Carnegie Mellon University Autonomous Prospecting and Extraction System

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Introduction:

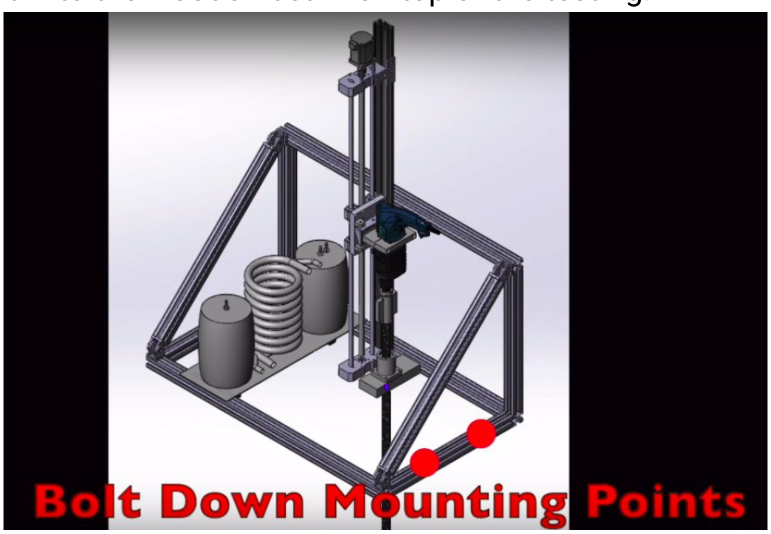
We apologize for the lack of quality photos in this report. The last several weeks have been complicated with scheduling conflicts and poor coordination on our part. Our school's engineering building is under renovation and APES was inaccessible when we planned to take photos of it for this report and the video. We assure you that steady progress has been made with the robot and we are in the final steps of full system integration and testing.

The Autonomous Prospecting and Extraction System uses a hammer drill with a cone penetrometer to dig a well and create a digital core on the martian regolith simulant. This drill has been tested very hard and packet dirt and proven to effectively penetrate at a rate of at least 0.25 meters per hour. The cone penetrometer houses a heating element and thermocouple which are used to belt the subsurface ice. When enough ice has been melted it can be pumped up through the cone penetrometer and drill rod into a thermal distillation system. By using a counterflow heat exchanger APES is able to turn muddy water into pure water at a rate of at least 0.5 liters per hour. APES is also a Rodriguez well which means it can send hot water back into the ice to increase the amount of ice melted.

Our inspiration for the drilling mechanism was the popularity of cone penetrometers in the geological surveying industry. These are commonly used to measure the pressure profiles of different layers of dirt. Our inspiration for the Rodriguez well came from research on how water is produced in Antarctica. Rodriguez wells are used to effectively produce large quantities of water from subsurface ice. We chose to use a thermal distillation system because that is what is commonly used to produce the purest water possible. A thermal distillation system offers a degree of reusability that is not possible with conventional filtration systems.

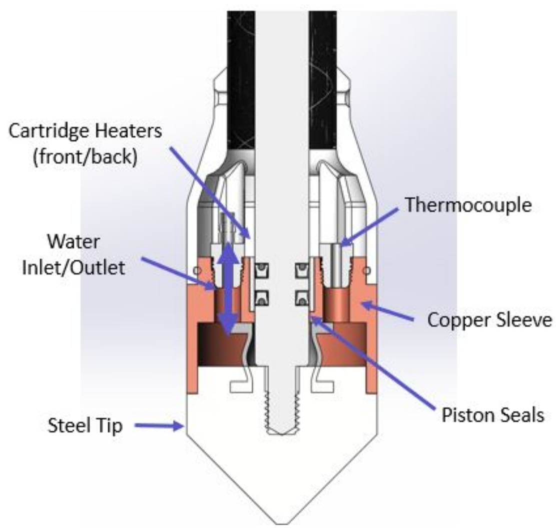
System Description:

- **Water Extraction:** APES extracts water from subsurface ice by first melting it then pumping it out. We have determined from previous experience that this a simpler and more feasible method for extracting water from a solid piece of buried ice. The 40W heating element at the end of the drill rod is enough to begin a pool of water within the ice. Once enough of this ice has been melted water can be pumped up into the robot. At this point the water can be heated and sent back down into the pool to melt more of the ice. This method is known as a Rodriguez well and has been proven to be very effective in similar environments such as Antarctica.
- **Digital Core:** Apes uses a variety of sensors to generate the digital core. WOB measurements will be taken periodically to determine the force being applied by the drill. Our hammer drill has a variable frequency which can be used to determine how much hammering is necessary for a given layer of regolith. Additionally we have a current sensor on the drill motor to determine if at any point their is a higher load on the motor due to a more challenging layer of regolith. Our z-axis is equipped with a motor encoder which will tell us precisely at what depth we are drilling. All these instruments will help us determine the rate of penetration as well as the force required for each layer of regolith. All this data will be used to generate a digital core.
- **Mounting system**: APES will be attached to the mount with wood screws and washers drilled into the wooden beam on top of the test rig.



- **System Excavation Operations:** The drill will be operated in cycles. The drill motor will be turned on for short periods of time to loosen the surrounding regolith. When the drill motor is off a WOB measurement is taken. If the WOB value is below a threshold the drill will be moved down a short increment while on . Then the drill motor is turned back on in cycles until the WOB value is low enough again.

- **Water Extraction System:** Ice is first melted by a heater in the cone penetrometer. When enough ice has been melted the cone tip can be dropped down into the water, exposing a cavity where the water is pumped up from.



- **Water Distillation System**: With the goals of reusability and purity, we have created a distillation system. Dirty water is pumped up the counterflow heat exchanger and into the heating tank. The water is then vaporized and condensed on the other end of the heat exchanger. The condensed water is then collected in the condensation tank.

- **Drill Freeze Protection:** One potential hazard on the Moon or Mars is the drill freezing in the ice. This is not a concern we have for the competition but it is something our system could theoretically handle. Since there is a heating element inside of the drill tip, in the event of freezing and getting stuck, it could be turned on to melt the ice holding down the drill. Additionally, since APES has the capacity to send hot water into the well, in the event of a serious and critical freeze over, this is a viable method for loosening the drill from the ice.
- **Control and Communication**: The APES control system is connected to the COMS computer via a direct network. Commands can be sent directly over terminal access. In the case of a lost communication, the APES robot will go into a preset state where heaters and motors are all disabled.
- **Datalogger:** A data logging program runs in the background at all times. Sensors are checked at known times and their respective variables are updated for the system to make decisions. This data is also logged with a timestamp into a USB which can be removed at the end of the day for analysis. The current usage data will be collected at a known sample frequency. The WOB data will be collected at specified points in the operation when the drill motor is off. This is because the high frequency and amplitude vibrations created by the drill motor results in noisy and unreliable data from the load cell. Therefore, the drill motor will be on for short periods of time and WOB data will be recorded when it is off.

Technical Specifications:

- Mass: 45 kg
- Volume: 0.5 m^3
- Drill Bit Length: 0.9 m
- Rated WOB: 100N
- Rated Load: 200 N
- Max Drilling Speed: 0.25 m/hour
- Max Torque: 0 Nm
- Computer: Raspberry Pi 3 B+
- Communication Interface: Direct P2P network
- Software: APES Control Software
- Power: Corsair ATX Power Supply for all DC power, regulated mains voltage for all AC power
- Telemetry: Load cell, thermocouples, current sensors, motor encoders

Design Changes/Improvements:

Since the mid-point review we have worked hard to optimize our drill. Many of the improvements have been within the drill and and drill bit itself. To maximize our penetration into the ice we have modified the drill motor mounting clamp to give us an additional 15 cm of penetration. After doing some drill testing we determined that our cone penetrometer was too wide. Because of its large diameter it was very difficult to penetrate through the regolith simulant. Since then we have cut down its diameter by almost half. Drill testing with the new cone penetrometer have been significantly more successful. One other issue we have encountered is that of drill rod deflection due to an uneven ground surface. To mitigate this problem we have designed a bearing block that guides the drill rod straight into the regolith simulant.

Challenges:

Our biggest challenge by far was not having a large enough team. This robot was not meant to be built by only 3 people. APES has demanded a lot of time and it has been difficult to accomplish this as full time students also working part time jobs. As a result we ended up hiring our university machinists to make some of our parts.

Overall Strategy for the Competition:

Our excavating and prospecting process will happen in a cycle. The drill motor is run for a short period of time and loosens the surrounding regolith, then a WOB measurement is taken. If the load has dropped below our threshold the drill will be lowered until it rises back to our threshold. By repeating this process, over time the drill rod will dig through the regolith, taking measurements along the way. This process will generate a lot of data points to use in constructing our digital core.

Once we have reached the ice the cone penetrometer heating element will be turned on. As the WOB data decreases we can continue to push through the ice. We will do this until we reach the maximum depth of our drill with the hopes of forming a narrow cavity which dirt will not fall through. Once the maximum depth has been reached and enough ice has been melted to form a pool, we will initiate the Rodriguez well process.

Summary of Integration and Test Plan:

From our testing we have determined that APES is capable drilling through regolith at a rate of at least 0.25m/hr. The regolith simulant we used was previously fairly but had dried up to form very firm dirt. The layers were almost cemented together. Because of this it was much firmer than the regolith simulant used in previous years in MMIPC. For this reason we believe we will be able to have a penetration rate greater than 0.25m/hr and will definitely be able to get through the new layers being added to the regolith simulant.

The water distillation system has been simulated and it has been determined that APES should be able to distill at least 0.5L of water per hour. It takes a long time to start this process depending on how much water you are trying to boil at a time. From experimentation we have determined that this rate can be increased by heating the water in smaller quantities at a time.

All aspects of the controls system have been tested and confirmed to work. The controls system has been used in all of the tests.

Although all individual subsystems have been tested independently, with the exception of the controls system, there has not been a “dry run”. This is as a result of end of semester scheduling conflicts. We performing a “dry run” in the following week. The test apparatus will consist of 2 large 5 gallon buckets. One bucket will be filled to the top with water then frozen. The second bucket will be placed on top with its bottom cut out. Once on top the second bucket will be filled with different layers of regolith simulant. These layers will consist of topsoil, small pebbles and golf ball sized rocks. The layered regolith simulant will allow us to run another test on our methods for creating a digital core. The thick ice bottom layer will allow us to test our methods of penetration by melting and to help determine the effectiveness of our entire water system.

Tactical Plan for Contingencies/Redundancies:

If at any point APES is not behaving as expected there is a quick stop command which will shut off all systems that could present any risk. Alternatively, there is an E-Stop that will immediately shut everything off. We have backups for several of the critical components, if something breaks we are prepared to fix it. One concern is misreadings of the temperature in the boiling chamber, for this reason we are bringing a laser thermometer and will be frequently using it to verify the thermocouple data.

Budget:

- Building: $4,793.00
- Testing: $200
- Transporting: $800
- No other sponsorship outside of Moon to Mars Ice & Prospecting Challenge Development Award

Path-to-Flight

Extracting Water on Mars:

This APES prototype was built for the purposes of preliminary technology testing and would therefore not survive on Mars. In the following paragraphs several essential modifications necessary to prepare APES for Mars will be described.

Power: Seeing as there are no AC outlets on Mars APES will need to source its on kilowatt of power by some other method. Solar panels are a common solution for many rovers but they come with many complications. Solar panels are particularly risky because of the Martian dust storms which can last well over a month. Mars receive ~590 W/ m^2 of flux(1). Assuming a solar panel efficiency of 25%, which is quite high, APES would need ~6.8 m^2 of solar panels to provide the 1 kilowatt of power, during the day. This is a very large solar panel array but it is not unreasonable. The biggest complication is that of dust storms. During a dust storm the sun can be almost entirely blocked out, and there's no telling if the solar panels won't be completely covered in dust once the storm has passed. This critical water mining system cannot be stopped due to bad weather. Therefore solar panels, although great for rovers, is not a viable solutions for the power demands of APES.

Alternatively, Multi-Mission Radioisotope Thermoelectric Generators (MMRTG) don't stop working regardless of season or time of day. The issue with MMRTG's is that they have a low power efficiency of 2.8W/kg (2). To supply enough power to APES, 8 MMRTG's would be needed. The mass of 8 MMRTG's is about 360 kg. This is the combined mass of both Spirit and Opportunity rovers. APES would have enough power to work day and night 668 sols a year, but this would likely become the most expensive Martian mission to date. If we reduced the operational time the mission begins to become more financially feasible. An MMRTG powered APES would be safer and more reliable than a solar powered one.

Weather and Atmosphere: Temperatures on Mars fall within -140℃ to 30℃ (3). Everything on APES must be made out of materials capable of withstanding these harsh temperatures. Lubricants must have a freezing point lower than -140℃ to mitigate bearing seizing. Plastics used cannot become brittle in the cold. Metals should have low thermal expansion coefficients. Electronics and battery technology are particularly difficult. Thermal isolation and low power heaters could be used to maintain these sensitive components within their operating temperatures. An added benefit of using an MMRTG is that it could help maintain operating temperatures by using excess heat. Due to Mars' thin atmosphere the opposite problem arises. Getting rid of excess heat becomes difficult without convection. As a result, efficient radiators must be used wherever possible. Poor convection could also result in having to stop certain operations while a component cools down.

Although the winds of martian storm aren't strong enough to pick up a kite (4), the dust particles that do get picked up pois a real threat to the mission. These dust particles could make their way into machinery like gears which could result in serious complications. Countermeasures for this can be taken by sealing everything as well as possible to mitigate the effects of dust.

Ice Depth: To ensure the success of an APES mission the robot must be able to excavate to much greater depths. This would increase the likelihood for a more considerable production of water. By adopting techniques from the natural oil and gas mining industry it may be possible to dig deeper for water. APES must be equipped with sections of drill rod/water piping that could be assembled together autonomously while digging. This is essential since you cannot send a single piece 20 meter long drill rod to Mars. It takes a lot of power and weight to drill deep into regolith. To reach greater depths a stronger and bigger robot will be needed. It is for this reason that I believe APES should be built into its lander. The lander can provide more weight which will allow for a greater WOB to drill deeper. If APES is landed on top of a large section of subsurface ice it is not necessary to make it mobile. Therefore, APES does not need to detach from its lander and can use it to increase WOB.

Water Transport and Storage: For small quantities of water it may be feasible to use replaceable and refillable tanks for collection. These tanks could be replaced by colonists whenever needed. For larger quantities such as what is necessary to fill rocket fuel tanks, another method for transporting the water is needed. In this scenario moving individual tanks of water from the water collection system to the rocket is a very time consuming and inefficient process. Alternatively, a system of tubing from the site of the water extraction to the rocket landing pad would increase the efficiency of the whole process while minimizing the number of necessary EVA's. Keeping the water in this tubing from freezing will take a considerable amount of energy. I believe that it would be more energy efficient to pump the water vapor out of the distillation chamber and into the tubing system instead of condensing it back down to water first. This would require pumps along the length of the tubing to ensure the vapor does not condense and keeps flowing.

Storing the water is just as challenging as transporting it. If the water freezes it becomes very challenging to pump out of a storage tank. The ice would have to be melted which would require a tremendous amount of energy for large quantities of water. If the storage tanks were buried under the regolith much of the heat energy could be conserved. Digging a large enough hole for a massive water storage tank is challenging even here on Earth. Alternatively, using already existing subsurface cavities such as lava tubes would enable colonists to deploy inflatable storage tanks without having to do much excavation.

The water extraction should be done a reasonable distance away from the colony or rocket landing sites. In the unfortunate event of a collapsed well cavity, much of the surrounding area would be affected. Colony location and water extraction site must be chosen concurrently to guarantee the safety of the colonists. On the other hand, the water storage tanks should be located near the colony. In the case of a leak or some other unforeseen accident, the colonists must be able to react and access the water reserves quickly and protect such a vital resource.

Autonomy: A large amount of water will be needed as soon as humans arrive on Mars. This means that the water extraction process must begin before we get there. A high degree of autonomy is a critical aspect to any Martian mining system. Due to the long communication delay, APES cannot wait for each command to come from Earth. Therefore, APES must be able to dig the well and begin extracting water mostly on its own. This can be very challenging but fortunately this is something that could easily be tested here on Earth. Once the humans arrive on Mars they will be able to efficiently operate the system and make repairs wherever necessary.

Communications: Autonomous or not, APES needs to be able to communicate back to Earth. Sending a signal such a long distance takes a lot of energy. This would consume a large portion of APES energy reserves depending on the rate of communication. A considerable amount of energy could be saved if the messages were relayed by a Martian satellite. Since the satellites are much closer APES can save power by sending the signal a shorter distance. These satellites are then tasked with sending the signals back to Earth, since this is oe of their primary functions they will have sufficient power to do this.

APES Network: As a colony grows the demand for water will also increase. Over time more APES robots will be needed. A larger region of ice can be mined and more water can be produced by landing multiple APES near each other. Tubing can be shared between them to reduce the amount necessary while maximizing area coverage. It is important to keep in mind that if wells are dug too close to each other the they could join and potentially cause complications in the whole operation. Once the colony reaches the point that more extraction systems are needed there will be enough colonists on Mars to ensure the proper placement of a new well.

Lunar Prospecting: The following section describes some of the essential modifications necessary to prepare APES for lunar prospecting.

Power: Solar power is a common solution for short term lunar missions. The lunar night is very harsh and lasts for 14 days. Any mission that is purely solar powered is very unlikely to survive the lunar night. For this reason an MMRTG should be used to power APES on the moon. Solar panels could still be used to supplement the power generated by the MMRTG. Since it is much cheaper to send things to the moon than to Mars it is not unreasonable to send an APES with more MMRTG's and therefore longer operating periods. With enough MMRTG's the mission could be completed more quickly and other complications from the lunar environment are less likely to be encountered.

Lunar Vacuum: Most of the greatest engineering challenges on the moon result from its lack of atmosphere. Preventative measures must be taken to avoid cold welding parts together. APES has many moving parts, if any of them get fused together it could result in premature ending to the mission. Materials that are resistant to cold welding should be used wherever possible to reduces the chances of parts seizing up.

Very large and efficient radiators must be used to release excess heat. Since there is no convection on the moon it is very difficult to get rid of excess heat. This could greatly affect the operating periods of APES since operation may need to be stopped to wait for components to cool down.

A hard vacuum such as that on the moon causes materials such as plastics to "outgas". When this happens the material greatly degrades and will likely become very brittle and crack. To avoid these issues only materials that do not outgas must be chosen for any parts that will be exposed to the vacuum.

Without an atmosphere APES will not receive any protection from solar radiation. The chances for a single event upset (SEU) on the moon are much more likely, particularly during the day time. For this reason, the avionics must be much tougher than they would be on Earth. SEU mitigation protocols must be implemented to reduce the chances of an unrecoverable failure on the APES computer. The avionics must also be well isolated to reduce any electrical spikes as a result on surface charges which can also occur the moon.

Weight on Bit: To increase the depth of drilling a greater weight on bit is needed. For this reason I believe APES should be built into its lander. This is a greater concern on the moon than it is on Mars since it has less gravity. If the digital core desired depth is not very deep then APES can be mobilized on a rover and could potentially take several readings. If the desired depth is several meters then it will be difficult to make a mobile robot because of the added WOB requirements.

Dust Particles: Although the moon does not have any winds to pick up dust particles it is expected that they be kicked up during the drilling process. These dust particles are incredibly fine and pose a serious threat to any moving mechanisms. Substantial sealing must be use to mitigate the possibility for these complications.

Reference:

1. https://space.stackexchange.com/questions/19924/solar-panels-on-mars
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3. https://mars.nasa.gov/allaboutmars/facts/#?c=inspace&s=distance
4. https://www.nasa.gov/feature/goddard/the-fact-and-fiction-of-martian-dust-storms