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The Adaptation of Terrestrial Mining Equipment to In-Situ Resource Utilization on Planetary Bodies

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Abstract

Future space missions to planetary bodies, both manned and robotic, will require the efficient utilization of in-situ resources to ensure longevity, success, and adherence to the "faster cheaper better" mantra now in vogue within various space agencies and upon which a number of new commercial space ventures are being developed. The Utilization of In Situ Resources, while requiring the development of new technologies and methods for commodity extraction, will still rely upon some method of mining technology for the harvesting and pre-beneficiation of the raw materials prior to processing.

The Northern Centre for Advanced Technologies Inc. is presently engaged in the development and adaptation of existing mining technologies and methodologies for use extra-terrestrially as pre cursor and enabling technologies for ISRU

1 Introduction

The Northern Centre for Advanced Technology Inc. is a private not for profit corporation located in Sudbury, Ontario, and operates an underground testing centre in the rim of the Sudbury Basin, an ancient impact crater. There are more than 750 registered mines within a 4-hour drive of NORCAT's head office. Sudbury has long been considered the world leader in mining technology and mining technology development.

NORCAT was formed in response to a perceived need to provide technology development expertise to Small and Medium Entrepreneurs in the area engaged in mining equipment manufacture. Recently, there have been an increasing number of requests from all areas of the globe for assistance in the development of mining technologies for use in In-Situ Resource Utilization (ISRU) on planetary bodies. NORCAT's unique expertise and position within the mining community offers space industry an opportunity to shorten the development cycle for ISRU technologies.

2 ISRU

In Situ Resource Utilization refers to the use of raw materials found at a mission site on a planetary body, such as landing site, exploration site or supply site. The raw materials found in such proximity will, in general, provide some form of commodity for mission architects and would support the mission in some manner. This would be in the form of propellant, power, life support material (oxygen and water) or some other material that would benefit the mission.

The raw materials range from lunar regolith for solar cell direct deposition in power plant production [10, 11] through Martian regolith [12, 13] for propellant and water manufacture to water ice recovery from dormant comets in NEO configurations. Some of the proposed processes require access to sub surface zones ranging from 10 metres to more than 4 kilometres in depth. [1, 6, 9]

While there is a growing interest in the technologies required to process the resources into such commodities [2, 14], much work still needs to be performed on the technologies for accessing and harvesting the raw materials.

It is NORCAT's position that the technology development cycle for these critical "enabling" technologies could be dramatically shortened by careful adaptation of existing mining techniques and equipment. To achieve this end, we have divided existing technologies into essentially three categories: sub-surface access, rock removal, and surface harvesting (see Table 1).

The table is for illustration only, and can be considered a partial listing with a focus on hard rock technologies and equipment of immediate interest. Others have generated similar lists, for more specific tasks and technologies [9]

Sub-Surface Access	Removal	Harvesting
Diamond drill	Controlled foam injection	Scoop
Jumbo drill	Explosive autoloader	Road grading
Raise borer	Tunnel borer	Roadbed smoothing
Top hammer drill	Jumbo drill	Backhoe
ITH drill	Rock bolter	Vibrating lip mucker
Tri-cone drills	Shotcrete/resin applicator	Scarifier
Blind borer	LHD	LHD
	Locomotive	Truck

Table1: Mining Equipment Categorization

3 ISSE

A relatively newer category of equipment development is in the area of In Situ Support Equipment. This category can include items as diverse as wheel jacks for Martian rovers to road building and maintenance equipment for Lunar and Martian habitats and even tunnel boring machines for sub-surface habitat construction. [5]

In this case, the technology development cycle can again be shortened by appropriate use of existing mining technologies as base platforms for the development. The underground environment is harsh and system longevity is critical. Many specialized pieces of service equipment have been developed over the years to support the underground mining environment, such as fueling systems, HVAC, power distribution systems, explosives handling, portable service vehicles, etc.

NORCAT has only just begun to address the issues of ISSE in conceptual form and in conjunction with documents such as MEPAG [5]

4 Adaptation to Planetary Exploration

Typical hard rock, terrestrial mining equipment is incapable of direct adaptation to planetary exploration. NORCAT has identified five critical stages in the adaptation process, based upon experience to date with its Planetary Sample Coring Drill and conceptual work on a Regolith Miner.

