Concept for Self-Indexing Lockable Drill Rod Segments and their Auxiliary and Storage Mechanism

Julien Marcil
Patrick Sabbag and Jean-Philippe Nolet
Department of Mechanical Engineering
McGill University
Montreal, Canada
julmar@cim.mcgill.ca

Abstract

The design of a self-indexing lockable drill rod segment and its auxiliary and storage mechanism is the focus of this paper. This project is subdivided into 3 parts: the drill rod segment, the auxiliary mechanism, and the drill rod storage mechanism. This system is to be integrated into a Mars rover for the exploration of the Martian soil. The short drill rod segments have locking mechanisms inside them, allowing them to lock to each other to form a drill string measuring 2 meters in length. When not in use drilling, these rods are stored in a storage mechanism. An auxiliary mechanism takes the drill rod segments from storage and transports them to the deployed drill string and vice versa. The auxiliary mechanism is a three degree-of-freedom manipulator. The system has a total of five degrees-of-freedom: four active, the auxiliary mechanism has three and the storage mechanism one, and one passive located in the drill rod segment activated by the auxiliary mechanism.

1 Introduction

One of the next crucial steps in the exploration of Mars is the analysis of the Martian soil located some meters deep for signs of past or present life. To accomplish this feat, a drilling and sample acquisition mechanism that can be integrated into a mars rover must be developed.

MD Robotics, which is developing such a device for the 2009 Mars SmartLander program, presented us with the task of designing and building a prototype [1]. The project was divided into two: the sample acquisition mechanism, and the drill rod segments and its auxiliary and storage mechanism. We were responsible for the second part of the project.

Drill rod segments that are assembled to form long drill strings are found in mining and many different arrangements allow rods to lock to each other [2]. MD Robotics is currently working with partners Norcat and EVC, both involved in mining, to develop such a device [3]. Mechanisms that can manipulate such drill rod segments are abundantly found in Computer Numerical Control (CNC) machines but are generally pneumatic which is not desirable for a mission to mars [4]. Furthermore, they are both generally not restrained by size requirements. The difficulty of the project arises in the volume allocated to such devices.

As it is impractical to carry a drill rod exceeding a couple decimeters in length, a system composed of several short drill rod segments that can be attached and detached remotely must be designed.

These rods must be stored into a compact package, since they will be located on the rover. The rods must also incorporate an interface allowing them to lock and unlock from each other, and transmit the necessary torque and thrust entailed in such a drilling operation.

In conjunction with MD Robotics, we have designed and built a prototype of the drill rod segments, the auxiliary mechanism that manipulates the rods, as well as the rod storage mechanism. Our design does not include the mechanism responsible for drilling.

The objectives of this project were to develop and test a robust system capable of assembling a 2-meter long drill string, and storing its segments compactly.

2 Problem Definition

With our client from MD Robotics, the requirements for the project were defined. The system was divided into three main sub-components: the rod segments, the auxiliary mechanism, which manipulates the rod segments, and the drill rod storage mechanism. It was initially unclear whether the auxiliary mechanism and the storage mechanism would consist of two separate mechanisms. The definition of the problem, and its possible solutions, evolved with the project.

The project requirements are as follows. The entire system must have a maximum height of 40 cm, length of 45 cm, and width of 40 cm, to fit into the envelope allocated to it within the rover. The system must contain the means of actuation and sensing. Total power consumption must not exceed an average of 10W per cycle, excluding the drilling itself, and a peak of 20W is allowed for a maximum duration of 20 seconds. The entire device must be activated and controlled autonomously. The design must be done with space-rated material; however, standard commercially available materials can be used for the construction of the prototype.

The principle drill rod requirement is that the outer diameter of the rod segments cannot exceed 20 mm excluding the helicoids used to remove soil. The length of the drill string must be of 2 m. The rod segments and their respective interfaces must transmit 2.5 Nm of torque and 500 N of thrust. The drill rod interfaces must allow remote attachment and detachment. The drill rod interfaces must also transmit eight electrical signals.

