KNECHT: THE MARS MINING SOLUTION
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To: HEDS-UP Forum
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Date: May 4 2000

Subject: Abstract of Mars Mining Project Final Report

The engineering problem presented in this report is that of a Mars mining vehicle. We feel that our design has met or exceeded most, if not all, of the criteria set forth by NASA and ourselves. We believe that this design is the best out of all those considered. We have come to this conclusion through discussions and interactions with mentors and others in the field. We never completely ruled out any design, but rather took parts and ideas from all of our previous designs. Our final design is loosely based on an earth-based dragline and is composed of six subsystems:

The frame will house the mechanical and computer subsystems, providing them protection from the 100+ degree temperature range and highly windy atmosphere, which would jam our machine with sand. It is also the support for the boom.

The mechanical subsystem consists of two motors, two spools of cable, and a dual clutch unit. The function of this system is to rotate the boom and retract/release cables of the bucket. By using only two motors to operate our entire system, we reduced the number of moving parts, increasing its reliability.

The boom will be a triangular tube that is six meters long. Its function is to support the cabling and the bucket and protect the pulleys from sand thrown by windstorms. Low wind resistance will be obtained by keeping the boom slender.

The bucket, having dimensions of 20 cm x20 cm x 30 cm, will collect regolith from the surface of Mars. There will be three cables in our design, functioning to retract the bucket and as a cantilever support system for the boom. The cables are strong, yet thin and lightweight. The bucket is unique in its design because it makes the machine highly efficient by carrying more regolith than needed to meet the requirement. Another feature of the bucket is its recessed top, which allows it to flip over large rocks when caught. Due to the buckets size it could flip over once per hour, dumping its load, and still meet its quota of regolith.

The computer will be a matchbox-sized pc that will control the functions of the entire system. It will be protected from the atmosphere and any radiation encountered on Mars. It was designed and developed at Stanford university and is perfectly suited for our system because if its lightweight and compact size.

Our sorting system will be capable of separating fine material from regolith greater than 1 mm by running it through several different sorting mechanisms. These systems will last 500 days with minimal clogging problems and are reliable because the rotating drum is self-cleaning.

This mining system design is reliable because it is made of durable materials and has few moving parts and is, therefore, less prone to breakdown or malfunction. It is simple and easily constructed, limiting the chances of error during operation. It is also highly efficient because it is capable of gathering more regolith than necessary.

Introduction

In early September Mike Duke gave us the goal of designing a lightweight, efficient, semi-autonomous, long lasting, mining vehicle for use on Mars. The purpose of such a system would be to extract water from the regolith for the purposes of using it as both water and components of rocket propellant for possible future manned missions to Mars. While mining here on Earth is relatively simple we were faced with many problems that are not present on here. The constraints placed on us are shown in the table, Table I, below:

Table I
Restrictions Given by Mike Duke

Requirement	Rationale
Excavate granular material from surface down 10 cm-12 cm	Collect regolith to be brought to the reactor and sorted.
Avoid surface rocks	Reduce hazards to excavator.
Discard rocks greater than 1 mm in diameter.	There is more water in finer grained materials. Heating of large fragments with little water should be avoided.
Transport material from excavation site to furnace. Maximum distance of 20 m.	Get regolith to water extraction location.
Deliver soil to furnace input hopper	So soil can be sorted and water extracted.
Operate 8 hrs a day under Mars ambient environmental conditions.	Operates only from the equivalent of 8 a.m. to 4 p.m., when maximum sunlight is available.
Operate continuously for 500 days.	Mission duration.
Operate semi-autonomously.	No real time communication available, instructions from earth can be provide only once a day.
Provide Sufficient power for excavation and transportation.	Power is required to operate systems.
Have a total mass of less than 20 kg.	Suitable for testing on Mars on a small exploration mission, later, this could be scaled up for human exploration missions.
Be capable of delivering mass of the system in soil to the reactor in one hour's time.	Meet total water requirements.