The five stages, in sequence of approach, are:
1) Elimination of fluids;
2) Anchoring/stabilization;
3) Algorithm redefinition
4) Miniaturization
5) Autonomy

4.1 Elimination of Fluids

Terrestrial mining equipment relies heavily upon the use of fluids for operation. Most equipment is hydraulic with either diesel or electric motors driving a hydraulic pump for the system. Air and water are used commonly for cooling of drive trains and lubrication of cutting faces, in drilling, or cleaning, “blowing off”, of buckets and scoop buckets, conveyors, etc.

The first step in any adaptation, then, is to remove these fluids from the system. This could be achieved via direct replacement, as is the case with some proposed deep drills for Mars, wherein a compressor is required to force Martian atmosphere down a drill hole for balings removal. Or it could be achieved by a re-design of the system motive engines.

Hydraulic systems MUST be replaced for use in hypobaric conditions, such as may be experienced on Mars or the Moon, and in low temperature conditions (below 220K). The drive systems must be converted to electrical power.

4.2 Anchoring/stabilization

One of the key factors of success in core drilling is maintaining accurate set-up for drilling. This is necessary to ensure control of the drilling direction and the control of the axial thrust at the drill bit. Diamond drills, although massing in excess of 5 tonnes, can exert more than enough reaction forces to lift the rig from the ground.

This stability is a requirement in all mining equipment, tracked haulage inclusive. This is primarily an issue of tractive effort, but becomes important when attempting to fill a scoop bucket manually, for example, and is exacerbated when tele-operating.

As systems are miniaturized for use in planetary exploration, care must be taken to ensure appropriate anchoring and stabilization for proper performance under milli-gravity conditions.

4.3 Algorithm redefinition

The control of hydraulic systems in mining equipment generally relies on one or more prime pumping mechanisms with filtering and appropriate cooling of the fluid. Various technologies are used to control flows and pressures in a system as it performs work ranging from swash plate control, through hydraulic pilot operated spools and relief checks to electronic pilots and spool dithering. Each of these technologies carry unique control problems beyond those associated with position control and problem correction. Existing hydraulic system controls are maturing in the mining industry. The removal of hydraulic systems as prime movers in planetary exploration equipment would necessarily require a redefinition of the controlling algorithms and the integrated system control to account for system dynamics.

In general, mining equipment used in hard rock rely on inferred sensing for closed loop control and feedback. System components introduce inertia and masses into the system dynamics that can and will vary with application. A prime example would be the control of drilling forces at a drill bit on an exploration diamond drill unit. The drill string is in excess of 100 metres long and, given its diameter, behaves much like pushing a wet noodle. Bit life, rock comminution, drilling direction, and accuracy are all dependant upon the control of the drilling forces at the bit/rock interface. These forces can only be controlled with inferencing techniques, as there is no technology presently available to allow bit/rock condition monitoring dynamically and from the face. Control input is inferred from drive system torque, drill string rpm, rate of penetration, and thrust, the sensors for which are situated at the top of the hole on the drill unit. Control output is achieved via manipulation of hydraulic system parameters such as system pressure, drill head rpm and/or torque, drill feed hold back pressure, and drill feed flow rate. This control is usually a supervisory type of control on top of a lower level controller delegated strictly to hydraulic valve pilot position control, such as a dithering driver. There are, at times, intermediate layers of position control units exercising direct control over one or more hydraulic axes in coordinated position control. In summary, the control of the actual forces at the drill bit is closer to open loop control than it is closed loop.

Exacerbating the problem are issues such as drill string mass, drill bit mass and inertia, buoyancy effects due to balings flushing, geophysical structures encountered during hole propagation, post propagation hole stabilization techniques, etc.

The system algorithm redefinition is required to account for the change in controllable parameters (ex: hydraulic pump swash plate versus DC motor variable speed drive) as well as the change in sensing techniques (ex: turning motor hydraulic pressure and swash plate position versus DC motor current).

4.4 Miniaturization

Because of the tremendous cost of transporting heavy equipment to planetary bodies smaller is better, when considering the use of mining equipment on planetary bodies. Initial mission specifications for a “deep” drill (max 200 metres) allow a total 150 kg (power supply not in) for mass of the system. In comparison, some drill bits alone used in terrestrial applications weigh more than the mass allocation for the entire system in planetary exploration.

The miniaturization of the mining equipment PLUS the single use concept resulted in a bit of a paradigm shift for manufacture of the mining equipment. Bigger is not better, in terms of performance and capabilities.

Nevertheless, the simple act of miniaturizing brings its own set of problems. We are experiencing new issues with unit anchoring, drive train design and layout, efficiencies and performance limitations.