The auxiliary mechanism must acquire, move, attach, and detach the individual rod segments, while the storage mechanism must constrain the movement of the drill rods when in storage.

3 Design process

When approaching a project of this magnitude, it is important to break it down into sub-problems, which can be surmounted in a sequential manner. As previously mentioned, the project was divided into three main parts: the drill rod segments, the auxiliary mechanism, and the storage mechanism. The design of this system does not allow the three sub-components to be developed independently and joined when finished. Thus, they must be developed in parallel.

An important issue was whether the rods would lock together with a purely linear motion or with a rotary motion. This characteristic dictates the design of the drill rod interfaces and the motion required from the auxiliary mechanism. Furthermore, the auxiliary mechanism motion dictates the motion required from the storage mechanism as the auxiliary mechanism must acquire the rod segments from the storage mechanism. We therefore addressed the locking motion issue first.

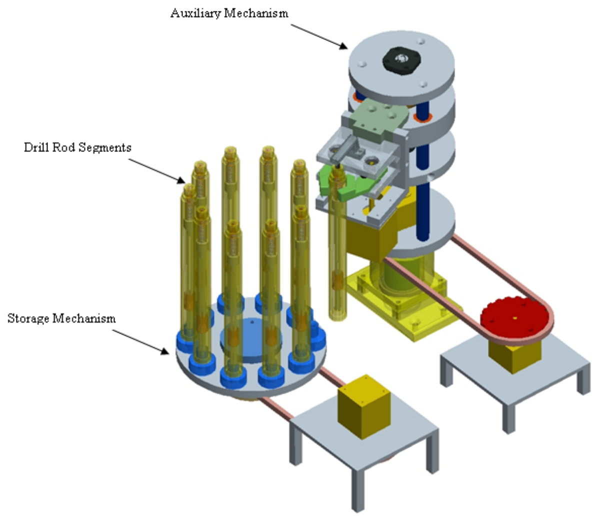
Devices using two threaded surfaces to lock together are most frequently seen of the two. These devices require a rotary motion for locking. Such a design could be implemented on the rod segments. The joining parts would be screwed together with a certain preload. In our particular application the preloaded would have to be higher than 2.5 Nm, so that when the drill string is run in reverse to bring it up, and an external load of 2.5 Nm is present, the segments do not unscrew and detach from each other.

Locking mechanisms that require pure linear motion are also common. In our case however, such a device is restraint to operate in an area with a diameter smaller than 20 mm.

The two options were studied and it was found that a linear locking mechanism in the rods would render a simpler auxiliary mechanism. MD Robotics also showed greater interest in the development of a linearly locking drill rod segment, as they were more familiar with rotary locking drill rod segments and wanted linear locking drill rod segments concepts to be explored. With such a design, the auxiliary mechanism would only need to move the rods vertically and horizontally, eliminating a degree-of-freedom.

With the knowledge of the motion required for the locking of the drill rod segments, it was possible to proceed with the design. The design of the drill rod segments is first examined, followed with that of the auxiliary mechanism and finally that of the storage mechanism.

3.1 DRIAM Architecture



(a)

(b)

Figure 3.1.1: Driam project (a) model; (b) prototype

3.2 Rod Segments:

Figure 3.2.1: Rod segment model

A drill string measuring 2 meters in length, capable of transmitting eight electrical signals, is required to sample the Martian soil. To accomplish this, it was decided that 10 drill rod segments measuring 20 mm each are to be assembled to form the 2-meter long drill string. The shorter the drill segments, the higher the amount necessary to form the 2 meter drill string. Consequentially, the time and energy requirements also increase with an increase in number of segments.

The body of each 20 mm rod must be able to withstand 500 N of thrust and 2.5 Nm of torque. The axial load is applied in two instances; when drilling down into the Martian surface, and when drilling out of the Martian earth. Therefore the 500 N is transmitted through the rod body when drilled down, and through the locking mechanism when pulling the rod string out of the Martian surface. Two simple stress analyses were done to ensure that these requirements were satisfied.

