Development of a Sampling System for the Axel Rover

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Abstract

Axel is a tethered lightweight rover with minimal complexity designed to access and sample the insides of crater walls. Currently, Axel has the capability to sample soil at slopes of 10°-40°. We seek to design a sampling mechanism that would allow Axel to sample rocks through drilling as well as extend its sampling range to any slope. Testing has been done to compare a novel ultrasonic drill (USDC) and a commercial rotary-percussive drill while sampling a near-vertical slope. Results suggest the rotary-percussive drill is less complex, more robust, more cost-efficient, capable of penetrating harder rocks, and less prone to overheating. A sampling system using a commercial rotary-percussive drill has been designed. Remaining work includes the installation and testing of this sampling system.

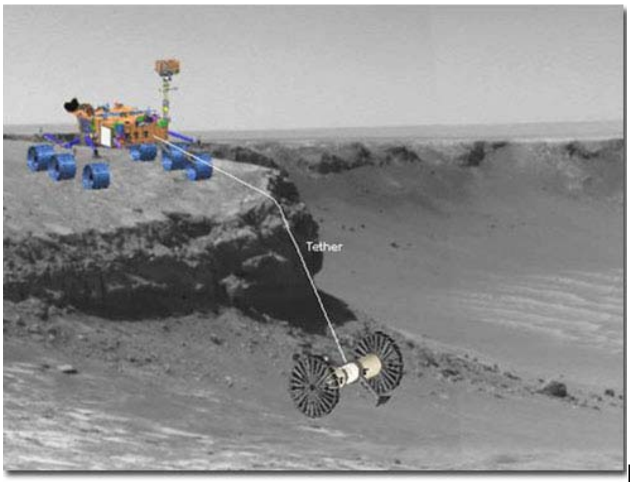
1 Introduction

1.1 Background

Interest in exploring conventionally inaccessible areas, such as Martian crater walls, has motivated the design of the Axel rover. Axel is a tethered, lightweight, minimalist rover with a symmetrical design that uses three actuators to maneuver. Axel utilizes an actuated caster arm to help ascend and descend slopes up to 90°. With the mounted sampling device, Axel can collect soil samples from slopes of 10°-40°.[1] See Figure 1 for a possible mission concept involving the Axel rover.

1.2 Problem

The current sampling device is a primitive scooping mechanism that relies on the actuated caster arm to scoop up soil. However, we desire a sampling mechanism that can sample rocks as well as soil. Ideally, Axel should be able to sample on steep slopes (approaching 90°) as well, where the caster arm cannot be effectively actuated for scooping. Moreover, possible destinations for Axel are the moon and Mars, so the sampling mechanism must rely on relatively low reaction force. This design constraint will compete with the need for a lightweight rover.



[1]

Figure 1: Axel Mission Concept (not to scale)

1.3 Possible Solutions

We considered two existing technologies that sample rocks: conventional rotary-percussive drills and the novel ultrasonic-sonic driller/corer (USDC). Rotary-percussive drills generally use a cam to couple rotation and hammering motion. The USDC was developed at JPL and uses a piezoelectric stack to actuate ultrasonic vibrations. These vibrations are transformed into sonic vibrations by a free mass that impacts a drill bit. To determine whether Axel could sample from a near-vertical slope, and which technology could effectively be implemented on the rover, the following experiment was conducted.

2 Methods

2.1 Setup

The general experimental setup can be seen in Figure 2. The setup imitates a tethered rover on a steep cliff face. To provide reaction force, two parameters can be adjusted: the tethered weight and the angle to the vertical. The following variables were varied for a comprehensive comparison:

1. Drilling option (rotary-percussive vs. USDC)
2. Reaction force
3. Power usage
4. Drill time
5. Rock type

Figure 2: Experimental setup: the USDC is drilling into kaolinite

Rock Type	Compressive Strength (MPa)
Kaolinite	2
Limestone	20
Breccia	19-35
Saddleback Basalt	117

Table 1: Comparison of rock types

Rock types were selected based on their compressive strength, with saddleback basalt taken as an approximate upper bound of rock hardness to be found on Mars or the moon. See Table 1 for a comparison. See Figure 3 for the rocks used.