It is obvious, however, that only really large missions, capable of supporting and delivering large payloads, massing tonnes, and heavy power sources, such as might be found on a Human Exploration and Development of Space (HEDS) mission, could afford the delivery cost of large pieces of mining equipment.

4.5 Autonomy

Mining equipment development is presently focussing on development of technologies to assist operators using tele-operations technologies. Drilling systems have been developed to intervene in an operator's decision making process and remove from them decisions deemed critical to hole accuracy and equipment longevity. A number of manufacturers have developed semi-autonomous systems designed to relieve a human operator of tedious and operationally critical tasks. This has resulted in achievements such as drift development jumbo drills auto drilling face rounds, In The Hole (ITH) drills auto drilling blast holes, exploration diamond drills auto tripping rods, scoops auto hauling from load outs to dumps, etc. In each of these developments, there is still a necessity for an operator to intervene, whether it is to set up the drill on a new hole and attach support equipment like water and power lines, or whether it is to intervene in the bucket filling process of an LHD.

There appears to be a divergence in philosophy between planetary mining and terrestrial mining, centred on the issue of autonomy. Terrestrial mining is focussed on tele-operation and some level of semi-autonomy, where-as, it is clear, that planetary mining equipment must embrace a higher level of autonomy. The main consideration here is the time lag issue, as experienced with the Martian Rover, but also extends to problem and error corrections. Some examples of such issues would include core tube blockage and wedging due to ground fractures, bit polishing and in-situ re-sharpening, drill system set up and target identification, core tube recovery, face round drilling limits, bucket filling success, etc.

Each of these is presently a form of operator and human intervention. Some are handled by direct human action, such as the attachment of water and power to a piece of equipment, others can be handled via tele-operation, such as bucket filling and core tube blocking. Autonomy of these types of tasks must be greatly improved to allow timely completion of the mining activity on a planetary body, even given the extended duration of the mining operation.

5 Sub-Surface Access

Drilling technologies, and core sample drilling in specific, are the focus of NORCAT's efforts at this time, in terms of sub-surface access equipment.

5.1 Drilling and Core Sampling

The CSEW2, sponsored by the Canadian Space Agency in Calgary in 1999, identified a number of potential scientific investigations that could take place on small planetary bodies using such a drill. Suggestions included: beacon implant on NEO's for hazard mitigation, transponder implant on NEO's for rotational dynamics studies, and seismic surveys on small planetary bodies using seismic sensor implants. [4]

NASA's Human Exploration and Development of Space realizes the need for sub-surface sampling and drilling [3]. Follow The Water [2] mandate is key to the search for life and for ISRU in support of human exploration missions.

The project is an enabling technology for planetary exploration, either robotic or manned. The timing of the project, as well as the "follow the water" and in-situ resource utilization mandates for space exploration beyond Highly Elliptic Earth Orbit (HEEO) [5], would make this technology an ideal candidate for an upcoming Mars exploration mission, such as Mars Scouts, planned for 2007. LANL, under contract to NASA has identified diamond core drilling as one of the short listed technologies for its Mars Deep Drilling program 200 metre class drill [6], [9]

The Northern Centre for Advanced Technology Inc. has embarked upon a process to develop an all-electric sub surface sampling drill capable of coring to a depth of greater than 10 metres on a planetary body with an end target of 100 metres.

Previous workshops and conferences hosted by NASA and Lunar and Planetary Institute [1], [2] have established minimum useable sample sizes as well as operational specifications for a sub surface sampling device. These operational specifications call for the drill to be capable of propagating and stabilizing a hole to between 2 and 200 metres (200 metre class) and actively extract core samples. The environment is Mars [6] and so the unit must operate at .37G, 10 Torr Atmospheric, and average temperature of 200K.

In addition, power consumption must average 1000 watts and drilling must proceed without lubrication fluids.

Parameter	Value	Units
System Mass	150	Kg
Power Available	1000	Watt
Total Energy Available	8700	Kw-hr
Hole Depth	100	Metre
Hole Diameter	20	Mm
Core Diameter	10	Mm
Rotation Torque (stall)	500	Nm
Rotation Velocity	200	Rpm
Axial Thrust at Bit	8000	Newton
Axial ROP	10	Mm/min

Table2: Operating Parameters
Mars 200 m Class Drill

These specifications were derived from work performed by Los Alamos National Labs and NASA's Mars Deep Drilling program. Note the total energy available. This is due to the long "mining season" available, given a continuous solar powered supply of 1000 watts. Standard "A size" terrestrial diamond drills consume much higher instantaneous power and consequently comminute the rock at much higher rates.