The mechanism inside the rods responsible for the locking and unlocking is similar to a collet as seen in figure 3.2.2 and will therefore be called a collet in this project. The collet is collapsed when an axial load is applied to the unlocking mechanism releasing the rod segment from the drill string or from the storage mechanism, since the rods attach to each other in the same manner as they attach to the storage mechanism (figure 3.2.3). When the force is removed, a spring pushes the slider back up, allowing the collet to expand and lock the rods together as seen in figure 3.2.4.

(a)

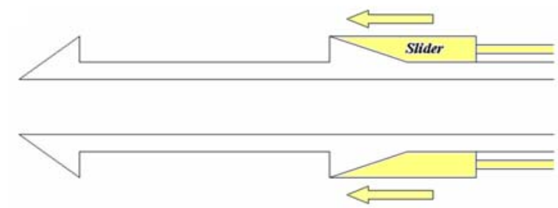


Figure 3.2.3: Rod slider collapsing collet

(b)

Figure 3.2.2: Rod locking mechanism (a) prototype; (b) model

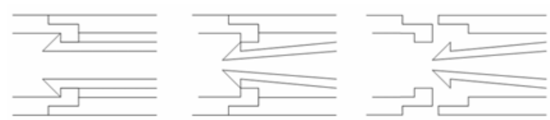
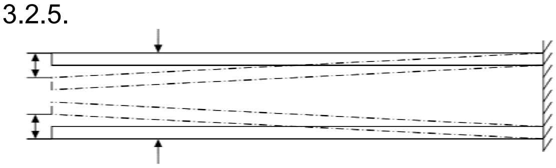


Figure 3.2.4: Rod unlocking when collet collapsed

To calculate the necessary force required to collapse the collet, the locking mechanism is modeled as a combination of two cantilevered beams, as seen in figure 3.2.5.

(a)

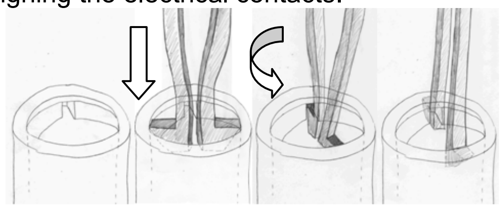


(b)

Figure 3.2.5: (a) Collet (b) collet modeled as cantilevered beam

The drill rods will need the capability to transmit electrical signals down to the acquisition mechanism at the end of the drill string. An electrical interface, transmitting these signals, requires precise radial positioning. The rod segments must therefore have the ability to self-index since electrical contacts on the drill rod interfaces need to align when rods are connected. A rod must position itself into proper orientation without rotational motion from the auxiliary mechanism since it was established that the rods would lock together without such motion to keep the auxiliary mechanism simple. This is achieved with the self-indexing characteristic of the rod segments depicted in figure 3.2.6.

As can be seen, the collet collapses when the rod is inserted into another drill segment no matter its radial orientation. The rods are partly locked when initially inserted; their movement in the axial direction is restricted, but they are still free to rotate. This is due to the fact that the collet partially expands. The collet only fully expands and therefore locks into radial position when rotated, aligning the rod segments into there desired orientation, aligning the electrical contacts.

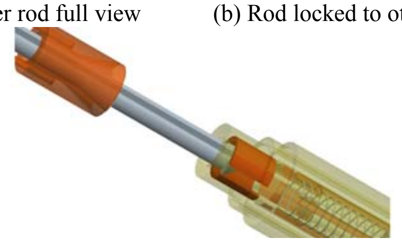


(a) (b) (c) (d)
Figure 3.2.6: Rod segment self-indexing:
(a) rod; (b) collet inserted; (c) in position; (d) expanded and locked

The rotation of the rod would be exerted by the same mechanism responsible for the drilling. A controller monitoring the applied torque will see a sharp increase when the collet expands into position fully locking the rods together signaling that the electrical contacts are aligned. At this point, the newly connected segment would be ready for drilling.

