Development of a Heuristic Thermal Control System for the Ultrasonic Planetary Core Drill

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1.0 Abstract

The Ultrasonic Planetary Core Drill (UPCD), recently developed by a consortium of European partners with co-ordination from the University of Glasgow, is a planetary sample acquisition and caching systems testbed, recently field tested at Alexander Island, Antarctica.

During the early development of the technology, laboratory-based drilling tests at ambient pressure, utilizing volatile-laden permafrost simulants, revealed the need for an enhancement of the existing control algorithm which autonomously governs the rate of progress of the drill through the terrain. Such modifications have been deemed essential if failure modes relating to re-solidification of unbound volatiles are to be avoided.

In the preliminary development of this thermal control algorithm, multiple sensors have been utilized in order to enhance the reliability of the system. It is hoped that this sensor suite may also allow data concerning the thermal environment of the terrain to be exploited, improving the scientific return of the mission. This paper details the early progress made towards a robust thermal control system for the Ultrasonic Planetary Core Drill, featuring results of laboratory testing under ambient conditions in to targets consisting of simulated permafrost, pure ice and frozen saturated rock. Results from this series of preliminary tests show that, when required, the control algorithm developed has proven to be a useful addition to the UPCD control system through its ability to prevent freeze-in faults.

2.0 Introduction

The future of Solar System exploration is tending towards further exploration of the subsurface of the terrestrial bodies in its search for the answers to fundamental scientific questions regarding the geological, and potentially astrobiological history of our planetary neighbors. Furthermore, the advent of In Situ Resource Utilization (ISRU) as a means of fortifying mankind's human spaceflight endeavors only strengthens the necessity of developing robust systems capable of robotically scouring the planetary subsurface.

The advancement of both pursuits share one commonality – a desire to explore volatile-rich regions, with a particular focus on the search for frozen water. While the mining of regolith rich in frozen water may provide a future means of sustaining planetary colonies or refueling spacecraft on long duration missions, it has been suggested by McKay (2013) that regions in Mars' northern latitudes (northwards of 60º) which exhibit ground ice may be excellent locations to further the search for organic biomarkers. Such latitudes have previously been explored by the Viking and Phoenix landers, though these missions have concentrated on near-surface excavation using robotic arm-mounted scoops, with the latter mission supplementing pure excavation with a rasp-like device as detailed by Chu (2008). In order to broaden the scientific search, reaching beyond the near-surface in order to extract pristine samples which are less degraded by the radiation or aeolian environment, proposed future missions aim to explore to greater depths with the aid of advanced drill systems. As detailed by Fisackerly (2015), the proposed ESA/Roscosmos Luna-27 mission to the South Pole shall utilize a sample collection system, ProSEED, capable of extracting ice bearing samples from depths of up to 1.2 m [Savoia (2017)]. This single string drill aims to acquire two different quantities of cuttings in order to fulfil the sample requirement for both onboard instrument types.

While the relative proximity of lunar missions may allow for teleoperation of the drill, proposed missions to Mars, such as the NASA Discovery class Icebreaker Life mission, must operate fully autonomously and as such, be capable of self-detection and recovery of faults. As detailed by Zacny (2013), the development of a 1 m class autonomous drill system allows the delivery of loose, ice-bearing cuttings to an onboard suite of instruments. As the relatively temperate summer conditions which may exist on Mars during portions of a typical Sol may permit the presence of stable liquid water at both high and low latitudes [Chevrier (2009), Martin-Torres (2015)], a combination of the proposed northerly landing site, and the relatively lightweight, immobile lander which shall form the backbone of the mission (a near re-flight of the Phoenix architecture) necessitates that the system must be fully capable of preventing freeze-in faults from occurring. Freeze-in faults may occur through multiple mechanisms, though perhaps the most devastating of these occurs when frozen water within the cuttings melts and freezes to both the auger flights and the borehole wall. As the adhesive strength of ice on drill steel is in excess of 1.65 MPa [Myers (1996)], it is likely that the axial pull-out force required by the drill to free itself would exceed that which could be reacted by typical lightweight landers such as that which would be utilized for Icebreaker Life. Furthermore, it is unlikely that the drill system itself would be able to provide the high levels of torque required to shear the bond through rotation alone. Therefore, depending on the scientific objectives of the mission, it may be possible to classify fault modes associated with the permanent seizure of the drill string downhole as single point failures which must be avoided at all costs. As the time scale of a freeze-in fault may be on the order of a few seconds [Timoney (2016)], it is possible to conclude that any mission which aims to deploy a drill system in icebound terrain, which does not wish to impose strict constraints on the scheduling of drilling operations, must have a means of sensing the onset of these faults in real time before taking measures to ensure that drilling activities do not result in a freeze-in. The mechanisms by which thermal control of the drillstring can be achieved shall be discussed in detail in the next section of this work.

