PENNSTATE

Hospitality Services

Mining the Foundation of the Future

Submitted by the 2001 Penn State HEDS-UP Team pursuant to the NASA 2001 HEDS-UP Student Design Competition

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1. Abstract

"In fact, a two-kilometer-wide asteroid holds more metal than all the ore mined on Earth since the beginning of civilization." - Mark Alpert, issue editor at Scientific American.

An asteroid mining mission presents the opportunity to obtain large quantities of raw material already outside of Earth's gravitational pull. Such materials would be best put to use for construction of infrastructure in outposts set up on either the Moon, Mars, or future space stations. Mining on an asteroid presents several challenges that prevent conventional mining techniques from being implemented. These challenges force a creative thought process with respect to the design approach. Given the difficulty of this situation, one mining method sticks out as the most practical.

We will be utilizing a three-component mission involving a ferry transportation unit, a canister unit, and a mining unit. This mission is designed to operate almost entirely autonomously. In the first stage of the mission, the ferry, which will be equipped with the VASIMR propulsion system, will bring the miner and canister out to the asteroid. The miner and canister will land on the asteroid and begin the mining stage of the mission. The miner will initiate the excavation of ore using the Laser Cutting System (LCS). With a series of intricate cuts using a drilling laser, the miner will slice a section of the asteroid into smaller pieces. The ore retrieval arm will transport this cut-up metal to the canister. Once the canister has been filled, the ore will be ready to be shipped. The ferry will return, bringing with it an empty canister, and then will carry the full canister back to its destination, most likely either Earth, Mars of the Moon. This process will continue as long as this is the most economical method of collecting metals. The process can also be expanded by adding a second miner and canister set.

2. Introduction

The date is July 20, 1969. Every American is on the edge of their seat as they watch Neil Armstrong make footprints in the Sea of Tranquility. They gaze into their brand-new color televisions in awe of the grandeur and brilliance of the men and women who fulfilled the dream of landing on the moon.

The date is now February 12, 2001: Just another mid-February Monday, or so we think. Not many Americans knew of the next "giant leap for mankind", as NEAR-Shoemaker successfully completed the first-ever asteroid landing. Though Americans may not have been as interested in NEAR-Shoemaker as they were in Apollo 11, it holds great importance for the future of the space program.

Since John F. Kennedy's mandate to go to the moon, Americans have been continuing to satisfy their curiosity and furthering their knowledge of space. In order to utilize all it has to offer, we must expand our explorations to greater magnitudes. By harvesting the raw materials of space, we can enhance and encourage further exploration.

Because of the need for vast amounts of raw materials to further our exploration and colonization of space, the Penn State HEDS-UP 2001 team decided on a mission to mine an asteroid. The main asteroid belt, located between Mars and Jupiter, is the prime location to send a miner capable of harvesting enormous quantities of ore. The main belt has many useful asteroids, making the job of finding a desirable candidate a little easier. There are also advantages to mining a near Earth asteroid, so we do not want to rule out that possibility. Our system will involve a miner, which will be remain on the chosen asteroid indefinitely, a canister, a versatile storage device, capable of handling liquid fuel, and solid ore, and a ferry ship, which will transport the canister, and initially the miner.

3. Approach

Students from a wide variety of majors at Penn State University met twice weekly throughout the course of the Spring 2001 Semester. The students participating in this extracurricular project did not receive any academic credit for their involvement. Many of the students had little knowledge of asteroids, or even space missions in general. The group began with a discussion of current space missions, as well as future planned missions.

Mission Criteria

Because there are so many potential mission ideas which we could have developed, we felt it necessary to establish base criteria that would serve as the guidelines for any mission ideas which we considered. Our main criterion was that the mission fit into the plans of NASA for the future of space exploration. By examining the current missions and future goals, we crafted a proposal to complement NASA's aims. In addition, we wanted our mission to be expandable based on its success. In essence, we wanted our mission to fit into a modular sequence of missions that would work together to establish a more prominent presence in space. These two main design criteria allowed us to narrow down our mission significantly.

Mission Selection Process

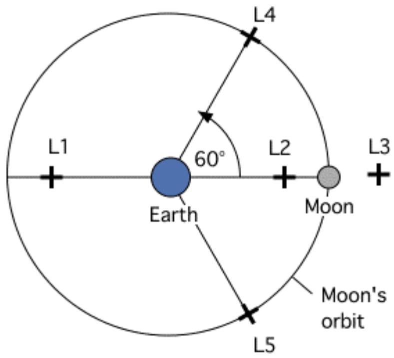
With the ever increasing potentials of the space program, one question keeps arising; “what next?” Since the initial voyages to the Moon, humankind has yet to venture outside of low earth orbit. Eventually humankind will desire to venture out to the further reaches of space. The Moon does not offer much of a quenching for our adventurous thirst, and we have already begun to look past that. The most logical next step will be to send human missions to our neighbor, Mars. Several different groups, such as the Mars Society, are looking into the feasibility of such a mission. Because Mars is the only hospitable planet within humankind’s current reach, plans are to send several missions to Mars, and eventually establish colonization efforts there. Depending on the success of these initial colonization efforts, such efforts could expand to support a large population there. As with any society, a certain amount of raw material is required for the construction of shelters and other infrastructure. The early structures will be constructed of pre-fabricated modular components that will be easy to set up on site. The materials will have to be shipped from Earth. While this is the most practical solution for the short-term missions, this will not suffice for any long-term efforts. In order to establish a society of any decent size, a rather exorbitant amount of raw materials will be needed. Because it currently costs about $22,000 to launch a single kilogram of material from Earth’s surface, it is not economically feasible to launch thousands of tons of materials from Earth. This leaves the dilemma of how to transport the needed materials to Mars. One possible solution would be to travel to an asteroid and mine this material. The costs to transport material from an asteroid would be only a tiny fraction of the costs of launching it from Earth. It is with colonization efforts such as this in mind that the Penn State HEDS-UP Team has decided to design an asteroid mining mission.