(a) Rod locked to other rod full view

(b) Rod locked to other rod close-up view



(c) Rod locked to other rod partly exploded view
Figure 3.2.7

The collet, when expanded into position as seen in figure 3.2.6 (d), transmits the torque from rod segment to rod segment. The collet therefore serves three purposes; the self-indexing and locking of the rods, and the transmission of torque. The design element that ensures that the torque can be transmitted without failure is represented in blue on the figure 3.2.8.

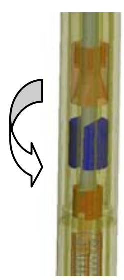
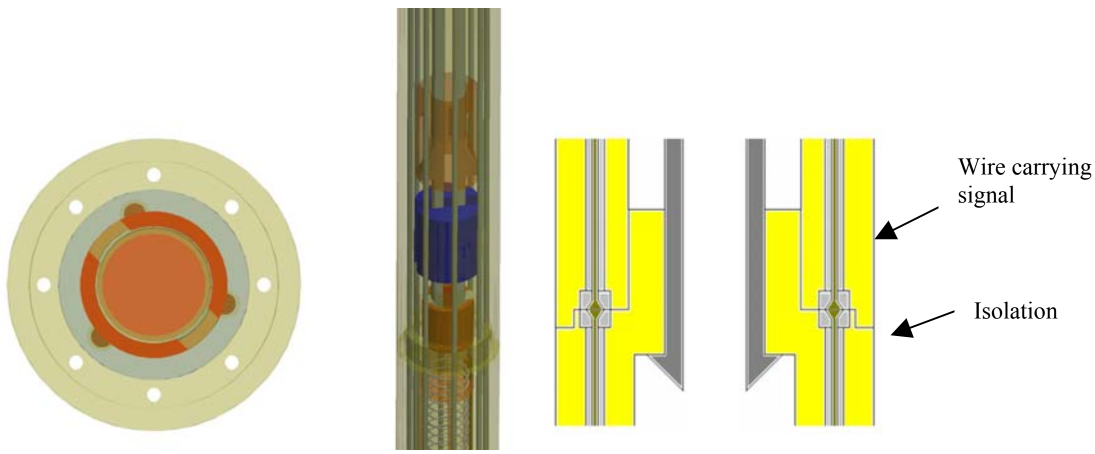


Figure 3.2.8: Torque transmission

If this element was not present the rod locking mechanism, as seen in figure 3.2.2, would alone be loaded when transmitting the torque. Since the collet was designed to easily collapse, it has a considerable length measuring 150 mm. This length greatly lowers the amount of torque it can sustain without failing. It was therefore necessary to introduce a feature to the rod that would transfer the load to the body of the rod, and do that near the point of contact between the rods.

The rods can lock together and align themselves into a given orientation; they can therefore transmit an electrical signal through isolated conducting surfaces. This is the concept used in this design. When the rods are aligned, the holes carrying the wires are therefore also aligned. At each end of the rod, the wire is connected to an isolated electrical contact surface as seen in figure 3.2.9, allowing eight signals to be passed down through the rods when connected.



(a) Top view of rod (b) Connected rods with visible wires (c) Representation of electrical interface
Figure 3.2.9: Electrical interface

3.3 Auxiliary Mechanism:

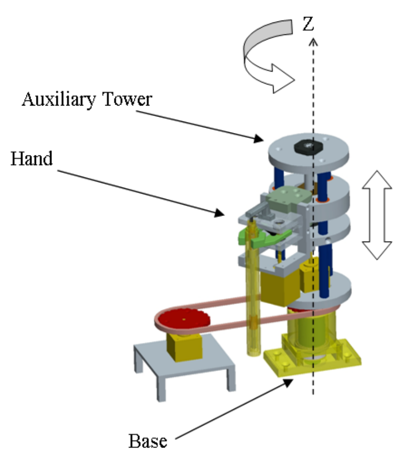


Figure 3.3.1: Auxiliary mechanism model

The auxiliary mechanism is a three degree-of-freedom manipulator. The hand, which grips the rods, can move vertically and horizontally around its axis as seen in figure 3.3.1. The auxiliary mechanism includes three sub-components: the auxiliary tower, the hand, and the base.

3.3.1 Auxiliary Mechanism Hand

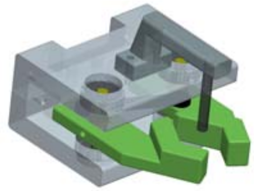


Figure 3.3.1.1: Auxiliary mechanism hand

The hand of the auxiliary mechanism [5] is responsible for the acquisition of the drill rod segments; it must unlock the rod segments and securely grip them.

As discussed in section 3.2, a vertical force is required to unlock the drill rod segment from the drill rod string or the storage mechanism. This force is applied by the pin attached to the hand assembly as seen below (figure 3.3.1.2). The pin pushes down on the unlocking mechanism, sliding the slider down the collet, collapsing it, and consequently unlocking the rod.

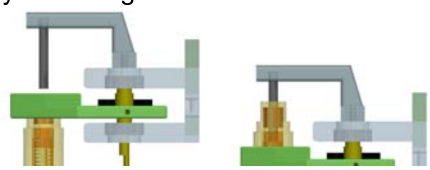
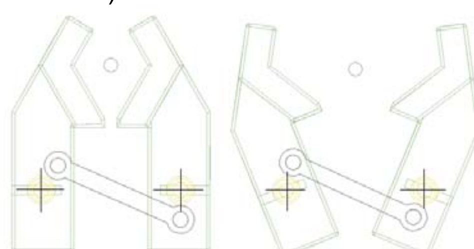


Figure 3.3.1.2: Hand pin unlocking rod segment

The hand grips the rod in a fashion similar to that in which a human would do so with his fingers. The desired motion for the two fingers of the auxiliary mechanism's hand is achieved with a four bar mechanism as seen below (figure 3.3.1.3).



(a) (b)

Figure 3.3.1.3: 4-bar mechanism in (a) close hand position and (b) open hand position

The two fingers are driven by a unique motor located directly below the first finger's axis of rotation. The force is transmitted to the second finger via the link coupling them. The torque requirement for the motor was found assuming the friction factor between the rod and the finger was 0.9, corresponding to the friction factor between aluminum and rubber. Rubber will be placed on the areas of contact of the fingers.

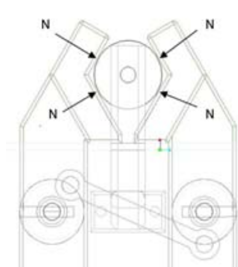


Figure 3.3.1.4: Force applied to rod through 4-bar linkage

3.3.2 Auxiliary Mechanism Base

The auxiliary mechanism base supports the weight of the auxiliary mechanism and the load produced when a rod is picked up. The base is composed of two radial bearings and one thrust bearing.

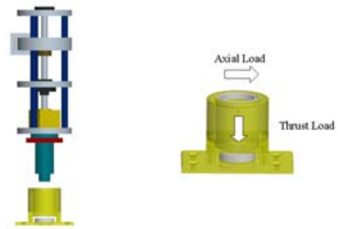


Figure 3.3.2.1: Auxiliary mechanism base

3.3.3 Auxiliary Mechanism Tower

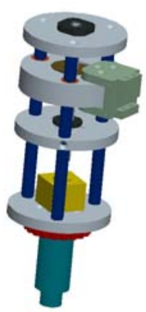


Figure 3.3.3.1: Auxiliary mechanism tower

The auxiliary mechanism tower was designed to hold two main components; the motor to drive the ball screw, and the ball screw assembly itself. It is also designed to rotate in its base, giving it its second degree of freedom. The ball screw assembly lifts and lowers the hand while a sprocket and belt assembly rotates the entire tower.

The mass to be vertically lifted and lowered is roughly 5 kg. The mechanical advantage of a ball screw is therefore used to move this mass. The shoulder, the component directly attached to the ball screw nut, slides along three guides. To minimize friction, linear ball bearings are used between the shoulder and the hardened steel guides.

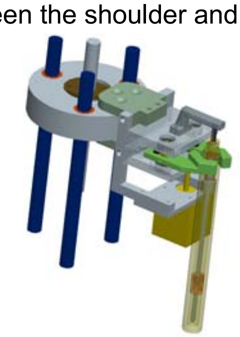


Figure 3.3.3.2: Ball screw and guide

3.4 Storage Mechanism

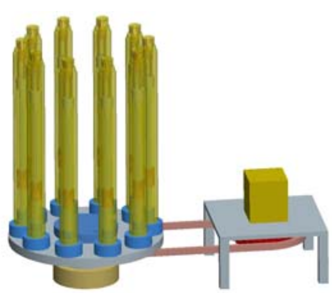


Figure 3.4.1: Storage mechanism

The storage mechanism must simply bring the drill rod segments to a predetermined position in which they are to be picked up by the auxiliary mechanism. The storage mechanism must move in increments of 36 degrees as there are 10 equally placed drill rod segments locked to the storage mechanism. This is easily accomplished with a sprocket and belt assembly driven by a stepper motor with a 1.8 degree step angle as seen in figure 3.4.1. 20 steps will move the storage plate by exactly 36 degrees since a one to one gear ratio is used.

The feature of the storage mechanism that is of interest is the clip on which the rods lock themselves, as seen on figure 3.4.2. This clip is almost identical to the top of a drill rod segment; the rods therefore lock to the storage mechanism in the same way that the rods lock to each other. The difference is that there are no slits in the clip as there are in the top of a rod segment that allow the collet to fully expand in only one orientation. The rod can therefore lock itself to the clip in any orientation, but will be free to rotate.

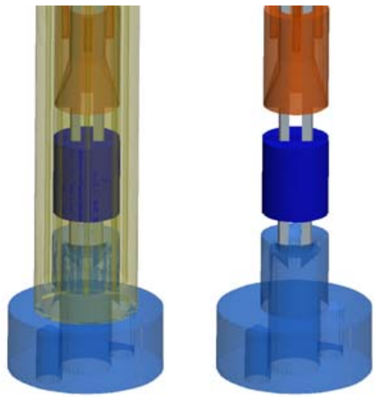


Figure 3.4.2: Rod locked to storage clip

3.5 Driam Layout

The layout of the sub-components of our project will enable them to work together as intended. The most important aspect of the layout is the distance between the axis of rotation of the auxiliary mechanism and that of the storage magazine's plate. The arm of the auxiliary mechanism, the rod to be picked up, and the axis of rotation of the storage mechanism do not form a 180^0 angle when the hand is in position to grip a rod. If the layout was in this manner, the rod being gripped by the hand would hit the next rod waiting to be moved into position to be picked up as seen in the figure below.

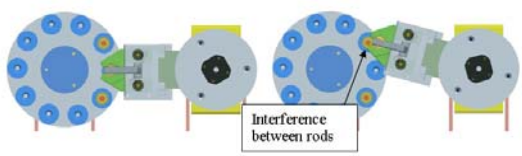


Figure 3.5.1: Improper layout causing interference

Instead, they are arranged with a 165^0 angle between them as seen in figure 3.5.2. This allows room for the rod to pass with no interference.

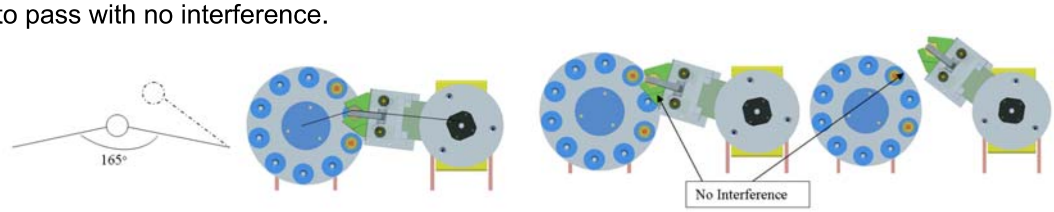


Figure 3.5.2: Proper Driam layout, no interference

Once the positions in which the auxiliary mechanism and the storage mechanism must be in for the pick up of a rod are known, they can easily be implemented through the programming of the controller.

4 Controller Architecture

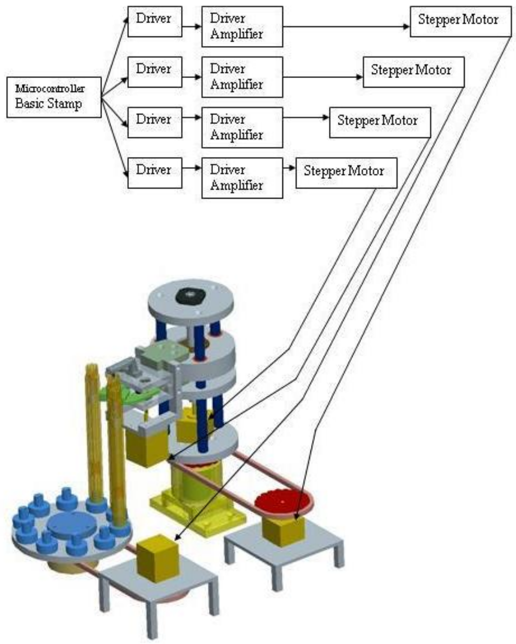


Figure 4.1: Control information diagram

The system has four active degrees of freedom, each controlled by a stepper motor. The commands that control our stepper motors are generated by a microcontroller (basic stamp II), sent to motor drivers, then sent to motor driver amplifiers, and finally received by the stepper motors.

The motors are supplied by 5 volts and draw 1 amp; the system is therefore never exceeding the 10 Watt limit since only one motor turns at any given time drawing 5 Watts.

5 Conclusions

The initial decision that was taken to have a linearly activated locking and unlocking mechanism transferred the complexity from the auxiliary mechanism to the rod segment's locking mechanism. A rotationally engaged locking mechanism would have brought more complexity to the auxiliary mechanism, however potentially greatly reducing that of the drill rod locking mechanism. This could be advantageous since there is considerably less volume constraints imposed on the auxiliary mechanism.

The drill rods are the most complex elements of the system. They consist of a rod inside of which a spring and collet assembly is used to lock onto an adjacent rod or the storage plate. The rods are complex because of their size limitation. It was found that they can easily sustain a load of 500 N and a torque of 2.5 Nm. Therefore, a recommendation would be to increase the inner diameter of the rods in order to increase the interior volume, allocating more room for the locking and unlocking mechanism.

The auxiliary mechanism's difficulties arise from the potential alignment problems encountered with such designs. To avoid such problems, extreme precision must be applied when machining its parts. The storage mechanism consists of a simple design allowing for easy manufacturing and high reliability. Its capacity to hold the rods while on its voyage from the earth to the red planet must however be examined.

The controls can and will be done by a different controller than a microcontroller used in the prototype when such a device is integrated into a rover. The rover's embedded controller will be in command of this sub-component of the rover.

6 Acknowledgements

Dr. Alexei Morozov, our advisor, guided us through the project with many meetings and helpful suggestions. Professor Jorge Angeles also helped us on key issues, such as the hand design. Our client, Howard Jones, helped clarify the task, while the team at McGill's Mechanical Engineering Machine Shop helped us tremendously with the machining ensuring that we would have a working prototype for the presentation.

7 References

[1] http://www.mdrobotics.ca/wwdframe.html

[2] Australian Drilling Industry Training Committee Limited (1997), Drilling: the manual of methods, applications, and management, 4th edition, Boca Raton, Fla., CRC Press.

[3] http://www.norcat.org/

[4] Crandell, Thomas M. (2003), CNC Machining and Programming: An Introduction, Second edition, New York, Industrial Press.

[5] Duditu, F. L., Diaconescu, D. and Gogu, Gr. (1989), Mecanisme Articulate. Inventica Cinematica, Editura Technica, Bucharest.