

# Excavation in Space: A Survey of Automation Technologies

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## Abstract

There is a real and driving need to integrate the disparate automation technologies in excavation for space mining. This paper describes the mining process on Earth as would be applied on another planetary body. Current technologies, commercial and research, are evaluated for their ability to autonomously carryout a task integrate with other tasks. A synthesized conceptual system design is considered to demonstrate the interactions between tasks. One task in specific, initial surveying, is examined in simulation and discussed. Finally, direction for future research to realize such an autonomous mining system is outlined.

## 1.0 Introduction

Excavation is a crucial construction activity on Earth and beyond. On Earth, excavation is done by human/machine teams for mining and site preparation for construction. Similar tasks will be undertaken in space. We will consider just the mining of resources, such as oxygen. Mining of resources is one operation that is essential for a sustainable human presence in space.

However, the concept of performing the standard, terrestrial man/machine excavation to solve the resource mining problem begs the question proverbial “chicken-and-the-egg” question. On one hand, mining is essential for sustainable human presence; but a significant amount of resources must be available to support any humans involved in mining. One way to avoid this issue is to automate the mining equipment at various level. After understanding the terrestrial mining process for mining, a process can be envisioned for space. From there the research in the automation of the mining process for terrestrial applications is transferable to the space domain. An overview of the current

technologies available will provide some insight to choosing future directions for excavation research to support mining in space.

### 1.1 Mining on Earth

Mining on Earth involves the obvious task of excavation, but also includes tasks such as: site surveying, production monitoring, pit planning, hauling materials, and processing materials [9]. These tasks are interwoven, and the interaction of the choices can impact the mining process.

Site surveying is the act of characterizing the planar surface for operations. For mining, this typically takes the form of a basemapping of the site. A basemap is a 2 ½ dimensional artifact which is composed of x-y (or more precisely latitude and longitude) coordinates with relative elevations with respect to a reference sphere. These basemaps are used in determining possible pit layouts and plans before the commencement of mining operations.

Production monitoring is used to determine if production rates are being met. In mining, this normally involves the measurement of weight (tonnage) or volume (square yards).

On Earth, there are many aspects to pit planning, such as applying for permits. However, the primary interest for mining automation revolves around determining the excavation pattern (derived from the pit layout) that the excavators operate and the loading locations of trucks to minimize loading time.

Moving material from the pit to the processing plant is the task of hauling. Principally done by trucks on Earth, this task is also done by conveyors, cable excavators, and scrapers. The principal concerns in terrestrial hauling is selecting the proper hauling

technique based on the anticipated volume of material to be moved.

Finally, the processing of materials is typically handled at multiple plants. The first plant, typically re-deployable, performs simple operations such as screening, crushing, and occasionally washing to reduce the volume and weight of the bulk material. Final processing is typically done at fixed plants, which convert the incoming material to the pay material (i.e. the desired material). The determination to use a deployable plant and the logistics of hauling to the fixed plant are the main factors in terrestrial mining.

### 1.2 Assumptions for Space

In moving from the Earth to space applications, this survey makes the assumption that the excavation will be done in non-micro-gravity conditions; specifically excavation on asteroids without sufficient gravity to counteract forceful interactions with material is not considered.

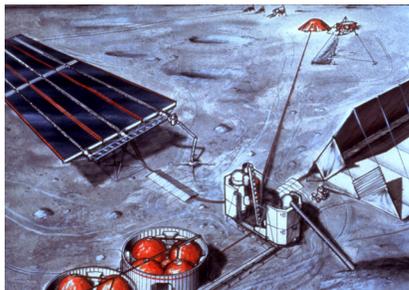


Figure 1.2.1 – Artist rendition of a Lunar ore processing plant [image courtesy of SEDS\*]

The scenario considered for discussion purposes is the manufacture of oxygen from lunar regolith [Figure 1.2.1], an application considered by many as a first source of extra-terrestrial oxygen [12] [3]. It is also assumed that a surface or open-cut method of excavation will be appropriate.

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\* SEDS – Students for the Exploration and Development of Space – <http://www.seds.org>

## 2.0 Available Technologies

Several technologies were reviewed to provide the basis for the design of an autonomous mining process. For each task domain, one or more technologies or research papers were reviewed. By no means were all technologies available for a given task evaluated, only sufficient technologies to establish the feasibility of automating the task.

### 2.1 Surveying

While GPS-style coverage is not anticipated for the lunar surface in the near future, other positioning technologies such as ArcSecond's 3D-I technology [1] can set up a local positioning system over an area of interest. Although ArcSecond's technology is currently limited to a non-overlapping cubes of 50m to a side, future developments are in the works at the company to increase range and allow cubes to overlap. However, a major limitation to the ArcSecond technology is that measurements within the cubes can only be taken when line-of-sight exists between the location to be measured and the two laser beacons. Fortunately, for open cut mining, there is little buildup of superstructures or "moonworks" to obscure the view. Such positioning networks can be utilized to generate a basemap by driving a vehicle with a position sensor over the area of interest while continually taking position samples [9].