Table 3 below lists some typical "A" size diamond core drill performance specifications. [15]

Parameter	Value	Units
System Mass	5000	Kg
Power Available	45000	Watt
Total Energy Consumed	1800	Kw-hr
Hole Depth	600	Metre
Hole Diameter	48	Mm
Core Diameter	27	Mm
Rotation Torque (stall)	1750	Nm
Rotation Velocity	1300	Rpm
Axial Thrust at Bit	35500	Newton
Axial ROP	250	Mm/min

Table 3: Typical Operating Specifications
Electro-hydraulic Diamond Coring Unit

Note the value for Total Energy Consumed is considered the worst case power requirement for coring to depth in typical hard rock (30,000 psi). Control algorithms limit the Rate of Penetration (ROP), preventing excessive comminuting rates and the associated problems, such as binding, bit run out, and impact damage on slips or structures during drilling. Optimization of the ROP reduces "dead time", the time required for a terrestrial drill operator to complete a hole, as time is literally money in the industry.

Utilizing the five steps to adaptation identified above, NORCAT determined five technology developments [8] critical to the realization of such a device:

1) Electric core drilling,
2) Anchoring/stabilization,
3) Rod and core handling,
4) Dry drilling, and
5) System autonomy.

The project presently encompasses three years of activity. Year one will commence with the construction of an all-electric drill incorporating tele-operations of the drilling process, set-up and anchoring, and the rod and core sample handling. Technology development will focus on the system integration and electric control of the necessary motions. Year two efforts will be to improve system autonomy and move the unit to a semi-autonomous mode for the set up functions, drilling controls, including block recovery, ground changes, etc, and core handling to 10 metres. Year three will move the system to a more fully autonomous level, with only set up being left as semi-autonomous.

5.1.1 Electric core drilling

A prototype electric drill has been constructed and set up in the drill test lab at NORCAT. Fig 2 is a digital photo of the unit on a simulated background of hard rock.

The unit masses approximately 50 kg and draws a nominal 1200 watts free wheeling at an approximate 150 rpm with peaks to 3000 watts. It is undergoing actual drill testing.

The rotation motor is a redesign and reconfiguration based on servo motor technology. The casing was reworked and the drive coils reset to lighten the unit from its factory weight of approximately 40 kg. Efficiency was lost, but delivered torque is still within acceptable limits. The drive train is a worm and bull gear reduction unit, specially designed for this application based on locomotive drive train technology. Control was originally a Commercial Off the Shelf (COTS)

Fig.2: Prototype Planetary Drill
Electric Vehicle Controllers Ltd.

motion controller, but that has since been reconfigured to include some proprietary PLC programs based upon locomotive load sharing programs developed for one of the partners in the development (Electric Vehicle Controllers Ltd.)

Linear thrust is a custom feed screw driven by a high speed servo motor and planetary gearing system. Axes interlinks are established through proprietary PLC programming using modified versions of PID control loops and simple servo control algorithms. The linear feed system is capable of both controlled feeds and fast tripping for rod handling.

Drive coupling to the drill string is via a dog bone arrangement for linear feed and a slip coupling for rotation. Electric rod clamping is yet to be installed for both head and foot clamping functions, a necessity for rod handling.

5.1.2 Anchoring/stabilization

The system is expected to utilize a primary and secondary anchoring mechanism. A secondary anchor mechanism has been developed by one of the partners in the effort, DMC Drilling Supplies Ltd. that will allow terrestrial diamond drills to eliminate manual drill anchoring. The system is purely mechanical, rides behind the drill bit, and will self deploy during hole collaring operations. (see Fig 3.)

This technique uses very low thrust and rpm to propagate a hole to stable ground, whereupon the anchor deploys and mechanically swages into the heavier ground, at which point it should then provide a stable anchor capable of absorbing the thrust and torque generated during drilling.

Fig.3: Prototype Secondary Anchor
DMC Drilling Supplies

A primary anchor system is required to complement the secondary system during secondary deployment on milli-gravity bodies. It is not in the project plan at this stage, as it is felt the electric drill will have sufficient mass on Mars to resist the forces encountered during deployment of the secondary anchor.