3.0 Thermal Control System Development

3.1 Considerations and Failure Modes

In order to maximize the scientific return from planetary missions which seek to explore the planetary subsurface and acquire volatile-bearing samples for in situ analysis or return to Earth, mission scientists, instrument designers and mission planners are often faced with the need to make compromises in order to ensure that these samples are of a quality which can fulfil the tier one objectives of the mission. One such compromise is an acceptance of the effects of the utilization of drill systems on the type of samples obtained and the quality of such a sample. While drills prove to be an efficient means of sampling small quantities of material at depth, the physical act of obtaining these samples, and the complex nature of the task means that it is likely that the mission output will suffer from some level of degradation in the process. For example, although the scientific objectives of a mission may favor the acquirement of terrain core samples over powdered cuttings, the design of a drill and sample handling/processing system is inherently more complex than systems which acquire loose cuttings. Therefore, such a system comes with increased costs and associated risks. While it may be possible to work around such compromises, other compromises associated with the drilling process are less avoidable. The work done in breaking terrain formations is directly proportional to the strength of the formation, and as the strength of water-bound terrain, such as permafrost, increases with a decrease in the temperature of the formation and an increase in the level of saturation, saturated permafrost at cryogenic temperatures may exhibit strength which is comparable to that of medium-hard sandstone [Zacny (2007)]. This poses a concern when drilling such formations as it is inevitable that heat from the drilling process shall be transferred to the drill bit, cuttings and borehole, melting water in the process. In fact, Szwarc (2013) calculated that during core drilling operations, the drill bit, cuttings and core received 11%, 6.6% and 2.5% of the total heat generated, respectively. Clearly, the direct heating of the core and cuttings will result in a degradation of the volatile ratios held within these samples through direct sublimation (assuming suitable atmospheric conditions) or, in the worst case, melting. In planetary applications, the drill bit may acts as a heat pipe, wicking heat away from the bit-rock interface to the colder surface. While this offers a means of reducing heat flow to the borehole, the warmed section of drill bit closest to the bottom of the borehole may act to thaw water held within the cuttings which may then refreeze on a colder section of the bit as the cuttings are conveyed upwards by the auger. If the thawed cuttings refreeze on to the auger flights, and subsequently to the borehole wall, the drill will be rendered immobile. In laboratory conditions, where the surface air temperature typically exceeds that of the downhole, the problem is only worsened as the bit temperature increases. These freeze-in events are typically unrecoverable at even shallow depths, as shown in Figure 1 [Timoney (2016)]. In this case, drill depth achieved before freeze-in was on the order of 30 mm and the drill bit was recoverable only with aid of a chisel.