While working on satisfying these requirements our team placed other restrictions on our mining vehicle to complement the specifications we were given. The following table, Table II, contains those restrictions.

Table II
Restrictions Stated by Team C.R.A.T.E.R.

Restrictions	Rationale
Low number of moving parts.	Aids in reducing wear and tear and thus maintenance needed on the mining system.
Simplify design as much as possible.	Reduces probability of mechanical breakdowns.
Provide for redundant systems.	Allows the mining system to continue to function even if it suffers minor failures.
Take a new approach.	Former rovers have had difficulty functioning in space environments; a new approach seemed logical.

We feel that we have met the most important of these criteria. While our system does not comply with some of the requirements, we believe we have found suitable ways around these problems and our system provides sufficient benefits that will have clear merit. We have looked at many other design options and believe this one to be by far the best of those we considered. The other designs are discussed below.

Approach

Our solution to the problem evolved many times over the course of two semesters. We considered many designs before finally designing on our dragline, Knecht. As the designs changed, they became less and less complex. Past designs include:

- Vacuum system on Mars
- Drilling Rig with continuous feed auger system
- Scraper
- Excavator with a conveyer belt
- Excavator with a combine
- Multi-Vehicle system
- Dragline

As a group, we first divided up the research between members. Topics for research included, but were not limited to materials, power systems, propulsion, Mars surface conditions and climate, previous Mars missions, guidance systems, Earth mining vehicles, and robotics. We came up with several interesting ideas, but chose only one based on a decision making process, outlined in Table III and IV. We never completely ruled out any system, but rather took parts and ideas from all, and combined the best aspects to form the best solution to the problem.

- Our first idea was a point drilling system, with two different continuous feed systems. This provided a simple solution to gathering and feeding dirt to the filtration system as well as a tried and true earth extraction system. However, there were numerous problems with this system. The first continuous feed system was a gravity fed system that would not work because of height and size constraints and wind problems. The second, an auger system, was rigid, and thus not very mobile in a rocky environment.

- Our second design dealing with excavation was the scraper system. This system was simple and extremely low maintenance. Unfortunately this system would have low mobility and would be highly likely to entrench itself and become stuck.

- The third design solution we posed was that of a vacuum system that would suck dirt from the surface. This system was simple, but ultimately, it was decided against because of the ineffectiveness of a vacuum at low atmosphere pressure.

- For a fourth idea, we considered using a combine excavation system with vehicular transport to and from the furnace. The downfall of the combine system was the wasted energy moving to and from the furnace, the tendency to entrench itself, and required high speed to operate, all making the design prone to mechanical failure.

Table III
Decision Matrix of Transportation

Designs	Cost	Durability	Efficiency	Flaws	Total
Gravity Feed	9	7	4	Wind (-6)	13
Auger Feed	7	6	7	Rocks (-2)	18
Vehicle Hopper	8	6	3	Maint. (-3)	14
Multi-Vehicle	6	5	6	Maint. (-4)	13
Vacuum	8	6	5	Atmo. (-8)	11
None*	10	10	10	None	30

Table IV
Decision Matrix of Excavation

Designs	Cost	Durability	Efficiency	Flaws	Total
Drill	5	5	6	Maint. (-3)	13
Broom	8	6	7	Wear (-4)	17
Scraper	9	7	4	Wear (-3)	17
Auger	7	6	7	Wear (-2)	18
Vacuum	8	6	5	Atmo. (-8)	11
Drag Line*	9	8	9	Wind (-3)	23

* (We selected a Drag Line, which requires no extra transportation beyond that during collection.)
Both tables are on a scale of 1 to 10, 10 being the best and 1 the worst.

Results

After considering these decision matrices we chose a final design using a dragline because no transportation is needed, and the system is very durable, christening it Knecht. We feel that Knecht is the best design based on our decision matrices. We considered many options and altered our design several times.