### 2.2 Autonomous Excavation

Work in excavator automation reached its pinnacle with the demonstration of a completely autonomous backhoe [4] [14]. This research integrated a LIDAR sensor and control of the excavator into a system that could perform continuous excavation. A LIDAR (Light Detection And Ranging) systems measures time of flight of light to determine range, and when combined with two angles for azimuth and bearing, yields a 3D point. In this demonstration, the backhoe followed a preset excavation "pit" pattern and automatically loaded several transport vehicles in sequence. Also, the backhoe performed local movement, again with the preset pattern, to be able to be optimally placed for continuous excavation. It is important to note from the research that the transport vehicles did not need to be precisely placed near the backhoe. The backhoe sensed the transports and loaded them appropriately.

One limit of the technology at this point is that the excavation “pit” pattern was hard coded into the system. Further work would be needed to develop a system that could accept, as input, different excavation patterns.

Previous research also looked at planners that could reason about spatial planning with consideration to be able to adjust the forces being utilized based on the strain in the excavator arm [2].

### 2.3 Automatic Excavation Assessment

Trimble SiteVision [18] integrates GPS and desired terrain model to aid in control of excavators; can be modified to use a local position system. This system has been deployed with human operating the excavation equipment, although closing the loop to full autonomous control is very possible. The system operated by providing visual feedback to the operator about excavator blade positioning. This system was designed to be used with dozer style machines, and may not be easily extensible to mining operations, but should not be overlooked as it provides insight into closing the loop between assessment and excavation control.

NIST research [6] focuses on utilizing LIDAR scanners to take 2 ½D points and then estimate changes in volumes between successive scans [Figure 2.3.1].

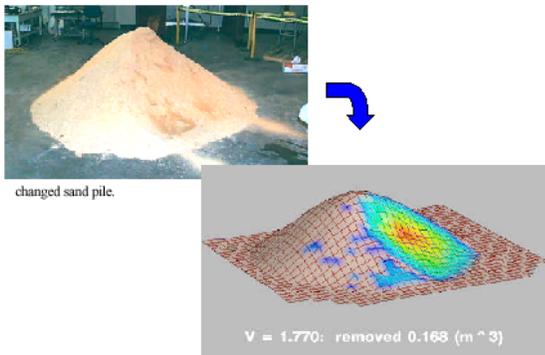


Figure 2.3.1 – Model based view of the area of a dirt pile that was excavated [6]

The NIST methods are very flexible and easily deployed for excavation assessment. However, while the status of the site is determined with the methods proposed by NIST, the use of the models in guiding the system is not defined by the NIST solution, unlike the Trimble system.

### 2.4 Autonomous Hauling

Researchers at CMU have demonstrated autonomous delivery of pay material via off-highway trucks in collaboration with Caterpillar [8]. This system has been used in the hauling of bulk material from strip mines and is currently commercially deployed.

### 2.5 Excavation Planning

A cognitive planner [10] tackles the task of generating a plan given the excavator and the dimensions of the desired excavation. Unlike the autonomous backhoe project, this planning can come up with a coverage pattern. However, the technology is intended for excavation and not necessarily continuous mining. The patterns that would be followed for these two items may be different.

Commercially, Caterpillar's CAES® (CAES - Computer Aided Earthmoving System) and Minestar® systems aid in high level planning of transports and excavators by being linked to position/state information to monitor productivity. This is done through an information system for the transmittal of designs based on engineer's design to an excavator operator and progress from field to office to aid in replanning. While this system is not fully autonomous, as the system interacts with a human, the interaction is at an abstract level that the plans communicated can be generated far away (in terms of transmittal time) by the human and executed in the field by the robots.

### 2.6 Process Software Systems

The crucial technologies that underlies all the tasks for autonomous mining are the process software systems. This system must be capable of transacting information about plans, surveys and process assessments, task control, and plan execution in a quasi-cyclic task manner.

Plan description can be done with a technology like the Task Description Language (TDL) [16]. TDL is a general software architecture concerned with programmatically describing tasks, task interdependencies, trees of tasks in concurrent and parallel execution, and enables task trees to self-modify. Further, TDL has been incorporated in

DiRA (Distributed Robot Architecture). DiRA uses multiple robots to accomplish an assembly tasks [17]. However, as a general architectures TDL and DiRA only enables description and execution of task trees in general with no specific guidance how to design the component systems to accomplish the mining task.

Data model exchange technologies have a rich history, starting with the first CAD systems. However, exchanging full CAD files is unwieldy. Another alternative would be to directly share sensory data with all agents, but this would create unneeded duplication of data analysis, and may not even be feasible if many video sources are used (current communications rates can be swamped by moderate resolution, 20hz updates of images from a camera). LiveView attempts to solve the information exchange problem by developing an infrastructure to enable communication about model changes between agents. has already been applied to excavation assessment task and sharing equipment state [13]. LiveView is an information exchange method under development by NIST and targeted at the entire construction domain. However, like TDL, LiveView has its limits; it doesn't directly support the execution of the tasks needed to generate the information that it transacts, and does not currently include methods for agents to discuss how to achieve information needed from the site. This shortcoming means that some other agent needs to determine how to achieve the input model changes that LiveView would be able broadcast later.