Before we settled on mining asteroids in the asteroid belt, we discussed other possible missions. We talked about expanding on our rover mission from last year’s competition, or possibly building outposts on our moon or the Martian moons. However, to do any of these missions we need materials. Transporting all of the raw materials needed build bases on other planets from Earth is very inefficient due to launch costs. Carrying building supplies to distant planets, such as Mars, or other moons, is not the best option as it is highly economically inefficient. The success of the NEAR-Shoemaker mission this past February brought with it inspiration. No longer is the space program limited to conventional mission approaches. This is where the idea to mine an asteroid arose. We began to realize that in order to establish humankind’s presence in outer space, the ability to use local and available resources is imperative.

Mission Destination

Once we decided on asteroid mining, we had to decide on where to go. With this in mind, we began to research the presence of asteroids in our solar system.

Many asteroids orbit the Sun in a 1 ½ AU wide area between Mars and Jupiter, known as the asteroid belt. It is believed that there are millions of asteroids in the belt, though the average separation between them is 10 million kilometers.



While Jupiter’s gravity affects the belt asteroids, it also controls some asteroids by holding them in the path of its own orbit. These points where asteroids are held are called Lagrange points, and they occur where the gravitation of the Sun and a planet cancel each other out. Lagrange points exist in many parallel situations, including the moon orbiting around the Earth, as shown in the figure above. There are two Lagrange points in Jupiter’s orbit, one 60 degrees ahead of Jupiter, and one 60 degrees behind it. The asteroids here are called Trojan asteroids, and almost 1,000 asteroids are contained between the two, though more are found at L4, the leading Lagrange point, than at the trailing point, L5. Asteroids are also found in elliptical orbits that bring them into the inner regions of the solar system.

These asteroids that pass through our area of the solar system are broken down into groups. The first, Amors, are asteroids which cross Mars’ orbit but do not quite reach Earth’s orbit. Another group are the Apollos, which cross Earth’s orbit with a period of greater than one year. The last group are the Atens, which also cross Earth’s obit, but with a period of less than a year. Currently there are approximately 250 identified near-Earth asteroids (NEAs) known of, and it is estimated that 100,000 others are yet to be discovered.

Besides identification due to their location, asteroids are also classified based on their composition. The most common type is C, compromising more than 75% of known asteroids. These are characterized by very low albedos, about 0.03, making them extremely dark, and giving them a virtually featureless spectra in the ultraviolet, visible and near infrared. These carbonaceous asteroids have a chemical composition similar to that of the Sun, without the hydrogen, helium and other volatiles. They are found mostly in the outer asteroid belt, along with D and P types, which are other classes closely related to C-type.

The next most common type is S, accounting for 17% of known asteroids. The S-types are relatively bright, with albedos between 0.10 – 0.22 and their spectra show absorption bands mixed with a reddish color. These asteroids are composed of metallic nickel-iron mixed with iron and magnesium silicates. S-types are located mainly in the inner portion of the asteroid belt.

Another type, M, makes up about 5% of the known asteroids. These asteroids are about the same brightness as the S-type, with albedos ranging from 0.10 to 0.18, and their spectra are somewhat reddish-slopping and straight. M-type asteroids are almost of pure nickel-iron. The inner-most edge of the asteroid belt is home to these types of asteroids.

There are other, less prominent classes of asteroids, many akin to C-types. After reviewing the composition and location of the major types, we decided that M-class are the only type that would yield the large amounts of metals we are looking for. We had been concerned with the possible presence of a silicate crust, but M-types appear to have an entirely metallic surface, which has been seen in examining 16 Psyche, 216 Kleopatra and others.

The best option which we have now would be to either travel to the asteroid belt or to a near Earth asteroid and mine a large M-class asteroid. We chose to narrow this down further to the asteroid belt due to the abundance of suitable asteroids, and its close proximity to Mars, which would be the most likely destination for the ore.

4. Study Results

4.1 Mission Overview

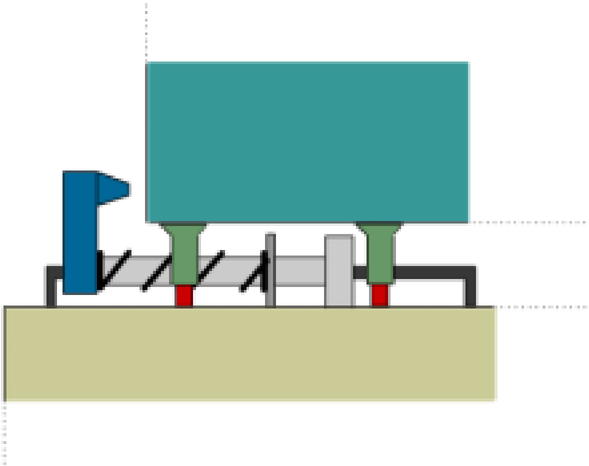
The mission will begin on Earth with the construction of the miner, canisters, and ferry, also know as Canister Linkage and Movement Project (CLAMP). These components will be transported to space aboard the space shuttle and assembled at an orbiting facility, such as the International Space Station (ISS). During the initial transit to the asteroid, the spacecraft will be composed of a stack containing the ferry, the miner, and the canister respectively. The spectrometer and computers on the miner will choose an asteroid before it arrives. Once a suitable asteroid is selected, the entire craft will descend into orbit using the engines on the ferry. At this time, the canister and miner will separate from the ferry and land on to the asteroid. Once in position, the miner will begin its operation. The canister will land and follow the miner around, transferring fuel and collecting ore. While the mining occurs, CLAMP will leave orbit and return to Earth for maintenance, refueling, and obtaining a new canister. When CLAMP returns to the asteroid, it will send the new canister to the surface. Meanwhile, the ore-filled canister will liftoff from the asteroid and rendezvous with the ferry in the asteroids’ orbit, using onboard thrusters and guidance. These two will dock and take the ore to wherever it is needed.

4.2 The Ferry

Ferry Overview

The ferry was designed to have three main components: 1) the engine block, which will consist of a VASIMR engine, 2) the ‘brain’ block, which will contain standard interplanetary navigation computers, as well as all the other hardware necessary to make it completely autonomous, and 3) the clamping system used to attach and detach from the canisters. The main purpose of CLAMP will be to bring the miner and the first canister out to the asteroid, and then shuttle fuel-filled canisters out to the asteroid, while bringing back ore-filled ones. (While multiple CLAMPs may be needed to shuttle the canisters to and from the asteroid, if production by the miner is higher than expected, the current proposal only calls for one.)

SWISH



The SWISH system (Securing With Interacting Springs and Hydraulics)

Canister securing clamps (a.k.a. the SWISH system: Securing With Interacting Springs and Hydraulics)

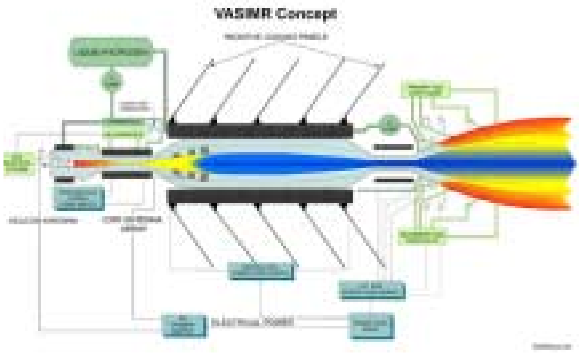
Due to the nature of the trip the canister-CLAMP system would undertake, and the shapes of the components of this system, a securing mechanism had to be designed. It would have to be reliable enough to work completely automated in interplanetary space and be able to perform its function many times without repair, while still being able to secure and control the canister for the long trip ahead of it. To this end, our group decided on using the following system.

The above picture is a side view of the SWISH system, with the canister at the top and CLAMP at the bottom. Shown in the picture is one of the several locking mechanisms, which will be placed in radial symmetry around the top of CLAMP. The SWISH system is centered around a rail, which will run from the center of CLAMP to its edge. Moving from the inside out, the first component encountered is a hydraulic press coming out from the top of CLAMP. This runs all the way to the locking claw, where it is attached. The rail runs unhindered through the center of the hydraulic press and tube. The next component is the spring base, which connects the spring to CLAMP, and provides support for the spring. The rail and hydraulic tube run unhindered through the spring base. The next component is the spring. It is important to note that when the SWISH system is in the closed position around a canister, the spring will still be extended beyond its relaxed length. This will provide a constant inward force on the locking claws, which will act as a fail-safe and prevent the canister from separating from CLAMP, should the hydraulics fail. The spring surrounds the hydraulic tube, but does not hinder its motion. The next components are the shocks, which are not drawn at their correct position, but only shown to aid the visual model. There will be multiple shocks on CLAMP, spread evenly over CLAMP’s top surface, which will aid the docking procedure. The final component is the locking claw. The bottom half of the claw is where the spring and hydraulic press terminate. The rail runs unhindered through the claw. The top half of the claw has a locking pin, shaped like a truncated cone, which will fit inside of the holes on the canister and miner, and secure them for transport.

It should be noted that the miner will have a SWISH system on top of it, too, in order to secure the first canister brought out to the asteroid, as well as any canister it is currently filling, if and when it decides to move to a different asteroid. This mission option will be discussed further in the **Mission Adaptability** section.

The SWISH system functions in the following manner: The CLAMP system contains an arm very similar in nature to the Canada Arm being built for the International Space Station. Initially, the Canada Arm on CLAMP will orient the canister and CLAMP, so that they are aligned in the necessary direction to facilitate easy docking. The hydraulics will push the claws outward, until the canister can clear them, and then hold them there. Then the Canada Arm will bring the canister and CLAMP together, until the canister strikes CLAMP’s shocks. The hydraulics will release pressure, and the claws will move in from the force exerted by the springs, securing the canister. Undocking is a simple reversal of this procedure.

Propulsion



For the propulsion system of the CLAMP, we choose to use the VASIMR (Variable Specific Impulse Magnetoplasma Rocket). It consists of three linked magnetic cells, one fore, one central, and one aft, each with a specific function. The forward cell handles the injection of the propellant gas and its ionization. The central cell acts as an amplifier and further heats the plasma. The aft cell is a magnetic nozzle, and converts the fluid energy into a directed flow. Plasma ions are injected from the forward cell, and then accelerated through an ion cyclotron. After the ions have gained enough energy, they are shot out the aft cell to produce thrust. A major reason for choosing the VASIMR system is its ability to use constant power throttling. This enables the fastest possible round trip time for a given amount of propellant. Since the miner will ore enough metal to fill a canister in approximately one year. This means that a canister has to be delivered to the asteroid at least once every year. Using the VASIMR, CLAMP will be able to make the round trip from the asteroid to low Earth orbit and back to the asteroid, again, in about one year. This makes VASIMR the ideal choice of a propulsion system for this mission.

4.3 The Miner

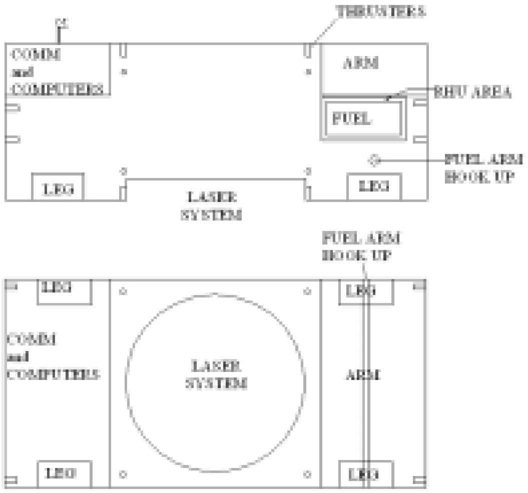
Initial Design Considerations

The most difficult aspect of our mission to design was the miner unit. Mining on an asteroid presents so many complications and unknowns that a radical design approach must be implemented. Not knowing very much about mining in general, we first did research into some of the mining techniques currently used on Earth. The more popular methods included drilling and blasting. However, if we wish to mine an asteroid, we must first look at the basic facts regarding asteroids.

First, an asteroid has a negligible local gravity. Only do the largest of asteroids have a gravity that is even remotely measurable. Secondly, asteroids do not contain any sort of atmosphere; they are simply part of the large vacuum of space. These two facts alone present obstacles as far as mining is concerned. If we are to drill, we are exerting a large amount of force into the ground. From basic Newtonian Mechanics we know that the ground will be exerting an equivalent reactionary force back at the miner. Such a force would easily throw the miner back off of the asteroid. If we decided to go about any sort of blasting process, we would run into several difficulties.

First of all, there is no atmosphere, and thus no oxygen to fuel an explosion. Assuming that oxygen cartridges could be provided to fuel the explosion, there are too many erratic factors. Aside from the unpredictability of using explosives in space, there is entirely too much of a danger presented to the miner. Having to consider these design constraints, we designed a miner unit that worked in a completely different manner.

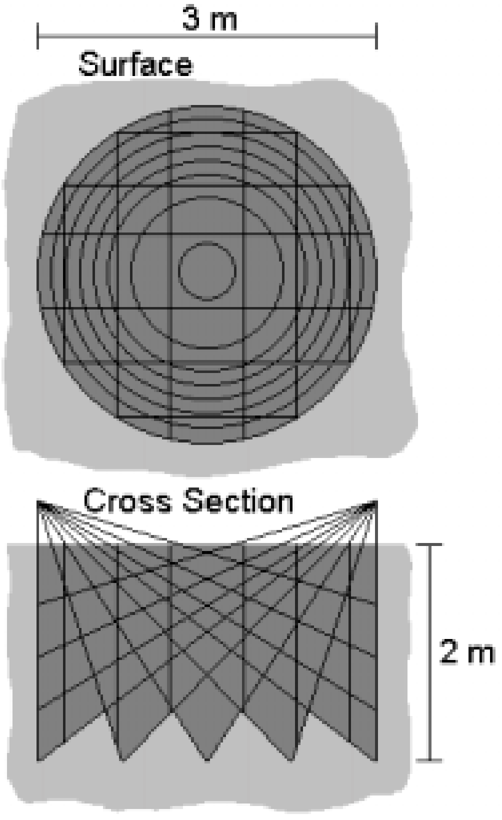
Miner Overview



Side and top views, respectively

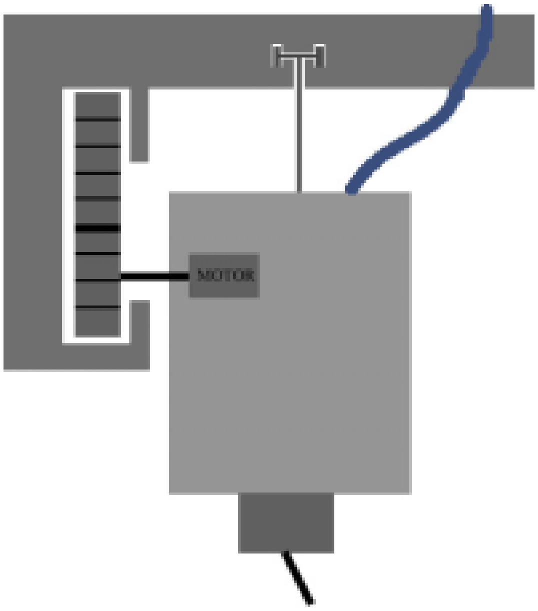
The asteroids present a natural reserve of minerals for future development. Yet for this resource to be useful, it must first be extracted from its current resting spot so that it may be brought to humans, so they can manipulate it into a more usable form. To this end, the miner will be able to break up the ore deposit into pieces between the size of gravel and soccer balls. The physical breaking apart of the rock will be done by a laser. The laser will vaporize a thin line through the rock, effectively slicing the rock into pieces. The gravel mix can then be loaded onto the ferry and returned to either the moon, Mars, or the ISS so that it can then be first processed into ingots of metal and then shaped into usable devices.

Laser Cutting System (LCS)



The laser drilling process will be the longest phase of the mining operation so much thought went into finding the most efficient pattern to use. There is inherently a trade off between the size of pieces cut and the time required to cut them. To maximize efficiency, the pieces must be as large as possible while still being easy to move around and store compactly. We concluded that the most efficient pattern would be to cut cones with progressively smaller angles until the entire cylindrical shape is cut into small pieces that are free from the surrounding metal. To prevent all the pieces from being shaped like a torus, the laser also cuts a grid through the area being mined. With the pictured cutting pattern, the entire shape to be broken up into pieces no larger than ~ 0.5 meters, with the majority being much smaller. The entire surface area cut is 140 m^2. The mix of small and large pieces allows for maximum space efficiency within the canister because the small pieces will fit in the cracks around the larger ones.

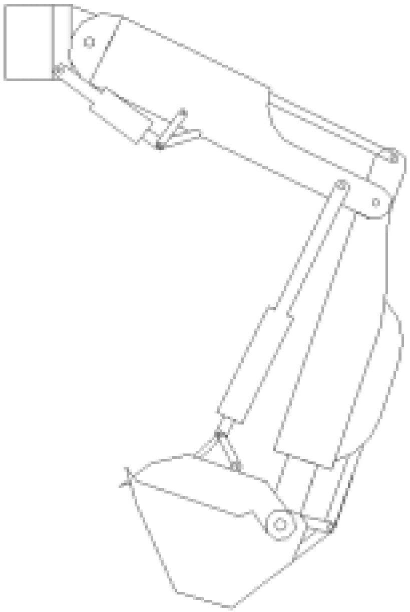
In order to cut the ore in this pattern, we have designed a circular track with a three-meter diameter that will hang just below the center of the miner. The track will be suspended by four hydraulic presses that allow it to be lowered out of its storage bay in the miner. If the miner is not sitting on level ground, these presses will be able to adjust to different heights in order to partially level the track and make drill the hole at the desired angle. A small motor and the emission point of the laser will hang from the track, moving on a circular gear fitting in a C-shaped joint. The entire apparatus will hang from a wheel above in order to support its weight (minimal on the asteroid). The laser will be mounted on a joint in order to allow it to make the necessary angled cuts. In order to cut a section of ore, the laser must drill until it reaches the desired depth, then advance on the track by the diameter of the laser and drill again. Once it completes the circle, it adjusts the angle and repeats the process. After all the cone-shaped cuts are finished, the laser drills a grid over the entire area by positioning itself along the track at a point perpendicular to the desired cut and adjusts the cutting angle every time the desired depth is reached.



Cutaway of laser and track

Because the canister holds 96 m^3 it will be necessary to collect material from seven holes to fill it up. With the round trip time of the ferry estimated to be one year, this would require one hole to be drilled and the ore collected approximately every 50 days. Collecting will only take a couple days at most, so that leaves a very conservative estimate of 45 days to drill the hole. With the above configuration it will require 140 m^2 to make the desired cuts. The speed required from the laser would then depend on the diameter of the laser. Assuming a diameter of 10^{-3} m, the total distance cut would be 140,000 meters, and the speed required would be ~ 2.2m per minute. The cutting pattern could be modified to reduce the number of cones and grid cuts. This would make the pieces more unwieldy and allow less ore to be transported back to earth, but if a sufficiently powerful laser is not developed by the time of this mission, the cutting could be scaled back to allow for enough time to mine a canister load of ore within the round trip time of the ferry.

Scooping Arm



In order to collect loose material and to transport it to the canister, we designed an arm similar to a backhoe. The arm connects to a top corner of the miner and rotates in all directions. The first section of the arm is about 3.3m and is hinged to the second part of the arm that is about 3.5m in length and its angle is controlled by hydraulics. The bucket is about 1m long and .5m deep and the width of all components is near half a meter. The flat bottom of the bucket contains electromagnets that can magnetically charge the bucket, further assisting the collection process. Excess silicates and other non-magnetic rocks will not be attracted to the bucket, minimizing unwanted debris. If the magnets would happen to fail, or if for an unforeseen reason we would need to resort to scooping with the bucket, a lid closed during transport ensures no debris is propelled towards the miner during the process. The two arm sections fold into one another with the bucket in between, so that the entire apparatus can be stored in 1mx2mx4m section on the topside of the miner, to be extended only when necessary. Both the lid and the bucket are controlled through hydraulics. The power requirements for the hydraulic pump and motors should not exceed 25kW, based on power requirements of backhoes. Technological advances and the fact that there is no gravity should lower this number.

As mentioned above, we were attempting to design a mining system that would cause no negative forces back against the miner. Unfortunately the arm will cause a small amount of these forces to be present. However measure have been taken to correct this problem, and will be described in future sections.

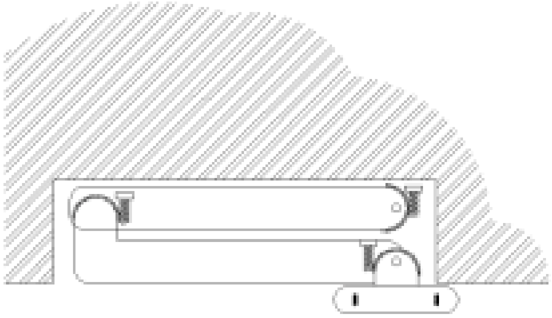
Thrusters/Legs

The miner is equipped with a total of 24 thrusters, 4 on each side of the miner. The dimensions of the thruster are 0.1 m in diameter and 0.25 m in length. The thruster will use a liquid fuel such as hydrazine, stored within the miner.

The thrusters are located equal distances from the center of mass, and spaced a close to the edges of the miner as possible. This balance is aimed to reduce moments being created from unequal thruster firing or from unequal shifts in mass within the miner.

This mobility is important for the positioning and movement of the miner for all aspects of the mining operation. Initially the thrusters will be used to land and move the miner to an acceptable mining position. After landing the thrusters become important as a backup system for holding the miner in place whenever forces, such as the ore scooping arm, lift it off the surface of the asteroid. When the thrusters are used in combination with each other three-dimensional rotation and translation becomes possible. This is necessary for moving from one mining site to another.

The legs are designed to be adjustable in height, holding the miner unit above the asteroid surface anywhere from about 5 cm to 60 cm. This allows the miner to rest flat on the surface despite small changes in the elevation of the asteroid under each individual corner of the miner. The legs extend and retract by a screw and thread system, as shown in the diagram. When the screw turns, the parallel threads in contact move up or down, thus pivoting each segment of the leg and changing the vertical height from the asteroid surface.



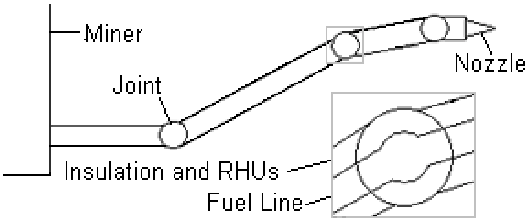
The miner unit is anchored to the asteroid by electromagnets placed in the feet of the legs. These electromagnets produce the necessary force to counteract any forces that might push the miner off the asteroid surface (mainly any digging by the arm). Using a design given in *Electromagnetic Devices* by Herbert C. Roters, such an electromagnet producing 500 N of attractive force on the asteroid would require only about 10 watts to run. This force, when exerted by each leg, should be more than enough to hold the miner on the surface and counteract all upward forces. The minimal temperature increase caused by resistance in the coils in the electromagnet is dissipated by driving a heat sink in to the surface of the asteroid. Of course, this heat sink must be made of a strong, highly heat conductive metal alloy, and is designed to have maximum surface area in contact with the "ground" of the asteroid, thereby dissipating the heat built up by the magnet into the heat conductive iron-nickel material of the asteroid.

Power

In order to power the miner, a new technology is needed. We expect that the arm will use about 25 kW of power and the laser could use as much as 30 kW. While these will not be operated at the same time, the continuous power consumption would be about 30 kW. To have a wide safety margin and to ensure that sufficient power is available, we believe the power source should provide 35 kW. With power consumption at this level, no traditional power generation technologies will work. The asteroid belt is too far from the sun to allow the use of solar power, which would be a bulky, unpractical alternative. Battery power would be nearly useless because we expect the miner to operate for about 10 years before returning to earth for maintenance and it would be drained quickly. The current solution to power generation for missions to the outer planets of the solar system is the use of RTGs (Radioisotope Thermoelectric Generators), but due to the large power requirement, this will not be feasible either. With current RTG technology, each unit produces about 280 W, so in order to produce sufficient power, 125 RTGs would be needed. This would be extremely expensive and would take up an unacceptable amount of space. The solution is to use a nuclear reactor, such as the SP-100, which is designed for use in space. It would be able to provide between 10 and 100 kW of power, which is exactly for what we are looking. This program was canceled a few years ago due to lack of a clear mission, but much progress was made. Extensive development and commercialization of space would require such a power source, so developing the technology would bring great benefits that extend beyond this mission.

Fuel Arm Connection

The thrusters located on the Miner will require fuel. The fuel, probably hydrazine, will be brought out with each canister. In order to transfer the fuel from the canister to the miner, a fuel transfer arm had to be designed.



The fuel arm is housed completely within the main body of the miner with an opening on the long side of the miner. It is assumed that the canister can be positioned on the side of the miner within 2 to 3 meters, thereby exposing the entry plug on the side of the canister for the fuel arm to attach to. The nozzle will find the entry plug by means of an automated docking procedure.

The entire length of the fuel arm is covered in insulation and a number of Radioisotope Heater Units (RHUs). These are imbedded in the insulating layer to prevent the liquid fuel from freezing. The fuel arm is equipped with three ball-in-socket joints that allow the fuel arm to be positioned into the entry plug. The joints have limited freedom of movement because they must accommodate the fuel line housed within the arm.

The fuel storage tank on the canister is equipped with a divider capable of applying pressure on to the fuel, which forces the fuel to flow through the fuel arm into the miner. Four hydraulic jacks evenly spaced around the edges would create the necessary pressure.

Asteroid Recognition and Science Components

The Miner will be equipped with various pieces of equipment to gather in-depth knowledge of the asteroid. The Miner will include a spectrometer to determine the chemical composition of the surface rocks along with the rocks that are mined. While most previous analyses of the solar system have relied on surface readings, the Miner will create a unique opportunity to study the internal body of a non-terrestrial object. Additionally, the ore returned to Earth will be studied in great detail to allow us to learn much more about the composition of asteroids.

A high-resolution, wide-angle camera would be installed on the side of the Miner to take detailed photos of the surface of the asteroid. A camera will also be placed on the underside of the Miner so that pictures can be taken of the internal walls of each hole being dug. This could reveal any layering of the metal or the depth of any minor surface reactions such as desert varnish or oxidation.

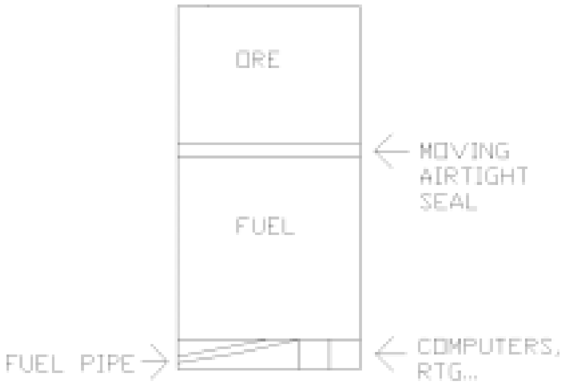
A strain gauge will be available to determine the strength of gravity on the asteroid. From the gravity readings, the overall density of the asteroid can be determined. This information should make it possible to speculate whether the internal composition of the asteroid consists of heavier elements. If the center does consist of heavier metals, it may become preferable to attempt to modify the mining operation such that deeper holes are dug, or holes are dug on top of previous holes, so that the heavier, rarer metals may be reached.

Such analytical devices will help scientists more fully understand the chemical composition and thus the geological and formational history of the asteroids and perhaps the solar system as well.

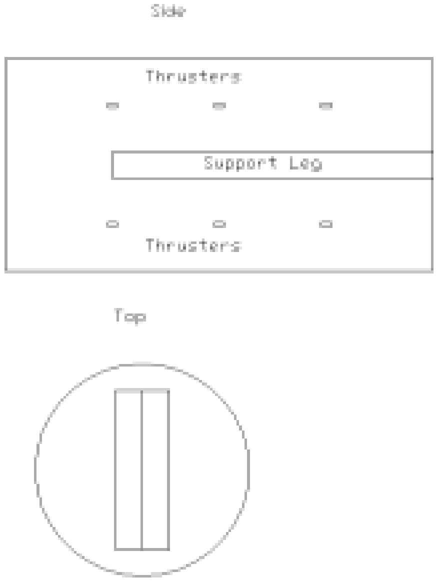
4.4 The Canister

Canister Overview

Mined ore can not be put to any good use if it can not be transported back to Earth's orbit to be processed. Therefore, it was necessary to design a system that would be able to transport the ore from the asteroid back to Earth orbit. Also, a system had to be design which could bring needed fuel and parts out to the miner, so it would not have to return to Earth for maintenance, but could rather stay and mine the asteroid for as long as possible. It was decided that a vessel that could accomplish both of these tasks at the same time would suit the mission's needs the best. With this in mind, the canister design was chosen.



Internal View



Side and top views, respectively

The canister will have the following features: first, it will be encircled by three rings of four positionable thrusters, which will allow the canister to hover along the surface of the asteroid when it needs to follow the miner around, as well as allowing it to position itself correctly for fuel hookup with the miner. Second, the canister will have three legs every 120 degrees around the outside of it, which will be placed down to stabilize the canister as it is being filled. Third, it will have a set of two sliding doors on the top, each 3m by .5m, which will provide an opening of 3 square meters for the mined ore to enter. Fourth, the canister will have SWISH docking points every 60 degrees around the bottom of it. Fifth, the canister will have a fuel hookup near its base, that the miner’s fuel arm will be able to attach to. Sixth, the canister will have all the necessary power supplies and computers in the bottom .5m of its height. It is from this point that all the thrusters, fuel discharge, and the orientation will be autonomously controlled. Finally, the canister will have within it a moveable pressure seal. This system will be discussed in more detail below.

It should be noted that there will have to be more than one canister active at all times: one at the asteroid, being filled, and one in transit with ore or fuel.

Fuel/Ore divider

In order for the canister to be able to hold both liquid fuel, and replacement parts and ore, a unique type of storage system needed to be designed. The storage area of the canister will act like a syringe. In the lower portion of the canister, liquid fuel will be kept pressurized by a movable, airtight seal against the inside perimeter of the canister. On top of this seal solid objects, such as spare parts, or the mined ore, will be able to be kept in a non-vacuum sealed chamber. As the liquid fuel is pumped out, the airtight seal will follow the level of the fuel down. This will make the chamber for the ore larger, enabling us to carry more materials to their destination. This will also keep the pressure in the fuel chamber at a high enough rate to push the fuel into the miner, as necessary.

Canister Power Source

The canister will require electricity for the computer and navigation system, the ore storage compartment doors, the stabilizing legs and the moving canister divider. No more than one system will be in operation at the same time, except for the computer, which will run constantly, so we estimate that peak power usage will be less than 1 kW. Heat energy will also be needed to keep the fuel from freezing. We examined possible power sources to find out what would be the most effective way to power the canister. Solar energy density decreases by the inverse square of distance, so available solar power in the asteroid belt will be about 10% of what it is at earth. Additionally, asteroids rotate, which keeps any given spot on them pointed away from the sun half the time. The canister needs to be maneuverable and able to land and take off frequently and having solar panels that are many of meters long would compromise this ability. Because of these considerations, we felt that solar power would not be an effective method of powering the canister.

The power source that most closely meets the mission needs is an RTG. An RTG (Radioisotope Thermoelectric Generator) generates about 250 W of electricity by using the heat generated by the natural decay of plutonium to heat a piece of metal. This is connected to another piece of metal kept at a lower temperature, which induces current through the metal. Current induction in this manner is called the Seebeck effect. The most recent RTGs used in space exploration are those that power Cassini. Three RTG units were used, producing a total of 888 W of electricity at launch. The amount of electricity generated is gradually reduced over time due to the fact that radioactive decay is a consuming process that eventually extinguishes itself. By the end of Cassini's mission, which will be 11 years after launch, the RTGs will produce 628 W, still a very usable amount. The RTGs on the canister can be replaced as necessary when it returns to earth to be unloaded, but the lifespan of the generators should allow for many years of operation. A useful byproduct of the electricity generation process is the significant amount of waste heat, which would be used to keep the fuel temperature above freezing levels.

4.5 Mission Window

There are certain times, or windows of opportunity, when we should send the ferry to the asteroid belt to ensure the shortest trip. The closest M-class asteroids in the asteroid belt are located at about 2 AU. Therefore, the shortest trip from the Earth to the asteroid is 1 AU, or 1.496e11 m. Using the VASIMR propulsion system, we are estimate that we can travel this distance in about 8 months, or 240 days. So we want to launch our ferry when the asteroid is lagging behind Earth 240 days, or 200 degrees. Eight months later, the ferry and the asteroid will both arrive at the same spot in the asteroid's orbit. One of these transfer opportunities will occur every 19 months. The best of these opportunities will be when Earth is at the opposition of its and the asteroid's orbit during the launch. If and when this happens will depend on the specific asteroid chosen and its relative position to the Earth, but it should be about every 13 years.

4.6 Future Adaptability

Due to the modular nature of this mission, it offers a wide range of adaptability to fit varying needs in the future as they arise. Should future technologies allow for higher mining rates, multiple canisters can be loaded during each stage of the mission. Also, multiple miner units can be employed. While the additional miners can be set up on the initial asteroid, they can also be used on different asteroids to obtain a wider variety of metal. With any of the situations described above, additional ferries would be needed to handle the extra workload. As can be seen, any combination of ferries, canisters and miners can be combined to obtain an optimum amount of ore.

5. Assumptions, Recommendations, Conclusion

Assumptions

For the design of this mission, several assumptions had to be made. Many of these assumptions stemmed from the period of when such a mission would occur. As discussed earlier, this mission would not be implemented until Mars colonization efforts or a similar large-scale mission sequence are underway. Such efforts we speak of would not take place for probably at least another thirty years. In that time, there will be numerous advancements in technology. Among those technologies include drilling laser capabilities, the VASIMR drive, and the SP-100 power generator. The VASIMR and SP-100 are both programs that NASA has cut recently due to budget cutbacks. We feel that these are two programs that are very important to the future of space exploration that will resume well before this mission would take place.

Future Studies

The results which we have presented are only the preliminary stages of a full investigation into the topic of asteroid mining. This was a one-semester long study that looked into only the more basic aspects of the mission approach. Any future studies will need to analyze the different components in much more detail.

Mining Process

The mining process, more than any other aspect of this mission, needs to be scrutinized on many levels. While the basic concepts are sound, much more extensive research and testing must be done with the details of the process. It would be very helpful to do testing of laser capabilities in such a situation. The specific laser cutting method must be tested and perfected. The laser design used on the miner involved the laser being on for extremely long amount of time. For such a high-intensity laser, it must be tested for long-term usage abilities. Also, the design of the arm must be perfected. The use of electromagnets on the bucket or the miner arm to retrieve the ore is an area that has not been thoroughly tested. Similar arm designs have been heavily tested in construction applications on Earth, however they do not involve the use of electromagnets of the buckets. This technology would obviously have relevant applications in terrestrial construction.

Mission location

The tests of determining the miner's exact strengths and weaknesses will also help with the asteroid selection process. Through the use of spectral analysis, and other methods, an asteroid can be selected that has an ideal composition on its surface. Current studies have only analyzed a small portion of the asteroids in the solar system so that we can not yet effectively select an asteroid to mine. However, a full analysis of both near-Earth asteroids as well as those located in the main asteroid belt will yield a better idea of where this mission is headed. This information will also offer much insight as to the time frame between launch windows.

6. Outreach

Throughout the semester we hosted or participated in the scholastic and public events and activities listed below in order to create appreciation for and spread information about the importance of space development and asteroid mining.

Friday, April 20, 2001
HEDS-UP Presentation to Dr. Chris Churchill's STS 497I Space Exploration Class.

Saturday, April 21, 2001
Exhibit with Mars Society at Space Day event at Penn Sate. This event, organized by the PA Space Grant Consortium (PSGC), allowed students and members of the community to view exhibits of various Penn State groups and programs whose purpose is space-related research and education. It was held from 10am until 3pm in Heritage Hall of the HUB-Robeson Center. For more information on Space Day at Penn State please visit http://www.psu.edu/spacegrant/spaceday/index.html.

Wednesday, April 25, 2001
Presentations open to public. Beginning at 7:30pm, the first presentation will commence, with a second following at 8:30pm, both held in 108 Wartik Lab.

World Wide Web
The group's web page http://www.personal.psu.edu/kfs113/hedsup/ was frequently updated throughout the project. The page not only provided team members with access to current information on the progress of the project, but it also was an educational tool for students and the community, having many links to sites on asteroids, Mars, and other space-related issues. Links to pages such as the NASA HEDS-UP page http://cass.jsc.nasa.gov/lpi/HEDS-UP/, the PSU Chapter of the Mars Society http://chapters.marssociety.org/pa/PSU/, and many others, enhanced the site by giving team members easy access to vital space-related information.

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