A Review of Extra-Terrestrial Mining Robot Concepts

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ABSTRACT

Outer space contains a vast amount of resources that offer virtually unlimited wealth to the humans that can access and use them for commercial purposes. One of the key technologies for harvesting these resources is robotic mining of regolith, minerals, ices and metals. The harsh environment and vast distances create challenges that are handled best by robotic machines working in collaboration with human explorers. Humans will benefit from the resources that will be mined by robots. They will visit outposts and mining camps as required for exploration, commerce and scientific research, but a continuous presence is most likely to be provided by robotic mining machines that are remotely controlled by humans.

There have been a variety of extra-terrestrial robotic mining concepts proposed over the last 40 years and this paper will attempt to summarize and review concepts in the public domain (government, industry and academia) to serve as an informational resource for future mining robot developers and operators. The challenges associated with these concepts will be discussed and feasibility will be assessed. Future needs associated with commercial efforts will also be investigated.

INTRODUCTION – TERRESTRIAL RESOURCES AND MINING

In 2007 the total global market capitalization of mining companies was reported at US $962 billion, (Businessweek, 2007) which is a substantial industry that provides raw materials to a successive variety of downstream industries that add value by producing products from these minerals to benefit human activities on Earth. In 2009, the global mining equipment market was valued at US $45.4 billion (Freedonia, 2009). However, the terrestrial resources are often hard to access and the mining activities involve substantial costs and logistics in remote regions, similar to space exploration. The role of humans interacting with mining equipment has also become a new topic for investigation as intelligent equipment becomes ever more pervasive on Earth and in space.

Asteroid and Comet Impact Mining

Natural impact craters are the result of the hypervelocity impact of an asteroid or comet with a planetary surface. Impact is an extraordinary geological process involving vast amounts of energy, and extreme strain rates, causing immediate rises in temperature and pressure that produce fracturing, disruption and structural redistribution of target materials (Grieve, 1994). Some economic deposits of natural resources occur within specific impact structures or are, in some way, impact related. Masaitis (1992) noted approximately 35 known terrestrial impact structures that have some form of potentially economic natural resource deposits. In a review of the economic potential of terrestrial impact structures, Grieve and Masaitis (1994) reported that there were 17 known impact structures that have produced some form of economic resources. In North America alone, the value of impact related resources was in excess of $18 billion/year (1994 $). Terrestrial impact craters are important geological and geomorphological objects that are significant not only for scientific research but for industrial and commercial purposes and many impact craters remain to be discovered on Earth with possible resource related economic benefits. The structure may contain commercial minerals produced directly by thermodynamic transformation of target rocks (including primary forming ores) controlled by some morphological, structural or lithological factors and exposed in the crater (Masaitis,1992). The 80 km diameter Morokweng crater in South Africa has approximately 500 ppm of nickel in its impact melt rocks which appear to have come from the impacting body which was an ordinary chondrite (McDonald et al, 2001).

Characteristics of Terrestrial Impact Natural Resource Deposits:

The location and origin of economic natural resource deposits in impact structures are controlled by several factors related to the impact processes and the specific nature of the target. The types of deposits are classified according to their time of formation relative to the impact event: progenetic, syngenetic, and epigenetic.

The three largest known terrestrial impact structures are the Vredefort dome (a central rebound peak), the Sudbury crater in Canada and the Chicxulub Crater in the Yucatan, Mexico. Much smaller, but older, is the 16km diameter water-filled Suavjärvi crater in Russia, which is estimated to be older than Vredefort (2020 million years), at approximately 2400 million years. The Vredefort structure is currently regarded as the biggest and oldest (but one) clearly visible impact structure on Earth (Figure 1). It just beats the Sudbury impact structure in Ontario, Canada for this ranking. The crater has a diameter of roughly 250 - 300 km (155 - 186 miles), larger than the 200 km (124 miles) Sudbury Basin, and the 170 km (106 miles) Chicxulub crater. This makes Vredefort the largest known impact structure on Earth (though the Wilkes Land crater in Antarctica, if confirmed to have been the result of an impact event, is even larger at 500 kilometers across). The Sudbury structure is estimated to be 1850 million years old. The significance of the Vredefort Dome is that when it hit the earth, the gold-bearing rocks of the Witwatersrand, which were deposited some 800 million years prior to the Vredefort impact, were covered with impact debris that protected them from erosion over the subsequent two billion years. Other impact related processes may have contributed to the abundance of economically beneficial minerals in this region. In general, syngenetic process with economic natural resources include impact diamonds, Cu-Ni Sulphides and platinum group and other metals (Grieve).

Epigenetic Impact craters often result in reservoirs for oil and gas. The fractured rock is porous and permeable, so hydrocarbons flow into it and stay trapped within it. In a 2004 paper, Kring et al. described hydrocarbons within the Chixculub impact crater, which is the crater his group linked to the extinction of dinosaurs. There are much larger deposits, however, associated with that impact event. The impact ejecta around the crater is a huge reservoir for petroleum; most of the oil that Mexico extracts from the Campeche Bank comes from that impact ejecta interval, as described by Grajales-Nishimura et al. (2000) and Grieve (1997). The Red Wing crater in the U.S. is another well-known site with hydrocarbons (e.g., Gerhard et al., 1982; Grieve and Masaitis, 1994; Grieve 1997). Likewise, the Ames crater is a reliable reservoir for hydrocarbons (Johnson and Campbell, 1997).