2.2 Procedure

The USDC was actuated by a function generator coupled with an amplifier (due to the high voltage requirement, up to 140V). Due to overheating, the USDC could not be continuously operated for more than one minute for soft rocks. Drilling into breccia was done with 20s runs alternating with 20s breaks.

The rotary-percussive drill was generally operated in percussive mode for 4-6 minutes to create an indentation. This prevented the drill bit from slipping out of its hole. It was then placed in rotary-percussive mode and operated 2 minutes at a time with 2-3 minute breaks.

Figure 3: Clockwise from top left: kaolinite, limestone, breccia, saddleback basalt

3 Results

3.1 USDC

The results for the USDC trials are in Table 2. As expected, drill rate declines as compressive strength increases. Saddleback basalt was not drilled because it was too hard for the drill and bit assembly. The missing trial numbers refer to trials done by measuring RMS current rather than average current.

Breccia trial 1 was done to investigate how quickly USDC performance degrades as the drill bit penetrates a rock. After 6-7 minutes of a drill/rest cycle, performance severely degraded. Several reasons may explain the decay in performance:

1. Breccia consists of minerals of varying compressive strength so the drill bit may have encountered harder minerals deeper in the rock.
2. The USDC operates efficiently within a narrow band of its natural frequency, which changes even while drilling. Even small deviations can result in tremendous decay of performance.

3.2 Rotary-percussive

The results for the rotary-percussive drill are in Figure 4. The rotary percussive drill easily drilled into soft rocks like kaolinite and limestone, so, due to time

Rock Type	Trial	Reaction Force (N)	Power (W)	Drill Rate (mm/min)
Kaolinite	1	11	33	9.4
	2	11	33	6.9
Limestone	4	11	35	3.4
	5	11	22	1.8
Breccia	1a	11	17	1.0
	1b	11	15	0.8
	1c	11	18	0.04
	2	14	28	1.2

Table 2: USDC performance

constraints, detailed trials were only run on breccia. Trials were also run on saddleback basalt, which the drill successfully penetrated.

Note that the drill required higher power (50W) and reaction force (20N) in exchange for more robust performance. The rotary-percussive drill sustained a drill rate of about 1 mm/min until core-breakoff occurred after 20 minutes of drill time (neglecting 18 minutes of cool-down). See Figure 5 for the 2g breccia core retrieved.

3.3 Conclusion

Based on experimental results as well as other relevant factors, a rotary-percussive drilling system was chosen for inclusion on the Axel rover. Several reasons include:

1. The rotary-percussive drill is capable of penetrating harder surfaces without overheating. The reliance on free mass impacts leads to excessive heat generation by the USDC.

2. The USDC lacks a rotary mode, which makes chip removal more difficult and decreases drilling efficiency.

3. The USDC is not robust enough. The drill bit fits loosely over the horn. Design of a new drill bit is extremely cost-prohibitive.

4. The rotary-percussive system is easy to operate. The USDC relies on a precise sinusoidal input tuned to its natural frequency to efficiently operate.

Regardless, the USDC still has several clear advantages over conventional rotary-percussive drills. It weighs just 0.7kg, while the lightest commercial rotary-percussive hammer drill weighs over 2.8kg. It also requires less power to operate. For space applications, these advantages are crucial, so the USDC should still be considered for future generations of Axel as the technology matures.