Figure 1: Freeze-in event at shallow depth. Note, chisel required to free bit from regolith. [Timoney (2016)]

In cases where the drill bit does not succumb to a complete seizure of the drill bit, it is possible that the thaw-refreeze event may still prove critical enough to effect the cessation of drilling due to bit glazing and/or auger blocking. Figure 2 details a particularly critical incidence where both of these failure modes occurred simultaneously. While it is possible to avoid a freeze-in event in such a case, it is likely that the drilling operation must be paused in order to allow the bit to thaw. The bit must then be cleaned and re-cooled before it can be utilized for future drilling attempts.

Figure 2: Bit glaze and auger blocking event as a result of thawing and refreeze of water present in cuttings.

3.2 Sensing Refreeze Faults

In order to develop a control system which is capable of sensing the onset of the fault modes attributable to the melting and refreezing of volatiles contained within cuttings and taking action to prevent seizure of the bit, it is critical that the ‘markers’ of such events are identified. Work by Zacny [(2005, 2013)] suggests that the surest method of sensing the onset of such faults is through a combined approach of monitoring both the physical state and the temperature of the fresh cuttings at the bit-rock interface. The need for sensing the physical state of the cuttings is necessitated by the presence of salts and minerals, such as perchlorates, which are found ubiquitously on Mars and act to depress the melting point of the eutectic briny solutions it forms [Hecht (2009)]. The resulting solution will have a melting point which is a few degrees lower than pure water, though there exists the possibility for super-eutectic ice lenses to form with concentrations of perchlorate far in excess of the average distribution and subsequently, a far greater depression of the melting point. It is this uncertainty which ensures that temperature data is insufficient as the sole means of detecting the presence of water downhole. In order to sense the physical state of the icy cuttings directly, an electrode system can be integrated in to the cutting face of the drill bit, protruding to a depth such that they are recessed with respect to the cutting teeth to avoid damage, but directly in the path of accumulating cuttings. The electrode circuit measures the resistance between two opposing electrodes and it is this change in the resistance value which can be used to sense a change in the physical state of the ice trapped in the cuttings. An example of a typical drill bit architecture, instrumented to sense downhole conditions, is as detailed in Figure 3. Icy cuttings which are completely frozen will inhibit the flow of ions between the electrodes, resulting in a resistance reading which is extremely high, analogous to that of an open circuit. However, the conduction properties of water in its liquid phase acts to close the circuit, allowing ions to flow between the electrodes and in turn, reducing the measured resistance. Thus, the presence of dissolved salts will act to aid the detection of liquid water due to an increase in the concentration of ions within the solution. Furthermore, it may be possible to utilize the drill bit as a scientific probe in itself by measuring the resistance of the terrain at increasing temperatures during drill operations. This, in turn, may allude to the concentration of dissolved salts in the regolith - useful data in the context of ISRU or astrobiology.

Figure 3: Drill bit instrumented with thermocouples and electrodes for use in thermal control system.

This combination of thermal and resistance data from embedded downhole sensors utilizes this raw data, and through a series of logical operations, commands the drill to reduce its rate of progress in order to minimize the thermal load imparted on the formation, or retreat from the cutting frontier entirely to allow both the terrain formation and the drill to cool off. Such a system acts as the first defensive line against the onset of bit freeze-in and can be coupled with data from the auger motor in worst cases.
The thermal control system can operate in multiple modes, whereby the logic based on the resistance parameter can act based on an absolute value or a change in the value sensed over time. Basing the system off of an absolute value, whereby the control system triggers a command upon receiving signal that the resistance has decreased past a certain threshold limit, is most robust when foreknowledge of the thermal behavior of the volatile is available. While such an approach may prove tricky to implement in in the context of planetary exploration, whereby knowledge of the terrain is not certain before drilling commences, the approach benefits from relatively uninterrupted drilling until a certain level is attained. Basing the control system upon a sudden change in the resistance level is more robust against uncertain terrain physical properties, but there may be a tendency for such a system to be overly cautious in its drilling approach, compromising drilling effectiveness.

3.3 Experimental Setup

In order to evaluate the preliminary performance of the instrumented drill bit architecture for use within the Ultrasonic Planetary Core Drill, a series of tests were planned which would utilize the instrumented hardware (Figure 4) in combination with the UPCD control system, previously tested in the laboratory and in the field. The hardware was tested in a chest freezer within the laboratory, with the contents of the freezer chilled to -25ºC, at ambient pressure. The bulk of the drill system was kept outside of the freezer until testing was to commence, but the instrumented drill bit was always chilled to freezer temperature before testing began. Although such a system would result in a large thermal soak to the drill bit due to the temperature differential, the short duration of testing meant that heating of the drill bit from external sources was minimized.

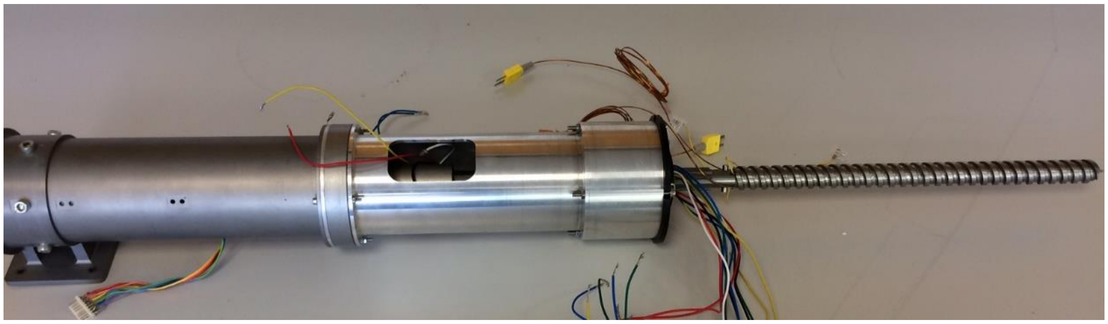
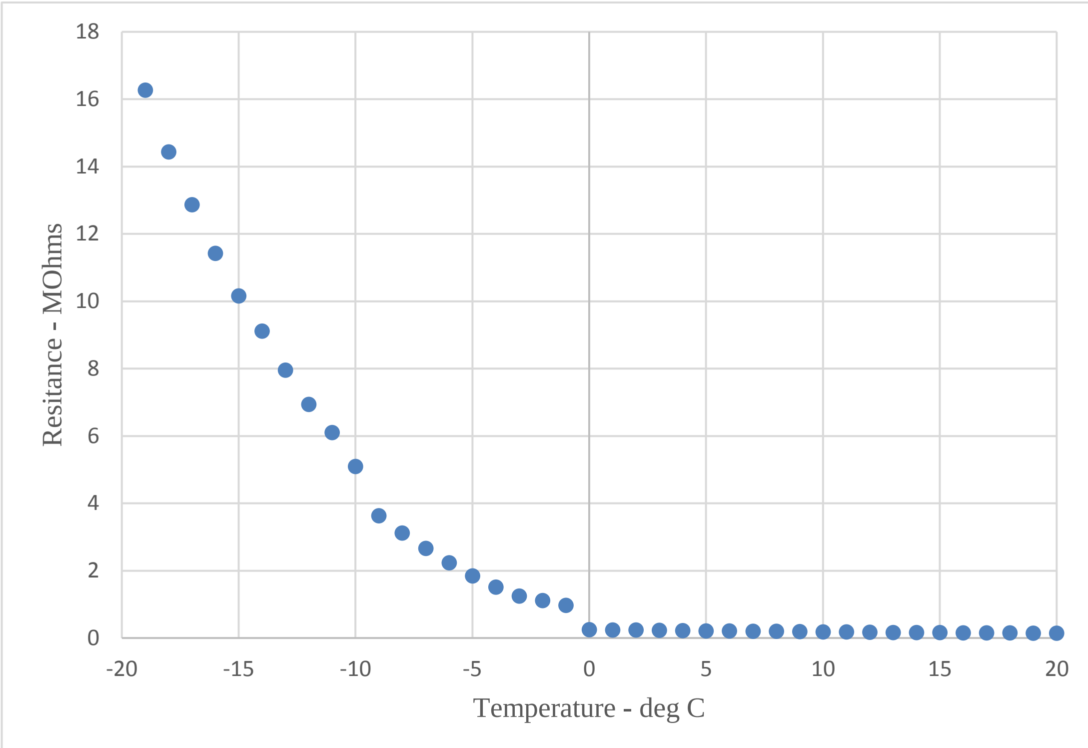


Figure 4: Instrumented UPCD hardware. Thermal control hardware includes the addition of downhole thermocouples and electrodes, and a slip ring assembly to transfer signal

Simulated permafrost samples were developed, using a sand mix previously characterized by Firstbrook (2014), frozen with 10% and 16% water by weight, respectively. The latter mix is represents the fully saturated case. These samples were compressed to 2 g/cc density and frozen overnight, with an embedded thermocouple to ensure the samples were completely frozen upon testing. Furthermore, small samples of each mix were made and tested using impregnated thermocouples and electrodes in order to characterize the thermal behavior of the samples. These results, presented in Figure 5, plot the resistance of the mix against temperature, allowing a baseline value to be selected for the thermal control system to act upon. It is of note that the 10% water/weight sample features multiple trends, with a transition zone between –9 and 1ºC. Knowledge of the expected resistance ranges proved extremely useful when designing the circuity to complement the electrode, allowing sensing accuracy to be improved within certain resistance bands, thus improving the robustness of the control system.



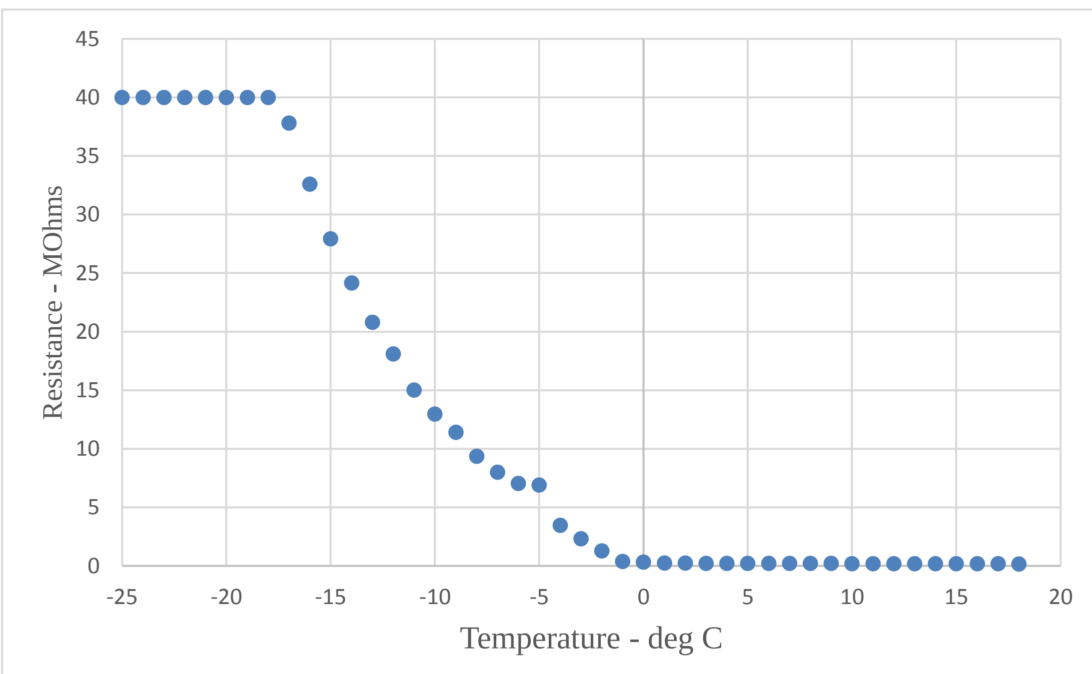


Figure 5: Temperature - Resistance plots for 10% water/weight (top) and 20% water/weight (bottom) simulated permafrost mixes