5.1.3 Rod and core handling

Rod handling algorithms are reasonably well understood in the mining industry and have been in use for some time, notably on In The Hole (ITH) drills like MTI's CD360M. The effort will be to adapt the system to an all electric framework and to ensure sufficient drill rod storage capability to complete the projected hole.

Core handling is different in that it has traditionally been a manual function. New techniques are in development for sizes "A" and "B" drilling units that increase the level of automation in the core handling. The challenge here is to electrify the process and design the mechanics of the drilling system secondary to core retrieval and handling. This is something that terrestrial manufacturers appear reluctant to do.

In both rod and core handling, the motion control algorithms are readily available and will be implemented as a slaved intermediate layer controller to the system controller.

5.1.4 Dry drilling

A separate project is underway to research and develop a drill bit capable of drilling in Mars conditions without the benefit of lubricating fluids like water and oils. The bit is required to survive a minimum of 200 metres but a target has been set of 600 metres. Research is just beginning with funding by the Materials Manufacturing Ontario Centre of Excellence.

In complement to this project, technology development of the drill rods must include a method of balings removal from the hole without using volatiles for flushing.

5.1.5 System autonomy

The first stage will be to incorporate the individual electric functions in a tele-operated test bed. A standard mining grade tele-operations unit will be used to develop a tele-operation methodology for the drill. Radio system components will utilize spread spectrum technology using low power rf components referred to as Extended Line Of Sight (ELOS) control providing approximately 500 feet of "around the corner" remote control.

The system developed in year one will act as the base for development work in year two. Drilling control algorithms will be enhanced to include core tube blockage recovery, bit sharpening, and mud slip detection in a semi autonomous mode.

Preliminary results from the dry drilling development project should be available during this year, and, if possible, would be integrated into the drilling algorithms. It is anticipated these results would have some relevant impact on the drilling algorithms. Physical Planetology issues, such as rock/ground changes would be evaluated using field test data obtained during this phase of the development project and incorporated into the controlling algorithms. Semi-autonomy would be achieved at a level within which some operator intervention would be required to ensure adequate recovery from some drilling problems, such as severe core tube blockage, or water swivel failure, etc.

Rod handling algorithms will be developed or modified from the Year one technologies to allow semi autonomous drilling off the rod pack (carousel) via autonomous rod make/break cycles. Since the drilling may initially be wet, water connection algorithms and mechanics will need to be addressed. Rod handling controls would be advanced in concert with the overall system development and in accordance with mechanical system development.

Core handling controls would be advanced in concert with the overall system development and in accordance with mechanical system development. Core handling algorithms would be developed that would allow the recovery of the core sample with a minimum of operator intervention. Wireline systems would be replaced with a core tube handling system that could better facilitate the development of semi autonomous core sample handling.

System set up and anchoring function enhancements will focus on the issues of anchoring on a planetary body having less than 1 gravity. The intent is to develop an anchoring process capable of stabilizing the drill in .3 G or less. This may require the development of a side shift capability for set up. More specifically, year two efforts would entail the development of semi-autonomous set-up dip and angle algorithms with the inclusion of perhaps some sideshift capability, to facilitate anchor deployment.

Significant systems modeling would be performed to enhance the reliability and reduce or eliminate operator intervention during drilling cycles. Control algorithms would develop into an integrated system solution. Results from the dry drilling research program would be incorporated into the drilling components, as would the results of the testing phase of year two efforts. It is anticipated that there will be some mechanical reconfiguration to the base structure of the unit as these results are incorporated.

Rod handling algorithms, developed in year two would be integrated into the overall system and the level of autonomy would be enhanced to reduce or eliminate operator intervention. Mechanical and control components of both the rod and core handling systems would be integrated to facilitate the incorporation of the dry drilling technology.

6 Conclusion

The Northern Centre for Advanced Technologies Inc., a private not for profit corporation located in Sudbury, Ontario, has embarked upon a course of technology development focusing on the adaptation of terrestrial mining equipment to planetary In Situ Resource Utilization. NORCAT believes that the development cycle for technologies for accessing and harvesting the In Situ Resources can be shortened by careful adaptation of existing mining equipment.

NORCAT has developed a “critical path” for the adaptation of such technologies based upon its experience with the development of a 200 metre class Mars sample drill.

The sample drill is in its initial development stages and work is progressing towards a unit capable of drilling a sample hole on Mars to a depth of 10 metres with follow on work expected to achieve 100 metres. The drill unit will extract core samples and leave, in place, a conduit for later sampling or commodity extraction.

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