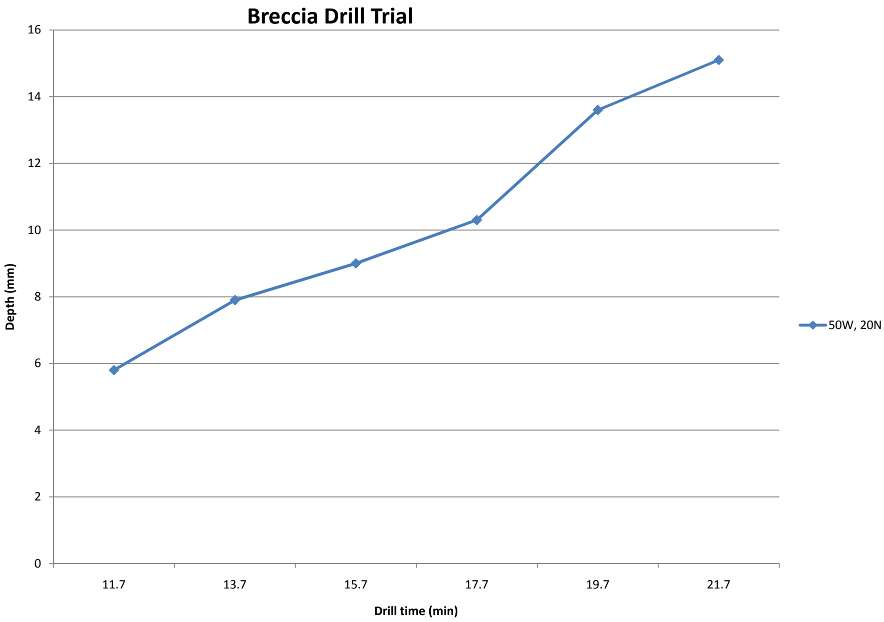


Figure 4: Rotary-percussive drill performance during rotary-percussive mode

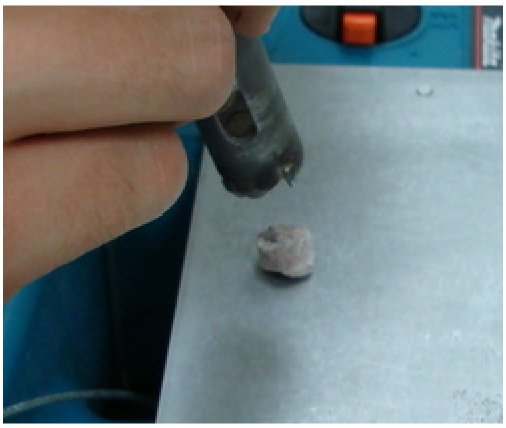


Figure 5: Breccia core

4 Sampling System Design

4.1 Design considerations

Once a rotary-percussive drill was chosen, a sampling system was designed. The key design considerations were location, drill type, and extension mechanism.

4.1.1 Location

The sampling mechanism could be mounted on several locations on Axel: the caster arm, the wheels, the body, or a sampling hub (still to be designed). The caster arm was chosen for several reasons. The current arm is detachable so a new sampling arm can easily be attached. The rover can maneuver when on a gentle slope to move the arm into an ideal sampling orientation. Finally, the current design does not have space for components inside the body of Axel. As a result, mounting on the arm would not inhibit Axel's clearance, while mounting on the body would.

Once the caster arm is chosen, a specific location on the arm had to be chosen as well. The drill could be mounted parallel to the arm when not in use for protection, and extended out when needed. The key design considerations in this case were: proximity to the center of mass of Axel and distance to drilling surface. The closer the drill is to the body, the more reaction force is available when Axel is nearly hanging on a steep surface. Also, moving the drill closer reduces the load on the caster arm motor when moving the arm. However, when Axel is on moderate slopes (say 30°-70°), moving the drill further down the arm increases the distance the extension mechanism needs to traverse to encounter a rock.

The location was chosen for the worst case scenario: Axel on a vertical slope. The caster arm would be perpendicular to Axel's body, so the drill bit must extend one wheel radius to encounter the surface. The drill was mounted about halfway up the caster arm; mounting any lower would leave no room for the motor.

4.1.2 Drill type

Currently, commercial rotary-percussive drills are designed with the mechanical hammering mechanism either inline or angled with respect to the bit. See Figure 6 for an example of each. The inline drills are preferable for a design with the drill mounted parallel to the caster arm since they minimize how much of the drill protrudes out from the arm. However, current commercial inline drills use the new Litheon battery standard which is very difficult to rewire to a power source, so an angled drill was purchased instead.

4.1.3 Extension mechanism

The primary purpose of the extension mechanism is to rotate and extend the drill so that the bit is perpendicular to the caster arm. The primary design constraint was the limit of just one actuator. To achieve coupled rotation and extension with one actuator, we designed a four bar linkage. The linkage mostly rotates in the first stage of actuation and mostly extends in the second stage,

Figure 6: Inline drill from Bosch (left) and angled drill from Hilti (right)

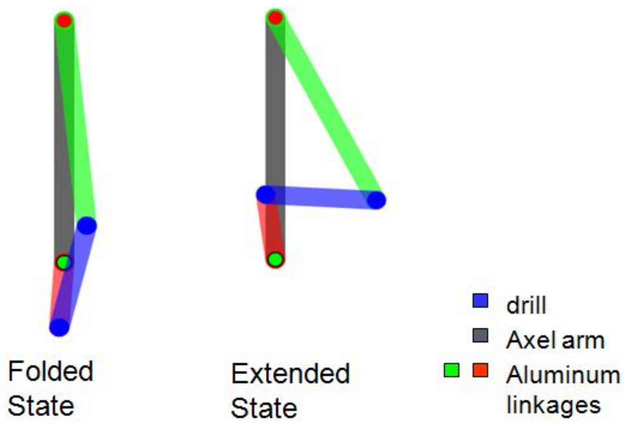


Figure 7: Four bar linkage design

as desired. This movement limits problems with the drill bit jamming up into a rock before fully rotating.

The extension mechanism was designed using an online four-bar linkage simulator. See Figure 7 for the chosen configuration. The ratios of lengths of the four bars were 35: 56: 110: 129 (red:blue:green:gray). We desired a linkage with continuous motion of the input link (red). This would allow the driving motor to actuate the extension and retraction mechanism by rotating in one direction. Also, we had to balance the need for efficient folding with the danger of an indeterminate state. In the indeterminate state, the linkage can switch between two orientations, where only one will produce the desired motion. This state can be avoided by not allowing the design to fully fold up.

4.2 Design & Fabrication

The four-bar linkage was machined using aluminum bars, using the caster arm as the fourth bar. The mechanism is actuated by a DC gearmotor. Worm gears are used to change the direction of rotation. The gears have the added

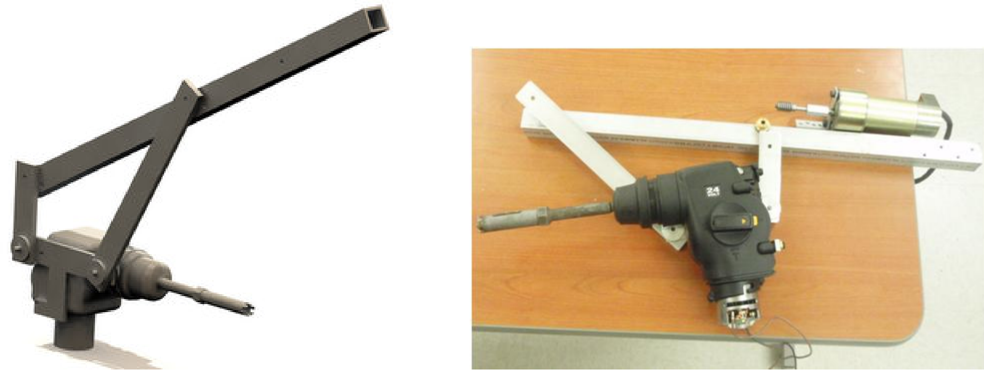


Figure 8: Overall design (left) and fabricated sampling mechanism (right)

convenience of jamming when applying force to the drill bit, thereby easing the load on the motor when providing reaction force. See Figure 8 for a general arrangement of the parts in the sampling mechanism as well as the fabricated result.

5 Further Work

The sampling mechanism must be mounted on Axel and sequentially tested on more challenging terrain. The caster arm motor may not be able to lift the arm in some circumstances (to be uncovered by testing). In this case a stronger caster arm motor needs to be installed. A more elaborate extension mechanism can be designed to more efficiently fold up and extend the drill. Some kind of sample collection mechanism needs to be installed to gather dust and cores during drilling. A new custom drill can be constructed to minimize weight.

6 Acknowledgements

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References

[1] Issa A.D. Nesnas, Pablo Abad-Manterola, Jeffrey A. Edlund, and Joel W. Burdick. Axel mobility platform for steep terrain excursions and sampling on planetary surfaces. 2008.