3.4 Test Results

In preparation for the 10% water/weight test, it was noted that the presence of a transition period between 4 MOhms (-9ºC) and 1 MOhm (-1ºC) would allow a baseline preset trigger value to be included within the control system, allowing the drill system to progress until this threshold was reached, then retreat. Upon testing, the drill system progressed efficiently through the sample without triggering the activation of the thermal control system. This was, perhaps, attributable to the low strength of the mix, only weakly bound by the low percentage of water present. Figure 6 details a typical run in the 10% water/weight mix, clearly showing that there is little deviation in the resistance measurement over the course of the run. The progress of the drill is never impeded and total drilling power averages 40 W.

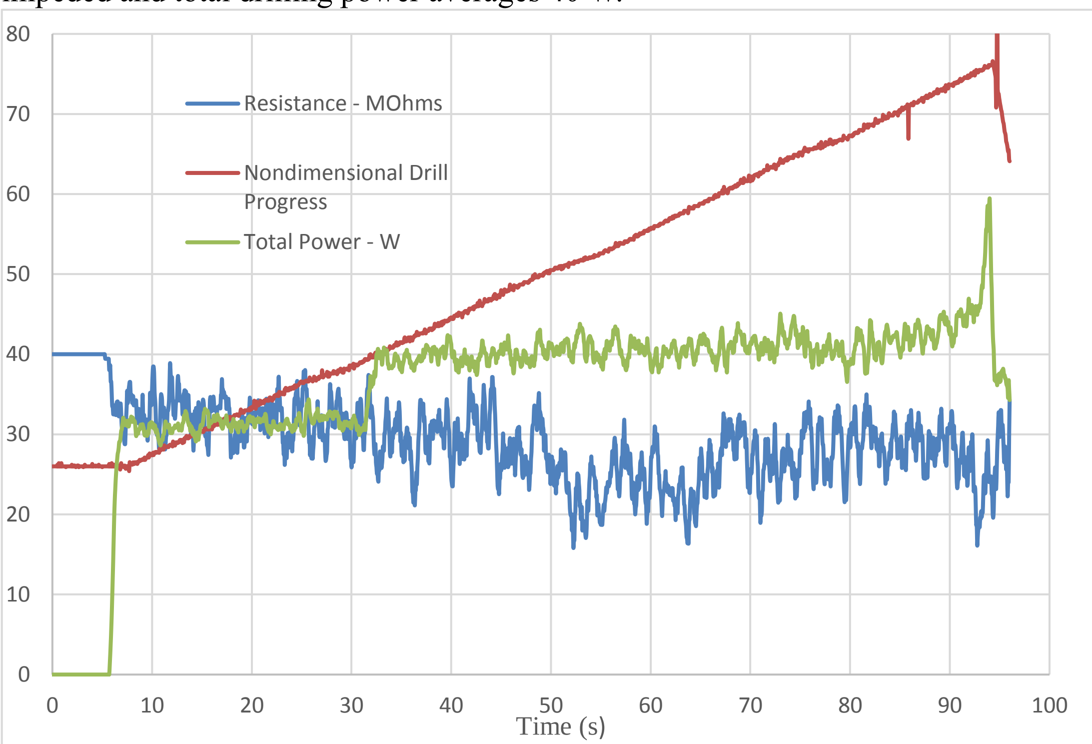


Figure 6: Result from test run in 10% water/weight sample. Note, drill progress unimpeded due to the low strength of the mixture. Thus, very little heat was delivered to the cuttings and resistance readings are always high.

Figure 7: Frozen 10% water/weight permafrost core.

The test setup allowed multiple runs in the same sample. Each result obtained presented similar results to that detailed in Figure 6, providing reassurance that even under laboratory conditions, weaker permafrost samples do not heat up sufficiently to engage the thermal control algorithm. Furthermore, the tests allowed the collection of multiple, still-frozen permafrost cores, Figure 7, providing further evidence to support this conclusion.

While the less saturated simulated permafrost mix proved to be of little challenge to the drill system, the harder, fully saturated mix proved more reliable in its tendency to engage the thermal control algorithm. The thermal control algorithm was programmed such that, upon the drill sensing a limit threshold resistance, the drill retreated from the bit-rock interface for a fixed period of time before it re-engaged the terrain. This behavior is noted in Figure 8. Following a period of drilling between T=25 and T=55 s, a gradual increase in total drilling power results in a gradual decrease in the resistance reading from the electrodes. As drilling power increases rapidly between T=55 and T=65 s, there is a sharp reduction in resistance, suggesting that the sudden input of power has resulted in an increase in the rate of ice melting within the cuttings. As the resistance falls below the preset minimum threshold, the drill suddenly retracts and idles for a portion of time, in an attempt to cool the terrain and the bit itself. As the bit advances forward, power is minimal until the bit-rock interface is re-engaged at T=110 s. Total drilling power then proceeds to ramp up, mirroring the behavior of the previous rapid increase, resulting in another drop in resistance and a subsequent withdrawal of the bit.

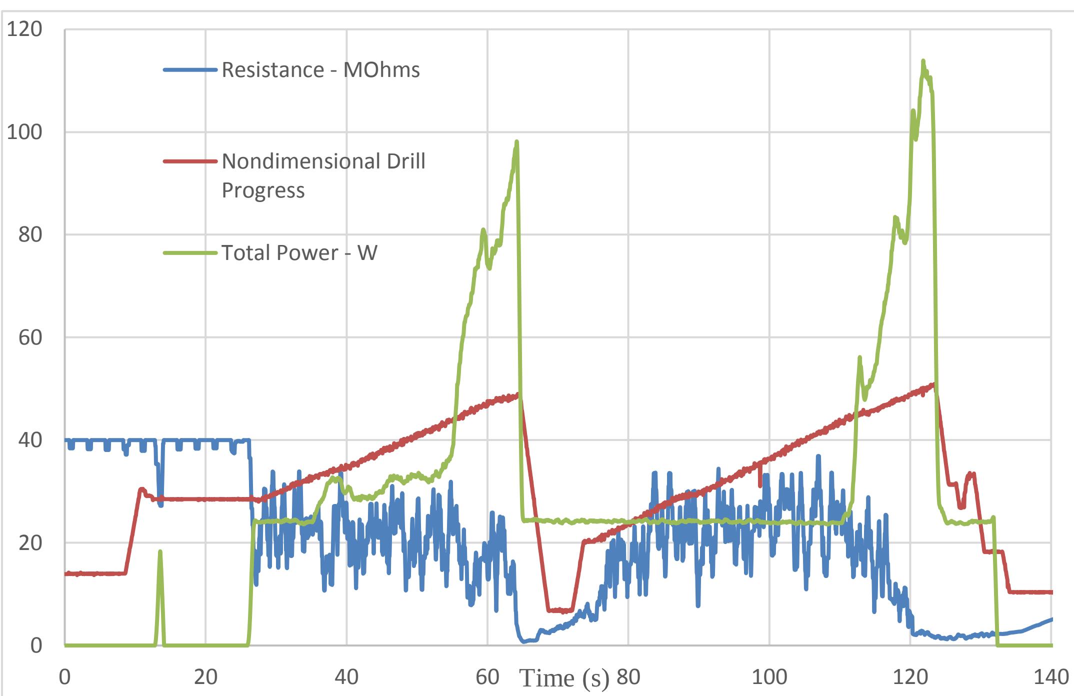


Figure 8: Result from test run in fully saturated sample. Engagement of the thermal control system can clearly be noted as the drill retreats upon surpassing a lower threshold resistance limit.

A further example of the thermal control algorithm in operation is detailed in Figure 9 whereby the control system is programmed to retreat when the thermocouple sensors detect a temperature in excessive of an upper bound. In the example shown, the drill retreats when a temperature of 0 °C is reached. Between T=50 and T=100 s the drill progresses into the target terrain, resulting in an initial cooling of the drill bit followed by a warming behavior as work is expended in formation breaking. This process repeats as the drill makes progress through the target terrain, retreating only when the upper temperature bound is exceeded. It is of note that there is a trend towards a general increase in bit temperature over time. Future control logic will alleviate this through increased periods of dwell, whereby the drill is disengaged from the target and powered down to reduce the thermal load at the drill tip.

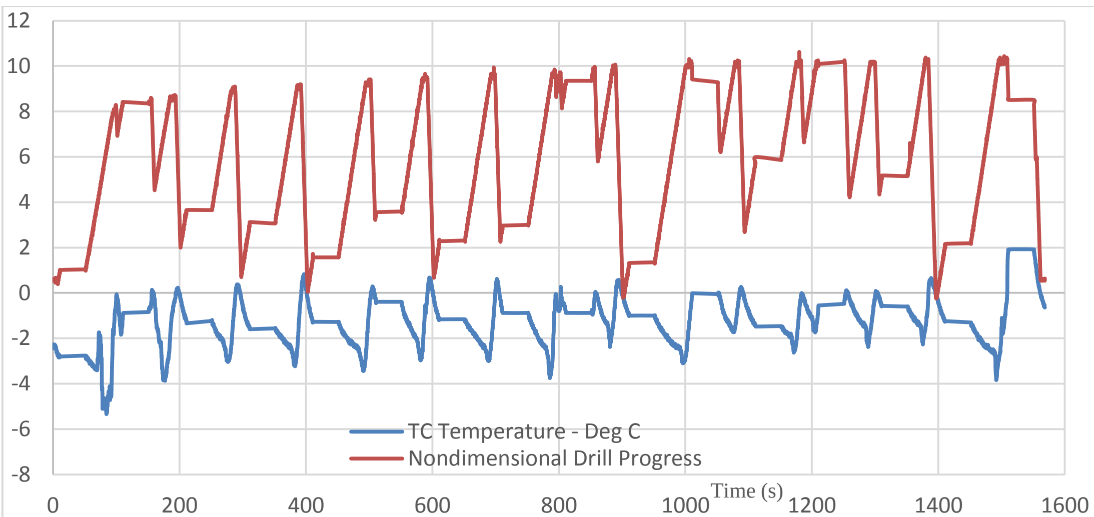


Figure 9: Results from test run in fully saturated sample. Retreat of the drill system occurs upon a surpassed upper temperature limit.

4.0 Conclusions

Testing of the Ultrasonic Planetary Core Drill in various ice-bound terrains, both in the laboratory and at the field site on the Antarctic Peninsula, has revealed that there is a need for the development of an expansion of the control system capability in order to prevent potentially mission-ending drill seizures caused by the thawing and refreezing of volatiles held within the drilled cuttings. Through the implementation of a sensor suite at the cutting face of the drill bit, data pertaining to the thermal and physical state of the volatiles can be attained, allowing the development of control logic which can provide the drill system with a safeguard against freeze-in events. Laboratory testing has proven that the preliminary development of such a system functions well in preventing bit freeze-in, and further refinement of the technique will only improve its functionality within the UPCD architecture. A planned campaign in a thermal-vacuum chamber shall allow the system to be tested at representative Mars temperatures and pressures, providing confidence in the use of such a technique when coupled with the ultrasonic-percussive – rotary drilling technique.

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