Technical Analysis

Our excavating machine is based on a dragline. It is composed of six subsystems, including a 6 m boom, a soil collection bucket, a control system, a mechanical system, and a regolith sorting system, which are all supported by the frame. The unit operates by first excavating the soil with the bucket, which is dropped from a cable hung from the boom. The bucket then takes the soil to the sorting system where the sorter removes the desired soil (<1 mm) from the unwanted soil and drops it into the furnace.

The frame and boom support the other systems, hold up the bucket, and protect the control and mechanical systems. They comprise the backbone of the unit. The mechanical system drives the unit and provides the necessary motion to collect the soil. It moves the bucket to and from the sorter and rotates the body of the soil to find new excavation sites. It is the muscle of the unit. The control system is the brain of the unit because it controls the mechanical system. It controls when the motors of the mechanical system operate and, therefore, controls the actions of the entire unit. The bucket is the arm of the unit since the system is designed to move the bucket, without which the other systems have no purpose. The sorting system sorts and channels the work of the bucket to the furnace and is the final part of the operation.

Our unit, Knecht, is efficient as well as durable. It is capable of surviving 500 days of labor under harsh Martian conditions per specifications by NASA. Unlike other systems, especially those consisting of a vehicle, our system has very few moving parts which makes it is far less likely to break or wear down.

The Frame

The frame of our mining system is one of the simpler parts of Knecht. It is a turret that sits on top of the sorting system, which in turn sits on top of the reactor. The design is a structural ring with a diameter of 1.0 m and two A-frames connecting the boom to the ring, illustrated in Figure 1. Instead of the boom being supported by the ring, the structure will be hanging off of the boom. Originally we did have the boom supported on the ring, but found that hanging the ring from the boom and providing direct support to the boom from the reactor was by far a superior solution.

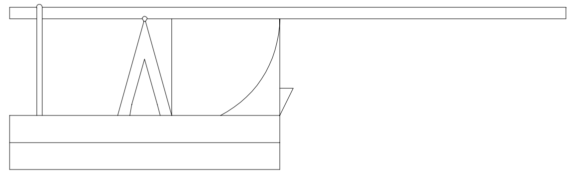

Figure 1: *Schematic of Boom Mounted on Tower*

There will be a tri-pod coming up from the interior of the reactor and connecting to the boom at a central pivot point that will provide the support for Knecht's boom. This solution will cause a drastic reduction in the friction due to movement. By adopting this system we reduce the friction points from the entire ring to just the central pivot point and the front edge of the ring. There will be another circular ring with a geared interior attached to the reactor, which will rotate the turret. Sealed bearings will be used to reduce the friction of the upper ring on the lower ring at the friction point.

While initially we had a full cylindrical enclosure the size of the ring diameter for the housing of Knecht's mechanical and control systems, but we found that there was an abundance of extra space in the turret. Because of this, we shrunk our enclosure in order to reduce weight and wind drag. In our final design the front half of the ring will be closed and will house the mechanical components and control system. The walls will be constructed out of carbon composite or a similar material. This material will be used for almost all of our structural components due to its extremely high strength and low density.

The Boom Subsystem

The design of the boom is lightweight and sturdy enough to provide support for the bucket, while allowing for the collapse of the boom for transport and storage.

We had many different and varying concepts on what our boom would be like. At first we were using a pendulum effect to swing our bucket the 20.0 m stated in the requirements but then modified our concept eliminating the pendulum due to the many complications involved with this system such as wind effects and the complexity of computer programming. We opted to collect only to the end of the boom and move the reactor system to another position on the Mars surface to facilitate further regolith collection. After running tests with the bucket, we determined that a boom of 6.0 m would be the best length to maximize our efficiency. In this concept our boom will have a reach of about 6.0 m away from the reactor and movement of the reactor and deeper digging will compensate for the shorter reach.

We then looked at the need for a method of collapsing our boom for transport and storage. Our first idea to fulfill this need was to use a folding boom that would fold back over the reactor and then be extended by tightening the cable for the bucket, pictured in Figure 2. This worked theoretically, however, when the boom reached the vertical it would fall the remainder of the way to horizontal and thus would probably break.

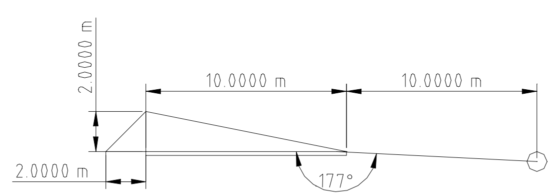

Figure 2: *Front View of Boom to Illustrate Operations*

The next concept for extending the boom was to telescope it and allowing for the modification of a method of extension best suited to our needs. We looked at the systems used for the extension of fire ladders, but found it too complicated for realistic application in this situation. We also looked at using a tubular balloon and filling it with expanding foam, but this had too many potential failures as well. Our final solution was that of a compressed spring with a catch that would give the inner boom enough force to slide out to the end of the outer boom and lock in place with a spring loaded pin. We were not given a size constraint, but you could conceivably collapse the boom using this method to whatever size necessary.

After research into the materials available, we found that there are many feasible and equally viable materials with which to construct the boom. Our first design incorporated magnesium alloy into the construction, however after further research it seems that the best material would be a carbon composite material. The carbon composite material will provide equal or greater strength while having a lower density, thus weighing less.

The boom construction will be that of telescoping triangular tube, we have only incorporated two pieces into the current design, illustrated in Figure 3; however, in the final design it would be feasible to have several. The outer tube has sides that measure 5.0 cm wide and 0.5 cm thick, while the inner tube has a measurement of just less than 4.0 cm on a side and 0.5 cm thick. The inner tube would be extendable by the process outlined above. The outer tube would extend back over the reactor and provide the top, central support for the mining system, and will have a total length of 4.0 m with 3.0 m extending from the turret. The inner boom's length would equal the distance that the outer boom extends out from the reactor, 3.0 m. The total boom length will be 7.0 m, with 6.0 m extending from the reactor. The cable would be run inside the tube and run out a slot in the bottom of the tube at the tip with a sealed pulley to guide the cable. At this length and using this construction and the constant of 1570 kg/m^3 as carbon composite's density the weight of the boom alone would be approximately 8.24 kg. The pulley will weigh approximately 2.3 g. The rod will have a weight of about 246.6 g. The pulley will be made out of magnesium alloy and, using 1800 kg/m^3 as its density, the pulley would have a weight of approximately 2.3 g. Using these weight approximations we find that this subsystem will weigh approximately 8.48 kg.

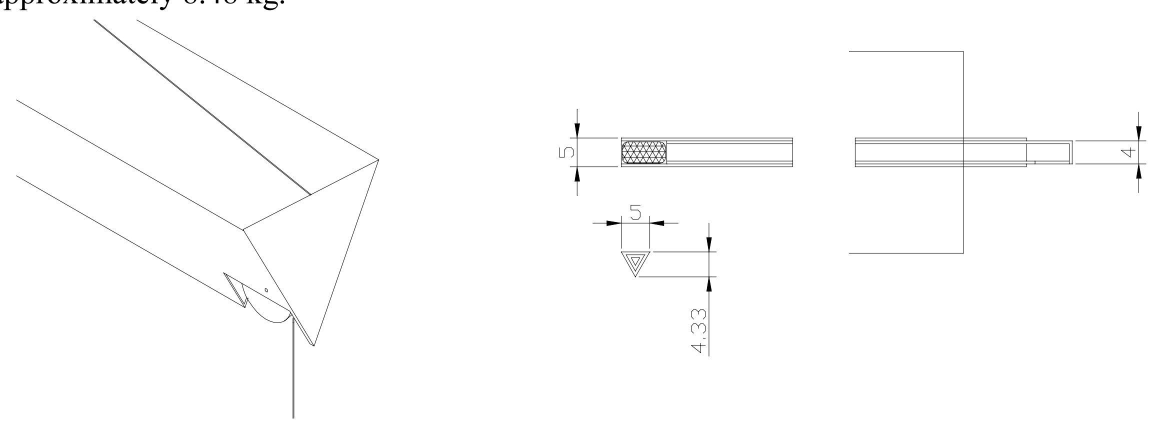

Figure 3: *Drawing of Telescoping Boom with Cable Pulley*

Using these dimensions will minimize the weight of our system thus aiding in fulfilling our weight restraint of 20 kg. The material chosen will be both lightweight, helping fulfill the requirement of our weight restraint, and strong. The material will also be highly resistant to temperature changes and should exhibit no problems coping with the atmosphere on Mars, including high winds and the temperature extremes ranging from -113^{o} C to 23^{o} C. Triangular tubular construction adds to its strength and also helps reduce weight and wind resistance. The tubular construction will also function as a protective element for the cable that extends to the end for bucket support.

The construction of this piece of our mining system is fairly simple and straightforward, since it is essentially two or more telescoping triangular tubes with the cable running through the center and a slot at the end to accommodate a sealed pulley. The pulley will be attached with sealed bearings to the walls of the tube and the cable will be run over the top of them. The cantilever support will have a small rod, 2.0 m long and roughly 1.0 cm in diameter, extending up from the base of the boom where it is attached to the main structure. A cable, approximately 8.6 m long, will be attached from the end of the boom to this rod and then run down to the main structure and attached about 1.0 m back from the base of the rod at the other end of the boom. The boom will be incorporated into the frame so that it will remain in a fixed horizontal position to the ground. The material for the cable will be Kevlar cable and will be covered in more depth in the subsystem analysis of the cables and bucket.

The Mechanical Subsystem

The mechanical system consists of two motors, two spools for the cable and a dual clutch unit. The system is the main force that moves the miner; it drags the bucket in by winding up the cable and also rotates the vehicle. This system has been split into two different parts: the first is the top assembly where one motor is dedicated to one spool. The spool will be used to wind up the top cable. This extends through the boom and to the bucket. The spool is approximately 5.2 cm long and has an inside diameter of 0.32 cm. The outside diameter is 4.0 cm.

The second part is the bottom assembly. This assembly, shown in Figure 4, is more complex than the top but still very similar. The motors will be identical except that the bottom will have dual drive shafts. On the ends of the shafts there will be twisted splines, illustrated in Figure 5, that act as one way clutches by allowing only the ratchet gear to engage the spool or the rotation gear. The splines do this by forcing the gear towards or away from the motor. These clutches will allow the motor to do two functions separately. This is accomplished by changing the direction that the motor is spinning. This clutching allows the bottom motor to turn the vehicle on its base and also wind the cable.

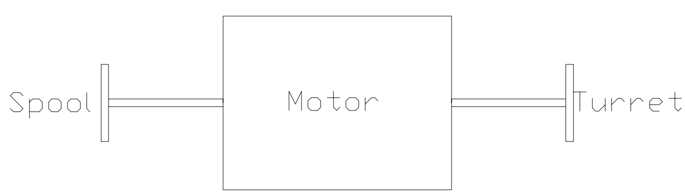

Figure 4: *Example of Motor Assembly*

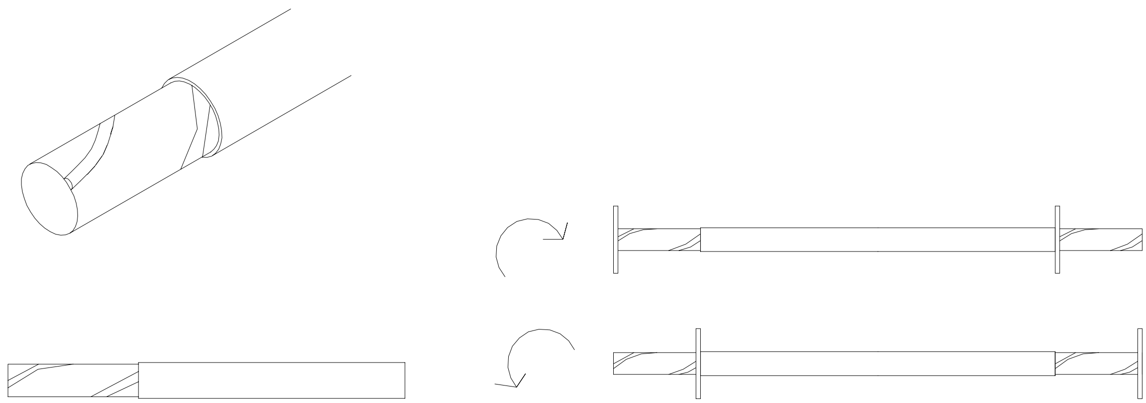

***Figure 5:** Illustration of Spline Gear Design to Serve as a Clutch Mechanism*

Both motors are brush-less to reduce friction, allowing them to operate at less than top speed, and hold one position. Their entire mass of motor and spools will be approximately 2.0 kg. The motors will have a maximum power usage of 150 W. The spools and clutches will be made out of a magnesium alloy with a density of 1.8 g/cm^3.

The top assembly will be mounted in line with the base of the boom to provide a straight pull on the cable. The bottom assembly will be in a vertical position. The spool will be above the motor as there needs to be a direct connection with the rotational gearing of the vehicle.

The design of the mechanical system was made to reduce the number of moving parts and to keep the power consumption to a minimum. Using the two separate motors and having the bottom assembly perform two functions achieves this. The clutch was designed to keep friction to a minimum by not using parts that would wear out over time such as a spring or a pure ratchet design. We believe that the design discussed in this report has fit these specifications well.

The Control System

The purpose of this computer is to control the entirety or our mining device. Specifically, it will run the motors that control the rotation of the boom and release and gather the cables. This computer will be what allows the device to mine the Regolith.

A tiny fully functional computer vehicle with dimensions measuring only 2.8 in x 1.8 in x .8 in will control the entire mining. It includes VGA, LCD, 10 Mb/s Ethernet, and a 340-MB disk; it is sufficient for a full version of Windows 98, Unix, or Linux. The total power consumption is only 2.0 W at 0.4 A with a peak power consumption of up to four watts at 0.4 A. We selected this PC, pictured in Figure 6, not only because of its power but its mass; coming in at only 70 g it is light enough to be readily used in our project.

The only protection the PC will have from the severe conditions on Mars will be the casing in which it is stored. The casing was designed out of the same materials as the rest of the frame with one small variation, the addition of insulation to the insides of the case and a heat sink machine patterned on the material. This should be enough to protect the PC from the severe temperature swings expected on the surface of Mars.

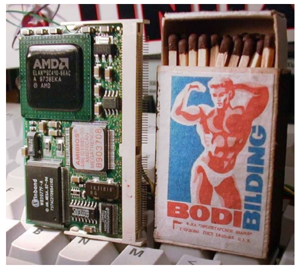

Figure 6: *Picture of the Stanford PC Recommend for the Mining System*

While on Mars the computer will be subject to a constant barrage of cosmic radiation, this will cause the computer to crash if left unshielded. One of the better ways of stopping radiation in a lightweight manner is to use lightweight gasses such as hydrogen, boron, and lithium. Lightweight atoms can shatter the nuclei of heavy elements, in cosmic rays without producing additional hazardous recoil products like neutrons. Out of these three gases we chose to use boron because it is the most stable of the three and therefore less likely to accidentally catch fire and/or explode during launch and landing (NASA).

This computer system will be able to communicate with NASA by linking to communications equipment on the furnace. The link will consist of a simple LAN connection linking the furnace's computer and the mining device's computer with a connecting wire. This will allow for any program errors or glitches to be repaired while on the mission.

We believe this viable design is superb in quality because it meets or exceeds all expectations for use on Mars. The extremely low mass of it allows for other systems to have more leeway in their design and structure. Also the low power draw will allow others to run with more power at more efficient levels rather than be forced to limit their ability due to power restraints. This will aid in the betterment of the entire team and project.

The Bucket and Cables

This subsystem includes the soil collection bucket as well as the supporting cables. More specifically, the bucket's purpose is to gather Martian regolith, while the purpose of the cables is to carry the bucket to and from the sorter.

The bucket, made of magnesium alloy, will have a volume of approximately 3077 cm^3. The longest side will be the angled bottom, with a length of 30.0 cm, where a blade will act as a scoop, shown in Figure 7. The top will have a length of 20.0 cm allowing a 10.0 cm open space to provide for a flipping mechanism to prevent the bucket from getting caught. The height of the bucket will be 10.0 cm and the width will be 20.0 cm. It will be making six trips to the reactor per hour. We chose to use magnesium alloy for the bucket's construction because of its strength, durability, lightweight, and resistance to temperature extremes.

We chose to make the cables of Kevlar because like magnesium alloy it is lightweight and strong, but is also flexible. Because of Kevlar's strength, the cables can only be 0.32 cm in diameter. The length of the cables will depend on the height of the reactor.

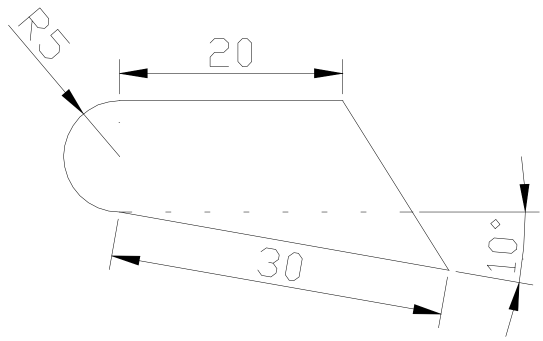

Figure 7: *Drawing of Bucket Proposed for the Mining System*

This design fits the specifications well because it is strong and lightweight. It is durable enough to perform its task for the time required. Also, the bucket transports enough soil per load so that it could spill its contents twice per hour and still meet the soil collection requirements. The construction of this design is rather simple. The bucket is to be built of magnesium alloy sheets with a 0.2 cm thickness. The location of the cables will allow the bucket to flip over any large rocks or obstacles it may encounter.

The Sorting Subsystem

The sorting system consists of a bin at the top of the sorting system, an initial sorting grate, and a trommel sorting system. The bucket is small enough that it cannot pick up materials larger than the sorting system can accommodate. The bucket dumps its load of regolith directly into the bin on top of the sorting system, represented in Figure 8. Once in the bin, the regolith will fall onto a grate, sized 30 cm^2, covered with Kevlar slats. The slats that do the initial sorting are 3.0 mm thick. All materials larger than 6.0 cm in diameter will slide over the grate and into a waste chute. All materials smaller than 6.0 cm in diameter will fall through the grate and into a trommel sorting system with a 25^0 downward from horizontal.

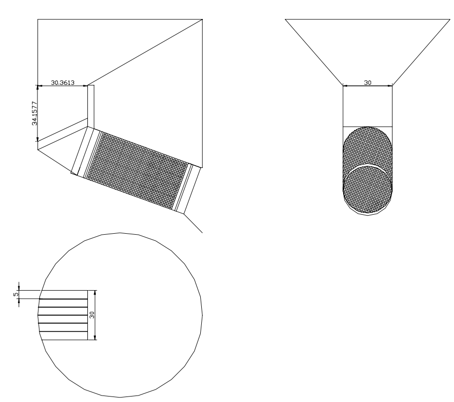

Figure 8: *Schematic Representation of the Sorting System for the Mining Unit*

The trommel system is made up of a perforated cylinder in which regolith is sorted. The cylinder rotates about its center axis and has two baffles, 6.5 cm tall, that spiral around the inside of the 30 cm diameter cylinder twice before reaching the bottom end. There are also four, 6.5 cm tall baffles that run straight down the cylinder, spaced at 90 degrees. The baffles stir, break up, and prevent the regolith from sliding straight through the cylinder. The perforations are 1.0 mm diameter holes, which allow the usable regolith to fall through into a bin where the reactor can access it as needed. The materials between 1.0 cm and 6.0 cm in diameter are dumped out the end of the cylinder into the waste chute.

The slats that do the initial sorting and the perforated cylinder will be made of Kevlar, due to its high strength and flexibility. The rest of the sorting system will be made of carbon fiber sheets and honeycomb structures. Kevlar is strong enough to stop bullets when used in vests, and will be strong enough to last 500 days.

This sorting system is very reliable because it is a self-cleaning trommel system. Every time the cylinder rotates, it dumps any material that may be clogging it back into the bottom of the cylinder where it can be resorted. Another thing that makes this system reliable is that it has only two moving parts, the rotating perforated cylinder and the small electric motor that drives it through a drive wheel system. The motor's power requirement is less than 100 W. A lot of earth-based research has gone into this system and the components have high reputations for reliability and longevity.

Future Recommendations

We have several different possibilities for the continuation of this design, contingent on funding. Among the loftier of these options, would be to see our completed design travel to Mars to perform its desired function. However, in the more immediate future, we hope to continue testing on the various subsystems, focusing on the bucket and mechanical subsystems. Ultimately we would like to build a full-scale, working prototype out of appropriate materials. We feel that this design has the potential for many uses including possible lunar excavation as well as the Martian surface.

Outreach

During the process of building and designing our miner we have had a good amount of publicity. Articles have been published in local Denver area newspapers, ranging from explanations of the entire project, to specific articles concerning our success at the school's Design (EPICS) competition. We have also had a few publications in hometown newspapers as well. Abby Bazin has had an article concerning all of her achievements with the Design (EPICS) department printed in The Plaindealer, the paper in Ouray, Co. Brent Pounds was mentioned on one occasion in his local paper, The Pueblo Chieftain. All of the members in our group are very talkative when people ask about our project. Many teachers at our school already know of our endeavors and our upcoming trip to Houston, as well as all of our friends and acquaintances. Our parents are very proud of our achievements, and have been telling anyone and everyone they possibly can. Our group has also been working with various engineers from Lockheed Martin who have visited the campus on a regular basis, assisting us with our questions, and providing comments of their own. The Trapper Mining Company in Craig, Co has been a big help in our design based on an Earth dragline. They have been kind enough to allow one of our group members to tour the facilities and ask questions. Many other people from the local area know about our project and are spreading word of our accomplishments around from the final open house presentation we gave in mid December, and our recent presentation to CSM students and faculty.

Conclusion

The overall design of our regolith collection system is very similar to that of a dragline used here on earth. The entire system consists of a bucket attached to a boom by two cables that drag the bucket along the ground collecting regolith. Once the bucket has filled and completes its trip back to the base of the furnace it is raised up by one of the cables and dumped into the sorting system. The sorting system, which discards all materials larger than 1.0 mm in diameter, dumps discarded material near the area from which it was mined. The entire regolith collection system is mounted on a turret on top of the furnace.

We have spent significant time researching and developing this design, which has very few moving parts making it far superior because of its reliability. With fewer moving parts our design is much less likely to break down or fail in any way during the 500-day mission. Since the entire system is stationary most of the time, there is almost no chance of it getting stuck which has been the downfall for many earlier Martian exploratory rovers. In comparison to other designs we believe our design is superior in all parts of the design.

In closing, this design has many benefits over other designs and, in our opinion, is the clear choice. Thank you for reading this design project report; we hope you are as enthusiastic about it as we are.

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