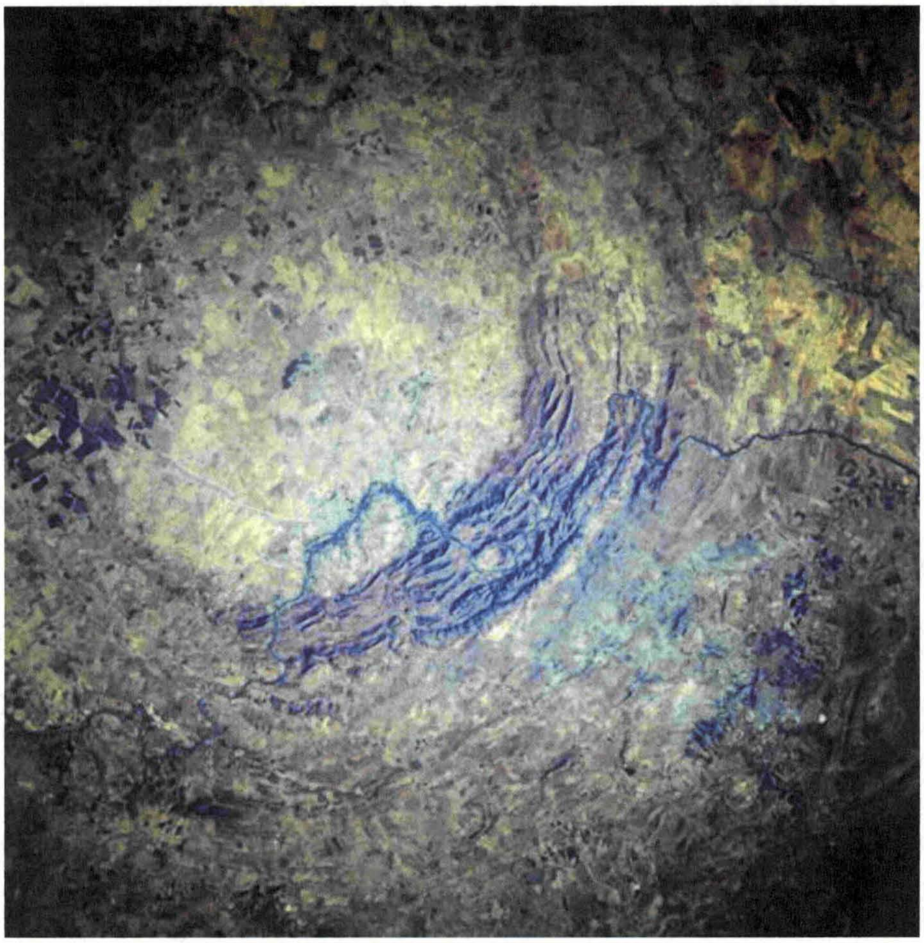

Figure 1: Vredefort Crater – 62 miles southwest of Johannesburg, South Africa, NASA

Since extra-terrestrial objects such as asteroids and comets have contributed to substantial resource deposits on Earth, in some cases by directly depositing metals such as nickel from chondritic bodies, and there are vast resources in outer space, a compelling case exists for the mining of these resources directly at the source, in our solar system. This may be at the asteroid itself, or on planetary bodies such as Earth's moon in local impact craters. If the costs of space transportation can be reduced, and the necessary technologies can be developed, then it is possible that in the future an economical and profitable case can be made for space mining endeavors for local use of these resources in space and eventually even for export to Earth.

SOLAR SYSTEM RESOURCES

During the Solar System formation, there were a variety of processes taking place that resulted in planetary body formation. Due to the varying conditions that existed in the vicinity of each planetary body, a zonal structure developed ranging from metal rich silicates near the Sun, through concentrations of organic and rocky material in the mid solar system to concentrations of various ices in the outer solar system. In addition, gravitational perturbations cause asteroids and comets to enter into the inner solar system in periodic orbits. In the early formative stage, a cloud called the solar nebula formed, and as it cooled down, the matter condensed to form various objects. Near the sun, the higher temperature only allowed metal rich minerals to condense (Mercury, Venus, Earth Mars), while further away in the inner asteroid belt between Mars and Jupiter, some chondrites formed (that were never affected by melting and collisions), while other asteroids show significant lava based rock and metal interiors. In the outer asteroid belt, carbonaceous (carbon rich) materials and other chondrites condensed, in various sizes and forms. (Mueller et al., 2010)

Further out, between the outer belt and Jupiter, the temperature and conditions are such that the presence of water ice is possible, so that in this region there are many moons with water and other ices present today. Jupiter, Saturn and Uranus all have rings that are composed of ice particles and they have many moons, some of which remain undiscovered. These moons contain a variety of icy compounds such as water ice, carbon dioxide ice, methane and ammonia ices. In this region, near Jupiter, compositions of 50% water ice and 50% mineral rock are not uncommon, while further out, near Saturn, the composition becomes mostly water ice. Finally in the outer solar system, the temperature conditions sustain ice that is made of methane and ammonia. (Mueller et al., 2010)

The resource pattern in the solar system indicates that there is more water ice available in the outer solar system, while the inner solar system has a higher potential for metallic ores. The Moon and asteroid belt have a variety of resources varying from iron-nickel to silicates and possibly sub-terranian water ice. A human-robotic architecture using ISRU with space mining is possible, where these solar system resources are used to sustain a human presence in outer space. (Mueller et al., 2010)

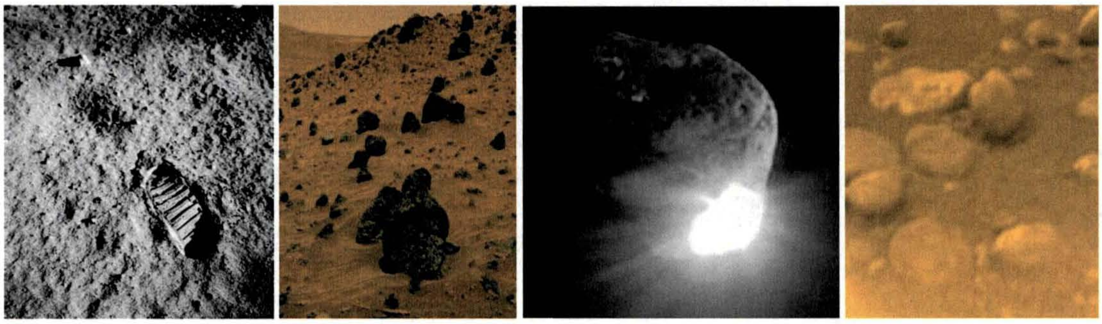

Figure 1A: Surfaces of the moon, Mars, Comet Temple 1 and Titan

Table 1 summarizes the resources known to be available in the various destinations of interest for human/robotic exploration.

Table 1: Solar System Resources (TBD = To Be Determined, this table is representative and not comprehensive.)

	Resources				
	Moon	**Mars**	**Asteroids**	**Comets**	**Outer Planets**
Regolith	H20 ice, O2, OH, Granular powder, Shielding, Insulation Structural, Manufacturing Feedstock	H20 ice, Rocky with sand, Shielding, Structural, Insulation, Manufacturing Feedstock	Varies – granular powder TBD	H20 ice TBD	TBD
Volatiles	H2O, CO, H2, Hg, H2S, NH3, He3, CH4, Ca, C2H6, CH3OH, C2H4	CO2, O, N2, H2O, Cl, Br, Fl, CO, TBD	H20, TBD	H20, CH4, TBD	H, He, CH4,N2 H2O, CO2, CO, NH4, C2H6 TBD
Minerals	Feldspars Pyroxines Olivines Oxides	Basalt Andecite Hematite Silicates Sulfates Carbonates Pegmatities Oxides, TBD	Silicates Oxides TBD	TBD	Silicates Oxides TBD
Metals	Al, Fe, Ti, Mg, Ca, TBD	Al, Fe, Ti, Mg, Ca, Na, Cu, Zn, Pb, Cr, Ni, Co, PGM, TBD	Fe, Ni, Ti, PGM et.c. TBD	TBD	Fe, TBD
Solar Power	Yes	Yes	Yes	Yes	No
Thermal gradients	Yes	Yes	Yes	Yes	Low
Vacuum	Yes	No: CO2, N2, H20, Ar, O2, CO, Ne, Kr, Xe, O3	Yes	Yes	No - varies
Rare Earth Elements	Yes associated with KREEP	TBD	TBD	TBD	TBD
Water	Limited - Poles	Yes	Yes	Yes	Yes - Abundant

The resources on the moon are fairly well understood, although ground truth data is essential to confirm orbital data observations, especially at the poles. Mars is geologically much more complex than the moon and is less well understood, although recent missions have increased the state of Mars knowledge significantly. Asteroids and Comet resources are not very well understood, but in recent years, missions such as "Dawn" and "Hayabusa" have increased that understanding. The outer solar system resources are poorly understood at this time.

IN-SITU RESOURCE UTILIZATION

The Earth's gravity well precludes the transportation of large quantities of equipment, supplies and propellants into space to support science and exploration goals. The average expendable launch vehicle transportation costs are currently estimated to be US $4,000 / lb which has prevented humans from expanding their economic sphere of influence past Geo-synchronous orbit. Nevertheless, if strategic location and energy are considered to be resources, then the near Earth space industry using space based resources already exists today. This consists largely of tele-communications satellites and has been valued at US $80 -$100 Billion in annual revenues. Meanwhile, the total size of the space industry has been reliably estimated at about $251 billion in 2007 according to the Space Foundation's "The Space Report 2008". This is evidence that, if the infrastructure is appropriately developed, and a market exists, then a space based industry is possible and beneficial to life on Earth.

In the early stages of human expansion into space, the markets for local resources will also be local. This methodology of using local resources and therefore substituting Earth derived resources is referred to as In-Situ Resource Utilization (ISRU).

When considering all aspects of ISRU, there are 5 main areas that are relevant to human lunar and Mars exploration (Sanders et al, 2010):

1. Resource characterization and mapping for planning and science
2. In-situ production of mission critical consumables and propellants for crew, power, and transportation
3. Civil engineering and construction for hardware and crew protection and infrastructure growth
4. In-situ energy production and storage
5. In-situ manufacturing, repair, and reuse

These areas are explained in Table 2, using the Moon as an example.

Other destinations, such as Mars, Asteroids, and the outer Jovian planets all have their own flavors of ISRU with various related needs and technologies. This paper will focus on acquiring resources through ISRU mining of regolith, minerals, ices and metals which is one of the first necessary steps and will benefit all aspects of ISRU.

TERRESTRIAL ROBOTIC MINING

With automation technology robustness and capabilities progressing rapidly, terrestrial mining is trending towards more automation which results in removing humans from dangerous areas as well as increasing production. This will result in:

- Increased safety and improved working conditions for personnel
- Improved utilization by allowing continuous operation during shift changes
- Improved productivity through real-time monitoring and control of production loading and hauling processes
- Improved draw control through accurate execution of the production plan and collection of production data

- Lower maintenance costs through smooth operation of equipment and reduced damage
- Remote tele-operation of equipment in extreme environments
- Deeper mining operations with automated equipment
- Lower operation costs through reduced operating labor
- Reduced transportation and logistics costs for personnel at remote locations
- Control of multiple machines by one tele-operator human supervisor

Table 2. ISRU Main Areas, Functions, and Purpose (Sanders et al.)

	ISRU Tasks & Activities	Purpose
1	*Resource Prospecting/Mapping*	*Measure and map potential resources for site selection and ISRU planning; Opportunistic Science*
1a	Chemical/Mineral Characterization & Mapping	Measure and map regolith geotechnical and mineral/chemical attributes of surface regolith and subsurface down to 0.5 m to select feedstock for ISRU functions (supports lunar science objectives)
1b	Hydrogen/Water/Volatile Characterization & Mapping in/near Permanently-shadowed Craters	Measure and map geotechnical and hydrogen/water volatiles down to 1 meter to assess potential for large scale extraction (supports lunar science objectives)
1c	Solar Wind Volatile Characterization in Regolith and Pyroclastic Glasses	Measure solar wind volatile concentrations in surface regolith (especially high titanium mare) and pyroclastic glass material (supports lunar science objectives)
2	*Consumable Production*	*Reduce Earth delivery logistics; Enable new exploration*
2a	Oxygen Extraction from Regolith	Produce oxygen for crew, EVA, and propulsion
2b	Water/Hydrogen/Helium Scavenging from Altair Lander	Convert residual propellants into water; Produce water with excess hydrogen and In-situ oxygen; Scavenge helium pressurant from tanks
2c	Solar Wind Volatile Extraction from Regolith	Extract and separate hydrogen, nitrogen, helium, carbon, etc. from regolith
2d	Water/Hydrogen/Volatile Extraction from Permanently-shadowed Crater Regolith	Extract and separate hydrogen, water, ammonia, methane, hydrogen cyanide, etc. from regolith
2e	Methane/Carbon Dioxide Production from Trash/Crew Waste Processing	Process trash and crew waste to produce methane and carbon dioxide
2f	Metal/Silicon Extraction from Regolith for Manufacturing	Produce silicon, iron, aluminum, etc from regolith as feedstock for in-situ manufacturing
2g	Cement and Modified Regolith for Construction	Produce feedstock for construction thru modification of bulk regolith
2h	Plant/Fish/Livestock Growth Support	Provide infrastructure and feedstock to support plant growth and fish/livestock food production.
3	*Civil Engineering & Construction*	*Reduce mission and crew risk; Enable infrastructure growth*
3a	Excavate and transport regolith for consumable production (2a, 2b, 2c, 2d, 2f, & 2g)	Provide regolith for in-situ processing
3b	Construct Landing Pads & Roads (clear areas, berms, sintering)	Protect hardware from plume damage; Mitigate dust around surface infrastructure
3c	Utilize regolith for Radiation Protection (burial or covering)	Bury/cover habitats to protect crew from solar/galactic radiation; Bury/cover nuclear reactors with regolith
3d	Construct Structures from In-situ Materials	Modify regolith and construct structures for hardware protection and crew
4	*Energy Production and Storage*	*Reduce mission risk; Enable infrastructure growth*
4a	Construct Thermal Energy Storage from In-Situ Materials	Modify regolith for use as thermal storage media for energy storage and generation
4b	Construct Solar Arrays from In-Situ Materials	Modify regolith and fabricate solar arrays on lunar surface for power generation growth
5	*Manufacturing & Reuse*	*Reduce Earth delivery logistics; Reduce mission risk*
5a	Hardware Scavenging and Recycling	Remove fluid and electrical components from dead landers and infrastructure for reuse (modularity required)
5b	Rapid Prototype Part Fabrication	Produce spare parts from powdered metals and plastics

This is currently achieved by establishing worker-free zones where autonomous transport and dumping is instituted. The excavation and loading are remotely controlled. This allows an operator to manage several automated machines simultaneously. Parts of such systems consist of the zoning systems, network systems, on-board control systems, operator control systems.

Sandvik is one of the suppliers that offer systems to install in underground and surface mining operations. Sandvik's AutoMine systems are currently operating at Codelco's El Teniente Mine in Chile (since June 2004), Inmet Mining's Pyhäsalmi Mine in Finland (since January 2005), De Beers' Finsch Mine in South Africa (since August 2005) and Williams Mine in Canada (June 2007). A system is also installed in Sandvik's Test Mine in Tampere, Finland, which is used as a platform for developing and testing future system developments and for demonstration purposes (Sandvik, 2011).

Rio Tinto's 'Mine of the future' project has been focused on remotely controlling mining operations thousands of miles away but with the goal of automating the whole mine-to-port chain. It aims to increase productivity, reduce costs, and improve health, safety and environmental performance. It was reported in the press that " in 2011 Rio Tinto signed a deal with Japanese firm Komatsu to buy at least 150 Autonomous Haulage System trucks over the next four years. These trucks will be used in Rio's iron ore mines in the remote Pilbara region of Western Australia. Packages to draw mine workers to the region — attractive salaries, food and accommodation, and weekly return flights home, have contributed to a 40% rise in operating costs in the past five years. The new driverless trucks will be remotely-controlled from Rio's operations centre at Perth, almost 1,000 miles from the mines, resulting in large cost savings".

Caterpillar is another major player in the mining machinery market offering and developing automation systems for use in the mining industry. In 2011 it was reported in the press that "Fortesque Metals Group has recently announced that Caterpillar will supply it with 12 driverless trucks by the end of the year, and is aiming to increase the fleet to 45 by 2015."

NASA and Caterpillar have teamed up to study the requirements and implementation of remotely controlled excavators for extra-terrestrial as well as terrestrial use. An example of one of the adapted machines is the 287C semi-autonomous Multi Terrain Loader (MTL) as shown in Figure 2.

Figure 2: The Caterpillar 287C semi-autonomous Multi Terrain Loader.

Maptek is a company that delivers the MineSuite software and measurement systems to gather information across mining operations. This includes sensors, communication networks and software to collect, store, process and display/report the data to the operators at a variety of level of detail. This is used by among others, Newmont Mining Corporation. Mine site technologies delivers communication, tracking and telemetry hardware and software and is in use in over 500 mines across the world.

The deepest mine today is the Mponeng gold mine located in South Africa, it is 13,000 feet (2.46 miles) deep, and the goal is to reach 14,500 feet (2.75 miles) At this depth, the mine shaft temperature can reach 134 degrees F (Xian, 2012). The South African mining industry has set the limit for human working conditions in underground mines at 83 F. To make working conditions tolerable, huge amounts of chilled ice slurry water are sent down into the mines and circulated to cool down the underground environment at a very high cost. The best, easiest accessible resources all over the world have been mined out, so that the mines have been forced to go deeper. As the mines get deeper, the appeal of substituting human labor with automated machinery becomes higher. Mark Cutifanti, Chief Executive Officer (CEO) of AngloGold Ashanti says that his company is "on the cusp of the most significant change we have seen in the deep-mining industry in 100 years", (Xian, 2012). Conventional methods for excavating mines below the ground are called "drill and blast", and new methods such as Shaft Boring Systems (SBS) built by the German firm Herrenknecht are being considered by Rio Tinto and AngloGold Ashanti. Current drill and blast methods are estimated to be feasible up to 16,500 feet (3.13 miles) depth, but gold ore deposits exist up to 25,000 feet (4.73 miles) deep in the West Witts mines, and the threshold for human mining is considered to be 33,000 feet (6.25 miles). However it may not be economical to use humans at those depths, so the need for terrestrial automated robotic mining equipment is increasing. (Xian, 2012)

The increase of automation has been enormous over the past 10 years and will continue to grow resulting in increased human safety, increased production and productivity.

With the rapid acceleration of information technology and micro-processor capability as empirically shown by Moore's Law, the technologies driving robotic control of mining equipment in terrestrial markets will be available for a "spin-in" to the space industry at relatively low cost. The terrestrial robotic mining technologies will have to be customized and adapted for use in space environments, but many parts, algorithms and sub-systems can be used for leveraging an extra-terrestrial mining industry. Examples include vision processing systems, LIDAR, sensors, harmonic drives, long life bearings, advanced mobility, micro-processors, end-effectors, human-machine interfaces and methodologies for operations.

EXTRA TERRESTRIAL ROBOTIC MINING CONCEPTS

The earliest writings on space industrialization recognized the need for materials to feed factories in orbit (O'Neill 1974; Johnson and Holbrow 1977; Billingham, Gilbreath, and O'Leary 1979). More recent writings (such as O'Leary 1983) have backed away from the concept of many large factories in orbit and concentrated instead on small, specific projects involving non-terrestrial materials. (Gertsch, 1992).

Most recent ISRU studies have concentrated on the production of oxygen as a product. Since approximately 75-80% of the mass of a liquid hydrogen / liquid oxygen space rocket propulsion system is comprised of liquid oxygen, this is considered to have the highest return on investment in the near term. The market being considered is consumables for humans and equipment on the lunar surface and propellants for transportation to and from the moon. If the lunar produced oxygen is delivered to low earth orbit (LEO), then substantial mass savings or effective payload increases can be incurred by loading it onto Earth departure stages in LEO, therefore avoiding the transportation of oxygen to LEO.

NASA has studied the use of ISRU in many different architectures related to the moon and Mars. The lunar Oxygen (LUNOX) architecture and First Lunar Outpost (FLO) architecture (Joosten 1995) were two studies performed in the mid 1990's, however other studies had been produced in the late 1980's showing potential for a favorable payback with lunar oxygen production (Christensen, 1988). Since the

1990's numerous internal NASA studies have been performed with the most recent example being the Constellation program lunar outpost architecture using ISRU derived oxygen for consumables as a technology demonstration. The first step in all of these studies is acquiring the natural resources to be processed for consumption. In the case of the moon, the resources for oxygen production are the lunar regolith and/or water ice. In the case of Mars, atmospheric capture is required unless the confirmed water ice is mined from the Mars sub-surface regolith. Assuming that the regolith and water ice will have to be mined eventually, then robotic mining machines will be required to either precede the crew arrival or assist the crew later on. None of the studies performed to date have examined, in detail, the role of robotic mining assets and the related technologies (eg. communications and autonomy) that will be needed. These robots can be tele-operated on the moon due to the small 2-3 second radio frequency signal delay, but on Mars the communications delay is 20-40 minutes, which means that advanced autonomy will be required to provide an efficient operation.

Robotic mining machines will require mobility and in this regard, there are examples of lunar and Martian mobility systems. The Russian Soviet era Lunakhod rover I & II (1970 & 1973) is perhaps the best example of a tele-operated lunar mobility platform. With modern technology it will be possible to improve on the performance of such machines. In 1997 the Mars Pathfinder mission landed the Sojourner rover on Mars followed by the Mars Exploration Rovers: Spirit and Opportunity in 2004, which showed a high degree of success in geologic assessments, but while moving at a snail's pace of 10 mm/second.

However, robotic mobility platforms must have enough reaction force from their weights or traction to counteract the digging forces encountered during significant regolith mining operations. This means that the mining machines must be very massive to overcome the reduced gravity weight effect, or the excavation forces must be reduced. Generally space missions are mass constrained – so the most cost effective method is to develop new technologies that can reduce the digging forces.

Some of the earliest known space mining machines were proposed by Eagle Engineering under contract to NASA in the late 1980's (Eagle Engineering, 1988). These consisted of large front end loader devices with associated hauling machines. Since the machines were rather large, the digging reaction force was not considered to be a problem, which is the same approach that is used on Earth. However, the payload mass and volume may be prohibitive, especially in the near term, since large launch vehicles (over 25 tonnes to LEO) do not exist yet and launch costs remain high.

An early innovative concept for reducing the digging forces was a pneumatic mining device proposed by David S. McKay & subsequently tested by Sullivan (1992, 1994). Zacny et al advanced this work and have done extensive terrestrial testing (Zacny et al , 2008). The pneumatic mining concept has shown great promise, and has achieved efficiencies of 8,000 grams of regolith excavated for every 1 gram of transport gas applied, making it a compelling concept for lightweight and efficient excavation machines, albeit at the cost of using a consumable gas, unless the gas can be recycled through the use of staged cyclone filtration systems.

Percussive excavation was the subject of some research at the University of Colorado in the mid 1990's (Sture et al, 1996), when a percussive bulldozer blade was tested in a lunar regolith simulant. Further work by NASA Kennedy Space Center, Honeybee Robotics and the University of California at Berkley has shown that the excavation forces can be reduced by as much as 90% in a lunar regolith simulant when percussion is used in the digging implement. (Green, Zacny, Mueller et al, 201). By using these percussive techniques, smaller robotic machines can be pre-deployed to the space mining destination site, and mining capacity can be scaled by using a modular approach, where many small machines operate co-operatively in a swarm.

Other approaches have consisted largely of reducing excavation forces through the use of shallow angle scraping plate devices (Caruso et al, 2007), (Whittaker et al, 2008), bucket chain devices (van Susante, Muff, King et al, 2010), bucket ladder devices (SysRand et al 2010) or bucket wheel devices (Muff, Duke, King et al 2007). Most of these approaches use many small scoops to dig many small quantities of regolith, resulting in a cumulative total that must then be stored ad transported in a hauling device. In Canada, NORCAT and various other Canadian Space Agency efforts have produced Load Haul, Dump (LHD) prototypes with front end loader types of mechanisms for mining regolith (Boucher et al, 2010) which were demonstrated in a NASA field test on the Mauna Kea volcano analog test site, in Hawaii.

In 2009, Lockheed Martin demonstrated an innovative evolution of the bucket wheel concept by stacking several bucket wheels to form a bucket drum (Figure 3), which then also formed a container for carrying the excavated regolith (Clark et al, 2009). This was demonstrated at a NASA ISRU field test on Mauna Kea, Hawaii in 2008. The tests showed that the bucket drum was very effective but still reliant on traction forces for efficient excavation and mobility. In 2011, NASA Kennedy Space Center conceived a new extra-terrestrial excavation method consisting of counter–rotating bucket drums on a bi-stable mobility platform with a zero – net reaction force to eliminate the traction reaction force problem. A prototype was built and demonstrated at the 2011 NASA Lunabotic Mining Competition and it is currently undergoing further testing and development (Figure 4).

In 2007, NASA offered a Centennial Challenge prize of US $500,000 to the team that could excavate the most regolith in 30 minutes. It was won by Paul's Robotics of Worcester, Massachussets in 2010 (Figure 5). This competition provoked many different approaches and concepts (Mueller & van Susante, 2011). Subsequently, NASA Kennedy Space Center created a spin-off competition for universities called the NASA Lunabotics Mining Competition, which is an annual event where mining robots compete to excavate lunar regolith simulant and deposit it in a collection hopper. In 2010, 22 USA universities competed and in 2011, 36 universities from around the world competed (Figure 6). In 2012, Over 70 teams were registered to attend. Each team had a unique design and so many more concepts were spawned by this competition, which are being evaluated by NASA for future applications (Mueller & Van Susante, 2011).

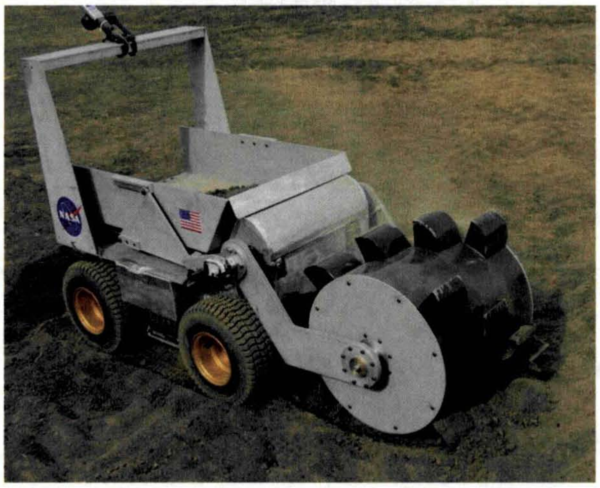

Figure 3: Lockheed Martin Corp. Bucket Drum Excavator (BDE) prototype.

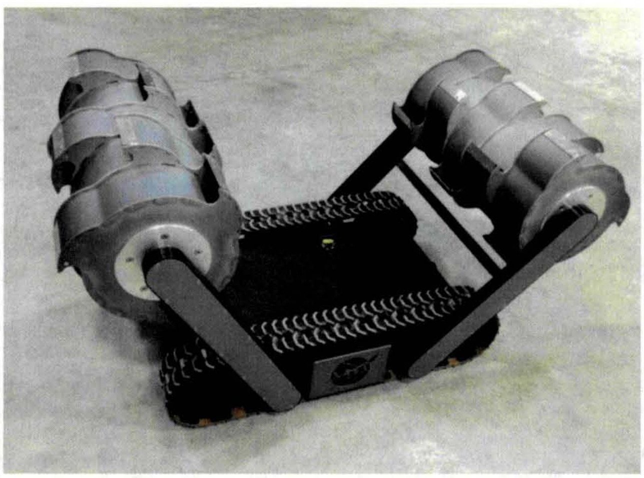

Figure 4: NASA Kennedy Space Center, Regolith Advanced Surface Systems Operations Robot (RASSOR) Excavator.

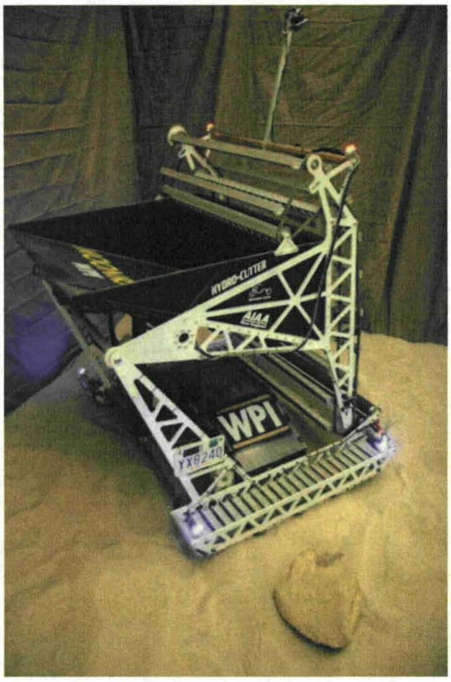

Figure 5: Paul's Robotics Centennial Challenges Winner, Worcester Polytechnic Institute (WPI), Worcester, Massachusetts.

Figure 6: 2011 Lunabotics Mining Competition Winner: Laurentian University "Production" Lunabot, from Sudbury, Canada

TAXONOMY OF ROBOTIC MINING MECHANISMS

King et al. (2005) studied what would be the best excavator system to provide feedstock to a small scale ISRU plant. The top three scoring alternatives were a bucket wheel, bucket chain and an overshot loader. Johnson and van Susante (2006) compared experimental production and power use data for a bucket wheel and bucket ladder prototype excavators and came to the conclusion that a bucket ladder is more efficient due to combining the transport function with the excavation function. Mueller and King (2007) described a variety of tasks that need to be performed to establish a permanent lunar outpost. Tasks are related to civil engineering to build roads, foundations, landing pads, etc. as well as ISRU for feedstock gathering and delivery. After comparing a bucketladder, bucketwheel, dragline, overshot loader, pneumatic transport and a scraper to a multipurpose excavator, they concluded that a multipurpose excavator would be the best at performing all required tasks. The multi-purpose excavator consisted of a mobility platform with a backhoe style deep digging implement on one end, and a modular interface on the opposite end that supported a front end loader implement which could be changed out with a bulldozer blade for site preparation.

Mueller and van Susante (2011) describe and classify the prototype lunar excavators developed for participation in the NASA Centennial Excavation Challenges in 2007, 2008 and 2009 as well as the NASA Lunabotics Mining Competitions in 2010 and 2011. From the 84 prototypes developed for the competitions, 44 used bucket ladder variants, including the winners of each competition (Table 3). The goal however, was to excavate as much regolith simulant in a limited amount of time. Versatility in performing different types of excavation tasks was not part of the competition. Most prototypes utilized a hopper to store the excavated material while only a handful used the excavator tool to store the material before dumping. A raising/tilting hopper was most often used to dump the material with chutes and conveyor belts a close second and third alternative. For mobility, most systems used two tracks or four fixed wheels with a myriad of other options chosen by a handful of competitors.

GAPS, FEASIBILITY, CHALLENGES AND RESEARCH TOPICS

Mining Robots face many of the same challenges as other robotic technologies in space and on Earth. A comprehensive review of these challenges was performed in 2010 by a NASA team under the leadership of the Office of the Chief Technologist (OCT). This resulted in a series of roadmap documents that included Technology Area 4: Robotics, Tele-Robotics and Autonomous Systems (RTA). The findings of this road-mapping team were summarized as:

1. NASA's four Mission Directorates are depending on Robotics, Tele-Robotics and Autonomy Technology.

2. Technology should aim to exceed human performance in sensing, piloting, driving, manipulating, rendezvous and docking.
3. Technology should target cooperative and safe human interfaces to form human-robot teams.
4. Autonomy should make human crews independent from Earth and robotic missions more capable.

Table 3: Lunar excavation prototype excavation mechanism classification

Regolith Excavation Mechanism	# of machines employing excavation mechanism
Bucket ladder (two chains)	29
Bucket belt	10
Bulldozer	10
Scraper	8
Auger plus conveyor belt / impeller	4
Backhoe	4
Bucket ladder (one chain)	4
Bucket wheel	4
Bucket drum	3
Claw / gripper scoop	2
Drums with metal plates (street sweeper)	2
Bucket ladder (four chains)	1
Magnetic wheels with scraper	1
Rotating tube entrance	1
Vertical auger	1

Further information on the technology gaps, challenges and research areas can be found in the NASA Technology Area 4 Roadmap: Robotics, Tele-Robotics and Autonomous Systems (NASA, Ambrose, Wilcox et al, 2010). A work breakdown structure (WBS) is presented and discussed in the report. The top technical challenges were identified in section 3.1 of the report and are listed below.

Top Technical Challenges

The RTA panel identified multiple top technical challenges, and these will be described in order of their associated location in the TA04 WBS, not in any particular priority. Each represents the top priority within its WBS sub topic.

- Object Recognition and Pose Estimation
- Fusing vision, tactile and force control for manipulation
- Achieving human-like performance for piloting vehicles
- Access to extreme terrain in zero, micro and reduced gravity
- Grappling and anchoring to asteroids and non cooperating objects
- Exceeding human-like dexterous manipulation
- Full immersion, telepresence with haptic and multi modal sensor feedback

- Understanding and expressing intent between humans and robots
- Verification of Autonomous Systems
- Supervised autonomy of force/contact tasks across time delay
- Rendezvous, proximity operations and docking in extreme conditions
- Mobile manipulation that is safe for working with and near humans

In the specific case of mining robots on extra-terrestrial bodies, we believe that some of the top technical challenges will be:

- Low reaction force excavation in reduced and micro-gravity
- Operating in regolith dust
- Fully autonomous operations
- Encountering sub surface rock obstacles
- Long life and reliability
- Unknown water ice / regolith composition and deep digging
- Operating in the dark cold traps of perennially shadowed craters
- Extreme access and mobility
- Extended night time operation and power storage
- Thermal management
- Robust communications

Extra-terrestrial mining is feasible today, but specific solutions must be developed in order to provide a reasonable lifetime, reliability and return on investment. Some promising concepts are being investigated by the space mining community, Lunabotics university teams and at least three private ventures have declared that they intend to mine the moon for profit: Astrobotics inc., Moon Express LLC and Shackleton Energy Corporation.

A large gap that exists today, is knowledge about, and characterization of, the water ice on the earth's moon. In order to excavate the water ice, its physical and geo-technical properties must be known. In addition, the thousands (millions?) of asteroids in the asteroid belt and planetary bodies beyond the asteroid belt are not cataloged or well understood, so that designing robotic mining equipment for these locations would not be feasible today without additional information about them.

CONCLUSION

This paper has reviewed the role of mining technologies and methods in the context of using solar system resources for In-Situ Resource Utilization (ISRU) in order to facilitate human and robotic exploration of the solar system bodies, as a first step in humanity's expansion into the universe. There are vast amounts of resources in the solar system that will be useful to humans in space and possibly on Earth. None of these resources can be exploited without the first necessary step of extra-terrestrial mining, but the necessary technologies for tele-robotic and autonomous mining have not matured sufficiently yet. The current state of technology was assessed for terrestrial and extra-terrestrial mining and a taxonomy of robotic space mining mechanisms was presented which was based on current existing prototypes. Finally, gaps, feasibility, challenges and research topics were reviewed as a guide for future efforts in this field. Terrestrial and extra-terrestrial mining methods and technologies are on the cusp of massive changes towards automation and autonomy for economic and safety reasons, and it is highly likely that these industries will benefit from mutual co-operation and technology transfer.

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National Aeronautics and Space Administration

A Review of Extra-Terrestrial Mining Robot Concepts

Earth & Space 2012
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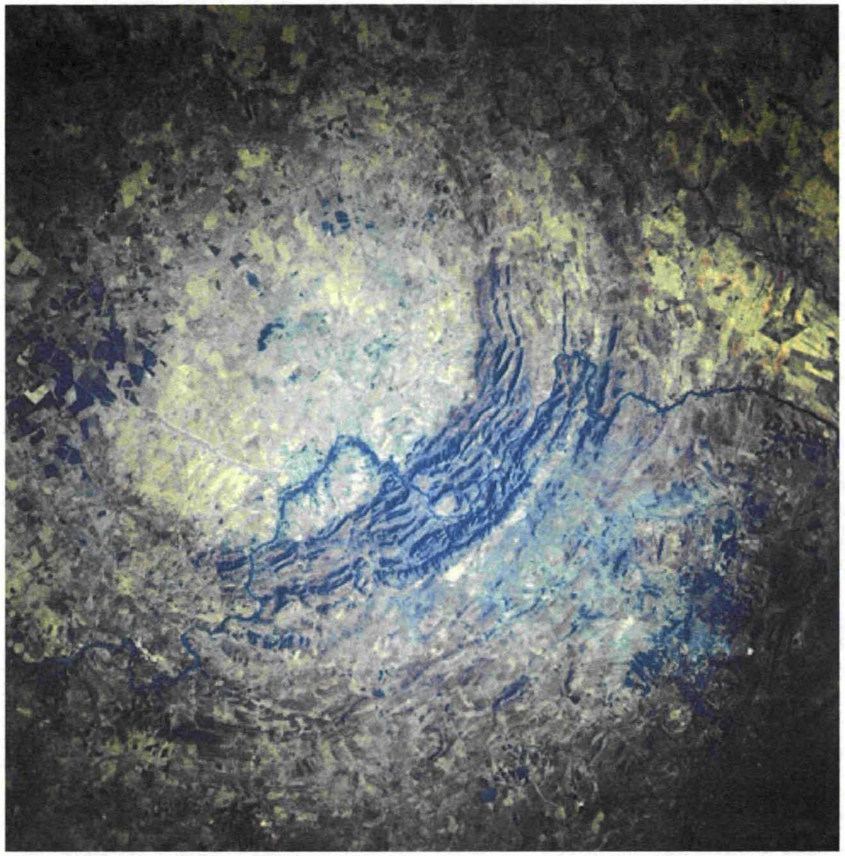
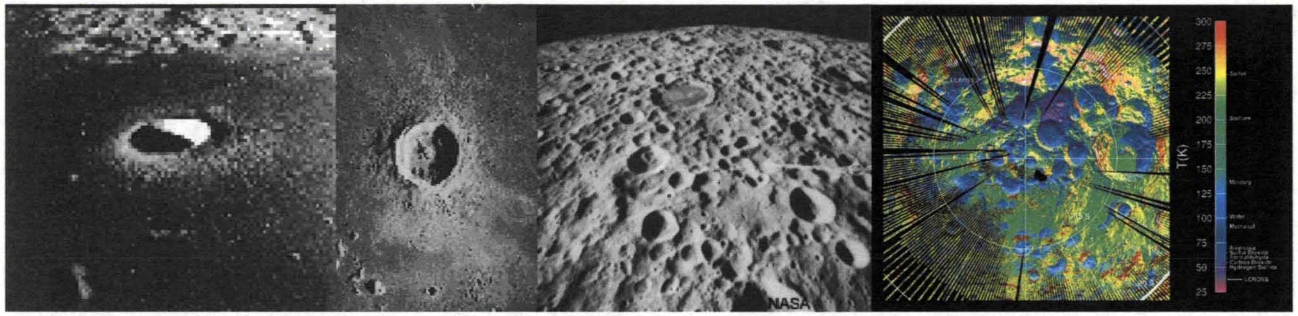
Terrestrial Impact Crater Mining



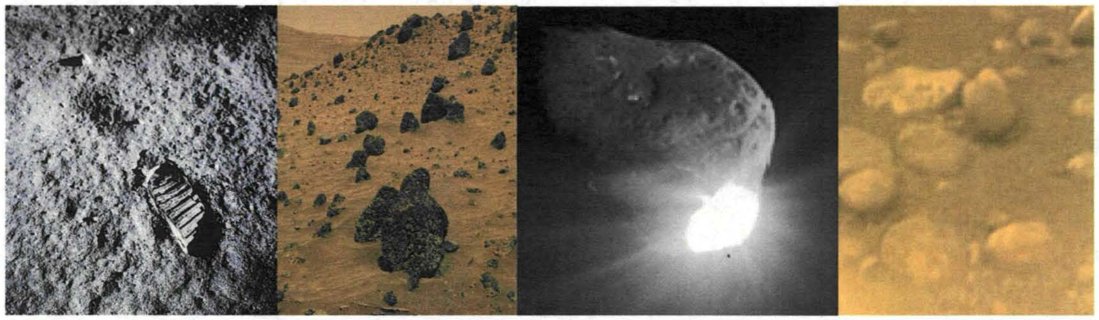
Vredefort Crater – Largest known terrestrial impact crater 62 miles southwest of Johannesburg, South Africa

Produces: Gold, Platinum & Diamonds

Extra-Terrestrial Impact Crater Mining



Lunar Craters were formed by constant bombardment from Asteroids, Comets and other Space Debris since the Solar System formation 4.5 Billion Years ago



Surfaces of Earth's Moon, Mars, Comet Temple 1 and Titan

Impact Craters can point us to the Resources: O_2, PGM, Titanium, Aluminum, Iron H_2O, Volatiles

In-Situ Resource Utilization (ISRU)

When considering all aspects of ISRU, there are 5 main areas that are relevant to human lunar and Mars exploration (Sanders et al, 2010):

1. **Resource characterization and mapping for planning and science**
2. **In-situ production of mission critical consumables and propellants for crew, power, and transportation**
3. **Civil engineering and construction for hardware and crew protection and infrastructure growth**
4. **In-situ energy production and storage**
5. **In-situ manufacturing, repair, and reuse**

Terrestrial Robotic Mining

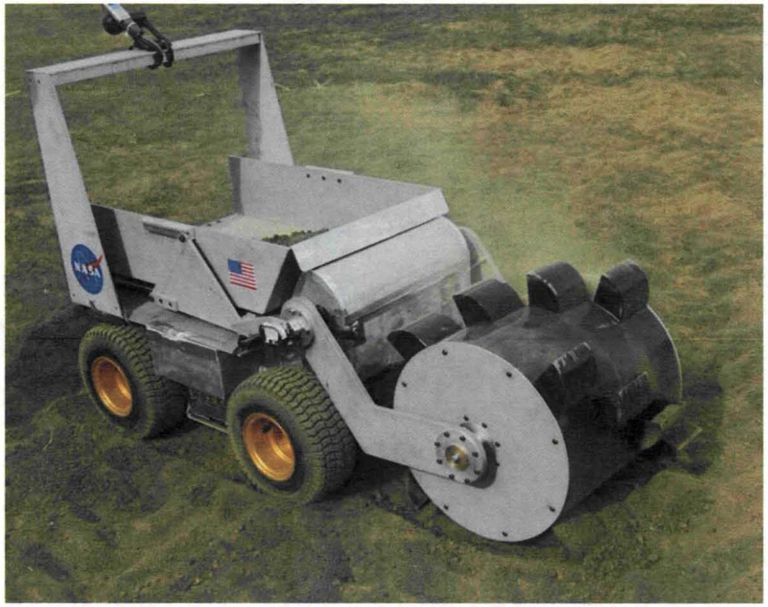
With automation technology robustness and capabilities progressing rapidly, terrestrial mining is trending towards more automation which results in removing humans from dangerous areas as well as increasing production. This will result in:

- Increased safety and improved working conditions for personnel
- Improved utilization by allowing continuous operation during shift changes
- Improved productivity through real-time monitoring and control of production loading and hauling processes
- Improved draw control through accurate execution of the production plan and collection of production data
- Lower maintenance costs through smooth operation of equipment and reduced damage
- Remote tele-operation of equipment in extreme environments
- Deeper mining operations with automated equipment
- Lower operation costs through reduced operating labor
- Reduced transportation and logistics costs for personnel at remote locations
- Control of multiple machines by one tele-operator human supervisor

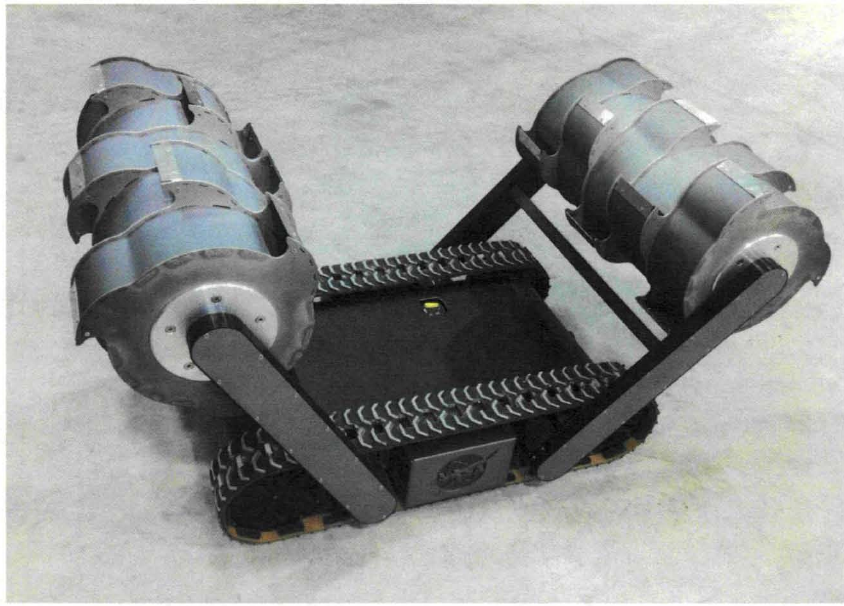
Automated Mining for Earth & Space

Caterpillar 287C semi-autonomous Multi Terrain Loader

Examples of Small Robotic Mining Systems (< 50 Kg)



Lockheed Martin Corp. Bucket Drum Excavator (BDE) prototype.



NASA Kennedy Space Center, Regolith Advanced Surface Systems Operations Robot (RASSOR) Excavator.

Competition Mining Robot Systems

Paul's Robotics Centennial Challenges Winner,
Worcester Polytechnic Institute (WPI),
Worcester, Massachusetts

2011 Lunabotics Mining Competition Winner:
Laurentian University
"Production" Lunabot,
from Sudbury, Canada

Regolith Excavation Mechanisms

All excavators from three Centennial Excavation Challenge Competitions (2007, 2008 and 2009) and two Lunabotics Mining Competitions (2010 and 2011)

Regolith Excavation Mechanism	# of machines employing excavation mechanism
Bucket ladder (two chains)	29
Bucket belt	10
Bulldozer	10
Scraper	8
Auger plus conveyor belt / impeller	4
Backhoe	4
Bucket ladder (one chain)	4
Bucket wheel	4
Bucket drum	3
Claw / gripper scoop	2
Drums with metal plates (street sweeper)	2
Bucket ladder (four chains)	1
Magnetic wheels with scraper	1
Rotating tube entrance	1
Vertical auger	1

Regolith Transfer Mechanisms

Regolith Transfer Mechanism	# of machines employing transfer mechanism
Bucket ladder	34
Conveyor belt	13
Impeller	3
Raising scraper with chute	3
Bucket belt	2
Bucket chain	2
Raising whole robot or main body	2
Auger	1
Catch bin with auger	1
Rotating tube (auger like)	1

Regolith Storage Mechanism

Regolith Storage Mechanism	# of machines employing storage mechanism
Hopper	56
Scoop	14
Scraper	3
Backhoe scoop	1
Bucket drum	1
Bulldozer	1
Inside tube body	1

Regolith Dumping Mechanism

Regolith Dumping Mechanism	# of machines employing dumping mechanism
Raising / tilting hopper	32
Tilting / raising scoop	9
Conveyor belt (with attachments)	8
Chute	5
Raising hopper with back chute	5
Bucket ladder	3
Ramp plus rotating valve bottom	3
Angled auger	2
Angled vibrating hopper (stationary)	2
Cable pulling up bottom of hopper	2
Horizontal belt / back opens	2
Separate lifting ramp/storage bin	2
Tilting / raising scoop with overhead dump	2
Raising whole robot on second robot, then tilting hopper with chute	2
Swivel of backhoe arm, rotating scoop	2
Raising bucket drum, counter rotate	1
Rotating scoop (overhead)	1
Clamshell scoop opening	1

Robot Mobility Method

Robot Mobility Method	# of machines employing mobility method
Two tracks	26
Four fixed wheels	24
Four fixed wheels with grousers	12
Stationary with swivel	5
Four individually steerable wheels	4
Four fixed wheels with super profile	2
Six fixed wheels	2
Four individual steerable tracks	1
Four steerable wheels with grousers	1
Four wheels with grousers and suspension	1
Six fixed wheels with grousers	1
Stationary	1
Three wheels (one steerable)	1
Two tracks and two wheels (half track)	1
Two very wide tracks	1
Four fixed tracks	1

Top Robotic Technical Challenges*

- Object Recognition and Pose Estimation
- Fusing vision, tactile and force control for manipulation
- Achieving human-like performance for piloting vehicles
- Access to extreme terrain in zero, micro and reduced gravity
- Grappling and anchoring to asteroids and non cooperating objects
- Exceeding human-like dexterous manipulation
- Full immersion, telepresence with haptic and multi modal sensor feedback
- Understanding and expressing intent between humans and robots
- Verification of Autonomous Systems
- Supervised autonomy of force/contact tasks across time delay
- Rendezvous, proximity operations and docking in extreme conditions
- Mobile manipulation that is safe for working with and near humans

*NASA Technology Area 4 Roadmap: Robotics, Tele-Robotics and Autonomous Systems (NASA, Ambrose, Wilcox et al, 2010)

Top Space Mining Technical Challenges

- Low reaction force excavation in reduced and micro-gravity
- Operating in regolith dust
- Fully autonomous operations
- Encountering sub surface rock obstacles
- Long life and reliability
- Unknown water ice / regolith composition and deep digging
- Operating in the dark cold traps of perennially shadowed craters
- Extreme access and mobility
- Extended night time operation and power storage
- Thermal management
- Robust communications

Conclusions

- There are vast amounts of resources in the solar system that will be useful to humans in space and possibly on Earth
- None of these resources can be exploited without the first necessary step of extra-terrestrial mining
- The necessary technologies for tele-robotic and autonomous mining have not matured sufficiently yet
- The current state of technology was assessed for terrestrial and extra-terrestrial mining and a taxonomy of robotic space mining mechanisms was presented which was based on current existing prototypes
- Terrestrial and extra-terrestrial mining methods and technologies are on the cusp of massive changes towards automation and autonomy for economic and safety reasons
- It is highly likely that these industries will benefit from mutual co-operation and technology transfer