### **3.0 Approach for Space Mining**

Mining in the lunar scenario has many similarities to its terrestrial counterpart. The essential technology to be deployed is the process software; the "electronic construction" glue that enables the systems to exchange information, perform tasks, and cooperate.

Some initialization tasks specific to this scenario, but not covered in depth, are: arrival of robots, establishment of position network, and establishment of field processing plant.

In this task, after the initial positioning network has been established and the robots deployed, robots

equipped with position sensors can be driven around the site to take the initial base map. Once the initial survey has been completed, the excavation planning system generates and transmits pit pattern to the excavators. The planning system may be automated [2] or can be done by a human spatially separated [11] [5].

The excavators can then proceed to generate their local plan for excavation based on the pit pattern and designs received from the planners. Their primary function would be to fill a hauler when one is present and idle otherwise.

The haulers also receive their plans from the excavation planners. In this case the trucks are told where their dwell points are relative to a given excavator. Then, the truck would proceed autonomously to the discharge point at the field plant. Therein, combination conveyor/dozer systems, as proposed in [12], would be used to provide continuous feeding of the field plant.

The field plant is primarily responsible for crushing and packaging of the regolith for transport to a final processing plant. The primary reason for choosing such simple operations in the field is to minimize the amount of equipment that needs to be relocated. [15] proposes various elements to support robotic mining, including a separator plant that would be the first stage.

As mining sites move, one cost specifically can be minimized: the cost to move the final processing plant that extracts the pay material from the bulk harvested during excavation. This can be done by having the plant in Earth orbit (for Lunar operations) and utilizing a mass driver to send the packaged bulk from the field plant.

### **4.0 Example Sub System: Site Surveying**

As stated previously, assuming that a local position network has been established, the task of creating an initial survey or base map can be achieved by having robots with position sensors cover the target excavation area. However, the planning of the first coverage pattern can be difficult if the environment is unknown. As a demonstration of how such as system in conjunction with robots may accomplish this initial survey task, simulated robots were given

the task to work as a team to cover an excavation area and take elevation readings.

A reactive planner was used to enable multiple robots to perform a boustrophedon-like coverage pattern [7], while attempting to minimize redundant coverage of the same area by multiple robots. A boustrophedon pattern is one where the robots move back-and forth through their area of interest. A more detailed description of this coverage algorithm will be published at a later date. In the simulated environment, elevation contours were established. Triggering the robots to turn for another pass through the environment was done when contours were too steep or when the robot was at the edge of the region of interest (represented in the simulation as yellow edges in both cases [figure 4.1]). Indeed, this task management would be handled by the task execution subsystem (such as TDL and DiRA). At regular intervals the robots would take readings from their position sensors and transmit that location (in 3D) back to a central agent that created the contour map. Eventually, when the task is completed, this contour map would be transmitted to the planning agent via the model exchange system (such as LiveView).

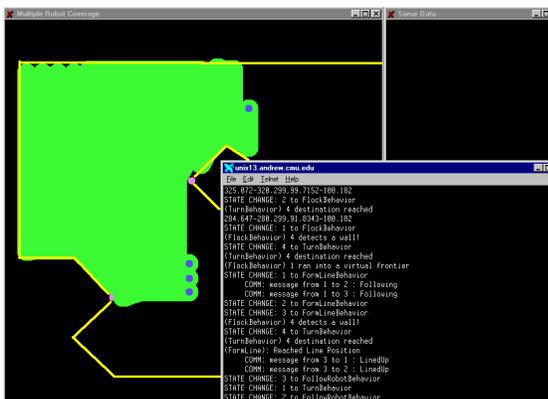


Figure 4.1 – Simulation of multiple robots (blue dots) covering an environment

## 5.0 Summary

This survey covers the design of an autonomous mining system from component technologies available or under development currently. Autonomous mining for resources in space is crucial and necessary as a precursor to sustainable human presence in space.

The activity of matching tasks to available technology is a long established engineering practice. The critical element covered for autonomous excavation was the exploration of the state of the existing technologies for autonomous mining and the identification of where gaps in capabilities may lay.

However, this observation of gaps is limited, and further analysis of excavation in space should be undertaken. Specifically, extension to micro-gravity (asteroid) environment will likely yield representational and measurement difficulties with surveying and excavation assessment. Further, to truly characterize the nature of the capability gaps, the design needs to be extended into component systems and scale implementation of entire mining process. Only in the detailed designs leading to implementation will all the issues of integration be capable of being specified. Finally work to formalize the description of excavation processes would be worthwhile. