional rotary and rotary-percussive drills, and with greater overall penetration abilities than the percussive techniques. The DRD has been shown to be able to penetrate further than static penetration, but experiences high levels of slippage. Lateral movements were also estimated to produce forces ten times greater than the traction generated by the backwards-facing teeth.

- The drill cylinder and teeth radii are by far the most important geometrical parameters that affect achievable drilling depth. As their estimated effects were similar, the total radius was considered, which was found to have an inverse power relationship with depth.

- The cone half-apex angle also has a small negative linear relationship with depth. However, the tooth rake angle and length had no noticeable effect.

- The NU-LHT-2M lunar highland simulant undergoes a rapid increase in penetration resistance when its icy water content passes 5 ± 1%. The time required for the DRD to penetrate the same icy simulant begins to increase slightly beyond this point, and greatly increases when the water content is between 10 - 12.5%.
• By having independent horizontal and vertical reciprocations of the drive rails in the Quadruple Cam design, it was possible to create both circular and diagonal burrowing motions, as well as the traditional reciprocation drilling.

• Experiments with the internal actuation mechanism showed that the complex motions reached greater depths than the corresponding simple motions. The depth gain increases as the horizontal amplitude increases, and remains fairly constant for different vertical amplitudes. Diagonal burrowing also tended to achieve greater depths than the circular burrowing. This confirms the observations made in previous experiments that identified the importance of lateral movements.

• Drilling at an angle also resulted in depths greater than those when drilling vertically for both the simple and complex motions, confirming the observations seen when the drill stem of the original test rig bent significantly.

• Cementation of Mars regolith simulants with water contents as low as 5% under simulated Martian conditions can create clumps with enough internal cohesion to cause failure of sampling mechanisms, as demonstrated with the PSDDS.

8.3 Research Novelty and Contributions

The major contributions to the state-of-the-art as a result of the work performed in this thesis are:

• There has been a full investigation into the effects of the geometrical parameters that define the shape of the drill head on the depths achieved by the DRD. This complements the previous experiments, which considered the operational and substrate parameters, furthering the study of the influence of the parameters that define the DRD design and operation.

• The DRD has been able to drill to depths of 760mm in both SSC-1 and SSC-2, limited only by the maximum allowable depth of the test rig and regolith container. Approximate estimates suggest that the DRD may be able to reach depths of over 1m in SSC-2 and 2m in SSC-1.
8. Conclusions

- The DRD has been tested for the first time in lunar regolith simulants, and the first examination of its performance with varying water and ice contents has been performed.

- The first characterisation of the properties of the icy lunar highland simulant NU-LHT-2M, which mimics the regolith found at the lunar south pole, has been performed. This also included the proposal for a standardised preparation procedure for creating icy simulants with controllable water contents.

- The design of a mechanism able to implement lateral motions into the traditional reciprocation motion. This resulted in the creation of two new drilling motions: the circular and diagonal burrowing complex motions.

- The reciprocating motion created by the test rig has been converted into an actuation mechanism, which has been integrated within the drill heads of the DRD and is able to produce the reciprocating drilling and burrowing motions. This has resulted in the first, and successful, operation and testing of an integrated internal actuation mechanism. The design was later modified to allow operation without the need for any external attachments, with the drill connected to the motor only.

- This mechanism has been used to perform the first testing of actively controlled lateral motions, as well as the first drilling experiments performed at a fixed diagonal angle. This has provided the first conclusive experimental evidence of the benefits of lateral movements and non-vertical drilling.

- The first formation of a duricrust in simulated Martian conditions, and an analysis of its component materials, has been performed, and a demonstration of the effects of cementation on the performance of sampling instruments has been given.

8.4 Publications

The work described in this thesis was published and presented in a number of journals and conferences, and has contributed to a book chapter, the details of which are summarised here.
8.4.1 Journals

- Craig Pitcher and Yang Gao. Analysis of drill head designs for dual-reciprocating drilling technique in planetary regoliths. *Advances in Space Research* Volume 56, Issue 8. Pages 1765 - 1776, October 2015. **Outstanding Paper Award for Young Scientists.** Awarded by the Committee on Space Research (COSPAR), Istanbul, Turkey, August 2016


8.4.2 Book Chapter


8.4.3 Conference Proceedings

Appendix A

Motor Gearbox Data Sheets

**Planetary Gearhead GP 42 C** Ø42 mm, 3–15 Nm

**Ceramic Version**

### Technical Data
- **Planetary Gearhead**
  - Straight bevel, stainless steel
  - Bearing at output
    - Preloaded ball bearings
- **Output Shaft**
  - Radial play, 0.2 mm from flange max. 0.2 mm
  - Axial play at small end + 0.5 mm / 0 mm
  - Axial play at small end + 0.5 mm
  - Max. axial load (dynamically) 150 N
  - Max. force on the outer flange 300 N
  - Convergence of rotation, difference to output max. 3000 rpm
  - Max. continuous input speed
  - Recommended temperature range -40°C to 100°C

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### Gearhead Data

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### Notes
- All values are in Newton meters (Nm).
- The values are approximate and may vary depending on the specific model and application.
- Always consult the manufacturer's specifications for the most accurate and up-to-date information.

---

*Image of the planetary gearhead with dimensions and technical specifications.*

---

*Image of the gearhead assembly with part numbers and dimensions.*

---

*Image of the gearhead assembly with technical specifications and part numbers.*
Appendix B

Test Bench Data Acquisition
Circuit Diagram

![Circuit Diagram](image)

Figure B.1: Circuit diagram of the test bench data acquisition system.
Appendix C

Experiment Procedure

Test Rig Set-Up

1. Choose drill heads and insert into drill stem
2. Insert drill stem into test rig and start motor. Check that the average current as shown by the PSU is lower than 0.8A
3. Remove drill stem and attach Arduinos to computers
4. Start SoftPot Arduino unit and check that readings are obtained for all distances from the SoftPot membrane potentiometers
5. Start motor Arduino and confirm that current measurements are being recorded
6. Check that the OHF is consistently 30 ± 2N by using a Newton meter at intermittent distances
7. Move test rig to starting position and attach weights to keep it held in position

Preparation

1. Attach dust protection sheets to test rig
2. Prepare sample by pouring buckets of regolith at a height of 40cm
3. Once barrel is filled, remove dust sheets and insert drill stem
4. Recheck the motor and Arduino connections

Starting the Experiment

1. Begin data acquisition for both Arduinos and check that the date is being saved
2. Run motor
3. Whilst holding the test rig, remove the extra weights
4. Gently hold the reciprocating stem so that it is not shaking and position it so that the drill stem and heads are as vertical as possible
5. Let go of the test rig. If the drill heads or stem show immediate bending, pull up test rig and abort the test

The experiment will be finished when one of these criteria is fulfilled:

1. The drill reaches the maximum allowable depth as determined by the barrel
2. The drill has either stopped progressing or is showing a very slow rate of progression (less than half a millimetre a second) for over a minute
3. The system fails, either through the drill stem jamming or the drill heads breaking

**Finishing the Experiment**

1. Stop the data acquisition
2. Attach the extra weights to halt further progression
3. Stop the motor
4. Begin removing the regolith
5. Once the lowest sleeve attachment can be seen, the drill can be safely pulled up. Note any bending in the drill stem or heads
6. Remove the drill heads and stem
Appendix D

Drill Head Design Experiments Performed

Listed here are each of the experiments performed for the exploration of the geometrical parameters. There were a number of levels of success, depending on the bending of the drill and faults in the experimental procedure, given by the following key:

✓ Successful experiment, minimal bending
  ○ Imperfect experiment with some bending slightly affecting results, but can be used to accurately estimate final distance and time
  • Significant bending seen, creating anomalous results
  × Failed experiment
### Table D.1: Table of all experiments performed and the levels of success for each.

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Total 48 44
Appendix E

Effects of Soil Cementation on Sampling Instruments

The presence of water in the Martian environment, as discussed in Section 2.5.5, can also lead to the formation of duricrusts on the Martian surface and cementation of the soil. As well as the drilling systems, the presence of ice and cementation may also affect any sampling systems that interact with the extracted material. The Powdered Sample Dosing and Distribution System (PSDDS), part of the ExoMars rover’s Sample Preparation and Distribution System (SPDS), tasked with feeding crushed Mars surface and subsurface material into other instruments for further testing, is one such mechanism [95]. These samples may spend several days lying in the system before being delivered to an instrument. Within this time, the water present in the soil and/or atmosphere may cause the collected material to become cemented and clumpy, which may hinder the operation of the mechanisms it will interact with. This could particularly happen with materials that contain large amounts of loamy analogue materials such as Montmorillonite.

In order to investigate this possibility, a series of tests were performed using a qualification model of the PSDDS developed by OHB System AG with Dr. Norbert Kömle at the Austrian Academy of Sciences. This included the first creation of duricrusts in a selected Mars analogue material under simulated Martian conditions, and an examination of the cementation of the analogue’s component materials. The sample funnels of the PSDDS were then filled with icy analogue material and exposed to Martian conditions, after which the operation of the mechanism was tested.
E.1 Duricrust Creation in a Simulated Martian Environment

The tests performed here used the S7 analogue material, an unconsolidated clay/salt regolith simulant verified for use in the validation and testing of the ExoMars Drill and SPDS systems [29], whose composition is given in Table E.1. The sample was filled in one of the containers shown in Figure 5.2, placed on a cold plate inside a vacuum chamber and wetted for two hours using the same water disperser as that used in Section 5.2. The vacuum chamber was then brought to a stable simulated Mars pressure of 6 - 8mbar, with CO$_2$ fed into it via an inlet. The chamber then underwent two cycles of cooling and heating totalling four hours, allowing the water in the sample to undergo freezing and melting cycles. After this, the cooling was switched off and the sample kept at this pressure overnight.

<table>
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Table E.1: Composition of the S7 regolith simulant [29].

The duricrust formation is shown in Figure E.1, with the granular material in (a) showing a cracked and uneven, but nevertheless consolidated, crust (b) approximately 5mm thick. Removing a section of the crust (c) reveals that the material below it is largely unchanged, retaining its powder-like texture.

E.2 Cementation Tests

To further understand the cementation process, two dedicated experiments were performed. For both, the samples used were held in small brass containers of 24mm diameter and 21mm height, which were placed in a single steel container, as shown in Figure E.2.
The first test aimed to determine the extent and speed of which the component parts that make up the S8 analogue are wetted. The S8 is another verified regolith simulant [29], consisting of 50% of the S7 mix and 50% of a fine-grained quartz sand, in this case the UK4. As this mix of sand and clay is also likely to be found on Mars, testing the permeability of the UK4, which is absent in the S7, is also required. The four sample materials tested were the magnesium sulphate, Montmorillonite, UK4 sand and the S8 mixture, and were wetted together for two hours. The water contents of the samples were measured before and after wetting. Given that the magnesium sulphate and Montmorillonite are extremely hygroscopic substances, they naturally contain a considerable percentage of bound water before wetting. Afterwards, the samples were carefully removed from their respective containers and qualitatively described, with the results presented in Table E.2.
Table E.2: Description and water content values of the sample materials.

From this test it can be concluded that it is difficult to obtain a homogeneous wetting of the S8 mix by simply keeping it in a water-saturated environment. This is largely due to the low permeability of the Montmorillonite, whose particles swell when taking up more water, quickly blocking the diffusion into the deeper layers. As a result, even these small samples of S8 are not homogeneously wetted, unless they are stirred and mixed during the process. This provides an explanation for the formation of the duricrust, and the rapid change from the cemented material to dry granules as observed previously.

The second experiment furthers this study by determining how much water content added to the dry S8 is required to create cemented material. To this end, three 50g S8 samples were given water mass contents of 5, 10 and 20% respectively. In this condition, the 5% sample had the appearance of wet powder, while the 10% and 20% samples had a paste-like consistency, which can be seen in Figure E.3 (a). These, along with a dry sample, were stored at −20°C for two hours, before being placed inside the vacuum chamber and subjected to a pressure of 1mbar overnight, after which they were inspected. It must be noted that creating a homogeneous distribution of water through the sample was difficult, due to the water tending to immediately connect with the local environment as the mixture was stirred. Because of this, small clumps easily formed that tended to remain separated from the rest of the sample, which naturally hindered local cementation.

The results of this test indicate that the samples will have a paste-like consistency if they contain enough water, likely equivalent to a value nearing saturation, and as a result become strongly cemented when dried in vacuum. The 10% and 20% samples were so strong that they could be removed from
E. Effects of Soil Cementation on Sampling Instruments

Figure E.3: The four S8 samples with varying water content (a) and the cemented 5% and 10% samples (b).

...their containers as single compact pieces, as seen in Figure E.3 (b), which could not be broken up without the help of mechanical tools. The 5% sample was quite similar to the dry sample, with no noticeable cementation, though with a number of globules of coagulated particles several millimetres in size that had cemented to hard material.

E.3 PSDDS Dosing Tests

The PSDDS mechanism consists of four key parts, as shown in Figure E.4. The material collected is deposited in the entrance funnel (1). A portion of this falls into a small opening in the dosing device (2). This material is transported into the lower exit funnel (3) by the action of a motor, which drives a hinge to rotate the doser 180° around a central pivot. Movement of the material is assisted by the use of a piezo vibrator attached in the vicinity of the motor (4).

In these tests, the S8 analogue material is used. 50g samples with 5% and 7.5% water mass contents were frozen overnight and placed in the PSDDS entrance funnel. The PSDDS was then placed on the cold plate in the vacuum chamber, whose atmospheric pressure was brought down to 6 - 8mbar. The cold plate was then cooled to −60°C, which created a minimum temperature in the sample funnels of −20°C. The piezo vibrator was applied in five consecutive bursts of five seconds at 250Hz every fifteen minutes throughout the day. The sample was allowed to rest overnight, and the dosing tests were performed the next morning, with the piezo actuated five times before and after each dosing.
The majority of tests failed, with the material failing to be transported through the system. Removing the sample from the funnels manually revealed that small clumps of coagulated material of up to 5mm width had formed, shown in Figure E.5. While the dry S8 would also tend to coagulate, when wetted to have even a low water mass content of 5%, these clumps developed a significant internal strength under Mars conditions, which is maintained even after the sample is brought to room temperature. The strength of these globules was enough to block the funnels and stop the dosing mechanism, effectively creating a single point of failure in the system.
Appendix F

Rejected Actuation Mechanism Concepts

**Piezoelectric Actuators** These consist of stacked crystals which vibrate, creating a linear motion. However, these vibrations can only create displacements in the sub-mm category.

**Electromagnetic Drives** This drive would be used in conjunction with permanent magnets to achieve linear motion. Issues such as very poor power to force ratio and amplitude as detailed in [33] suggest this method would be unsuitable.

**LinMot Linear-Rotary Motors** These motors are able to provide simultaneous rotation and linear motion of a shaft. Although this could greatly simplify concepts 2 and 5 by eliminating the need for extra cams, converting the linear motion from a motor to a reciprocating motion for the two separate drill heads requires an off-centre shaft and gear system, as shown in concept 4, or two separate motors.

**Scotch Yoke Mechanism** This mechanism converts rotary motion to linear and vice versa. The piston is coupled to a sliding yoke with a slot that engages with a pin on the rotating disk. Although this is a simpler version of the drive shaft, in converting the motor’s rotary motion to reciprocation, the main disadvantage is the rapid wear of the slot in the yoke caused by constant friction.
Rhombic Drive This drive is able to convert the reciprocation motion of a piston to rotary motion simultaneously to two wheels, by using a joint rhomboid. The piston’s motion forces the wheels to rotate, however the motion is in opposite directions, resulting in the drill heads splitting apart instead of remaining together.

Rack and Pinion This uses a gear to link into a double-rail cylinder. The gear has half of its teeth, so that they engage only one half of the rail at a time, and as such move it either up or down. This mechanism is an alternative to the drive rail system used in the DRD004 and subsequent concept designs. However, although this removes the need for rods to connect the gear to the drive shaft, the teeth requirement for the wheels and rails result in this being significantly more difficult to manufacture.

Crankshaft This is the traditional form of reciprocation, in which a rotating wheel causes linear motion of a piston. This is similar to the drive shaft system, but has the disadvantage of being able to drive only one end of the drill, whereas the drive shaft system can connect to both ends of the drill head.
Appendix G

Assembly of the Quadruple Cam

G.1 Assembly Instructions

Ball Bearing Fitting

1. Insert wheels into bevel gears and secure with grub screws
2. Ball bearings pushed inside holes in Holds 1 and 2
3. Bevel insert pushed inside ball bearings
4. Bevel gears and wheels are pushed into insert, with the wheel protruding out from the bearing flange and Hold by 0.5mm

Rail Guide Fitting

1. Reciprocating rail guides (RR) put loose into rail holds (RH)
2. Top RHs wrapped around top extensions (TE) and screwed in place
3. Bottom RHs wrapped around Hold 1s and screwed in place
4. Lateral rail guides (LR) screwed into drive rail 2s (DR2)

Hold Fitting

1. Top bevel gear and extension fitted on to motor shaft using grub screws
2. Ball bearings pushed inside holes in Hold Top and Hold Base
3. Top bevel extension pushed inside top ball bearing
4. Bottom bevel gear and extension fitted on to motor shaft using grub screws
5. Bottom bevel extension pushed inside bottom ball bearing
6. Hold support fitted around hold top
7. TE, hold top and Hold 1 parts are screwed together
8. Hold 2s are slotted and screwed into Hold 1s

Drive Rail Fitting
1. Lateral slide supports (LSS) fitted on to lateral guide rails (LGR)
2. LGRs fitted into lateral slide holds (LHS), which are screwed into the DR2s
3. DR2s slotted into recesses in Hold 2s
4. Rod attached to Hold 2 wheels and fitted to DR2s using rod holds
5. Reciprocating slide holds attached to drive rail 1s (DR1 and DR1v2) and the force sensor
6. Force sensor screwed into sensor hold, which is then attached to the DR1v2
7. DR1s are fitted on to all RRs
8. Rods attached to Hold 1 wheels and fitted to DR1s using rod holds

Shell Fitting
1. Slide reciprocating guide rails (RGR) small end first through the large hole in reciprocating slide supports (RSS), then through the RSH and into the small hole of the RSS
2. Secure RGRs with grub screw through the RSSs
3. Screw RSSs into the shell tops (ST) and shell bases (SB)
4. Screw shell part 1s (SP1) into STs
5. Screw shell part 2s into SP1s, SBs and LSSs
6. Place drill head plate onto cone, and slot through holes in cylinder, and screw together
7. Slot drill head through holes in SB and screw into SP1s

The parts and assemblies are also presented as exploded and completed SolidEdge drawings. Each drawing is shown in the correct orientation.
Solid Edge

Reciprocating Rail Guides

Drive Rail 2

Drive Rail 1 v2

Lateral Slide Hold

Lateral Guide Rails

Reciprocating Slide Hold

Reciprocating

Hold Support

Sensor Hold

Force Sensor

Rod

2 PL ±X.XX
3 PL ±X.XXX

ANGLES ±X.X°

DIMENSIONS ARE IN MILLIMETERS

UNLESS OTHERWISE SPECIFIED

FILE NAME: driverails.dft

SCALE: A4

DATE 04/19/16

REVISION HISTORY

REV DESCRIPTION DATE APPROVED

1

Solid Edge

Reciprocating Rail Guides

Drive Rail 2

Drive Rail 1 v2

Lateral Slide Hold

Lateral Guide Rails

Reciprocating Slide Hold

Reciprocating

Hold Support

Sensor Hold

Force Sensor

Rod

2 PL ±X.XX
3 PL ±X.XXX

ANGLES ±X.X°

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Rod

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3 PL ±X.XXX

ANGLES ±X.X°

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SCALE: A4

DATE 04/19/16

REVISION HISTORY

REV DESCRIPTION DATE APPROVED

1
G.2 Circular and Diagonal Cam Wheel and Rod Positions

In order to produce the required circular and diagonal motions, the set-up of the cam wheels and the connecting rods must be set up as shown in Figure G.1. Each wheel’s label corresponds to those given in the SolidEdge drawings provided in Section G.1, and the positions are shown when looking at the face of each individual wheel.

Circular

![Circular Cam Diagram]

Diagonal

![Diagonal Cam Diagram]

Figure G.1: Diagram of the starting positions for the cam wheels and connecting rods required to produce the circular and diagonal motions.
Appendix H

Force Sensor Circuit Diagram

Figure H.1: Circuit diagram of the force sensor, amplifier and data acquisition system.
Appendix I

UK4 Uniaxial Compression Strength

Figure I.1: Graph of the uniaxial compression strength with deformation of the loose UK4, with a density of 1.4kgm$^{-3}$. 
Figure I.2: Graph of the uniaxial compression strength with deformation of the compacted UK4, with a density of $1.7\text{kgm}^{-3}$.
Appendix J

Sampling Systems

A major contributor to the worthiness of a drilling technique is the ability to acquire a sample for delivery to a scientific instrument, whilst retaining the sample’s fidelity and information as to its nature as best as possible. This section explores the types of sample that can be obtained, and describes the techniques developed for different drilling systems.

J.1 Core and Powder Samples

Samples can come in the form of solid cores or powdered drill cuttings. Cores have a significantly greater scientific value than cuttings, and are able to provide much more information. For example, a core can be split to reveal a fresh, uncontaminated surface and microscopically imaged to determine its morphology, with the ability to sub-sample layers of interest. Volatiles may also be preserved within a core, and the core can be sliced or crushed to allow for further analysis [123].

J.1.1 Core Drilling

Coring bits cut an annular space in the rock instead of drilling out the entire volume of the hole, reducing the power, torque and WOB requirements. However, obtaining a cored sample is much more complex from a mechanical design and robotics point of view, as it requires a core break-off mechanism, a core catcher and a pushrod inside the drill string to push the core out [10, 123]. Most present and near-future rotary and rotary-percussive drills
include a coring mechanism, with various techniques used to collect the samples. For example, Rosetta’s SD2 retracts the drill by 1mm once the desired depth was reached, and releases an integrated sampling tube, after which the drilling would resume, with the tube acting as a coring device [31]. The Exo-Mars drill/corer uses a shutter which remains closed during drilling, shown in Figure J.1. At the desired depth, the shutter is opened and drilling resumes until the cavity is full, and the sample is cut off by the shutter closing. The sample is discharged by opening the shutter and pushing the sample out with a central piston [10, 120]. The Mars Sample Return drill and the USDC use similar mechanisms, in which two nested eccentric tubes within the bit are aligned while drilling, collecting the core as the drill progresses. The inside tube then rotates the core off the bit’s axis, breaking it off and retaining it [126, 6].

Figure J.1: Picture of the ExoMars drilling and sampling configurations [36].

### J.1.2 Powdered Cuttings Collection

Some drills are unsuited for coring, such as percussive drills, due to the hammering motion. Drills that do not take core samples, known as full-faced bits, may still have hollow segments housing sample acquisition instruments that take unconsolidated cuttings. This can simply be an internal space that opens and closes, into which the cuttings are collected [123]. This is the case with the USDC sampler, in which trapping cavities allow upwards-travelling powder to enter hollow sections of the bit [10, 9]. The PLUTO and MMUM moles also include similar sampling mechanisms unique to the mole design, shown in Figure J.2. The front tip is held closed during drilling by a tension string. When sampling, the motor that controls the shock mechanism operates in reverse, causing an extendible internal screw to force open the
mole’s front cone. The mole then continues driving into the soil until the chamber is filled, after which it is closed by the screw releasing the extra tension force on the spring [96, 110].

Figure J.2: Sample collection mechanism of the MMUM in the open and closed configurations [110].


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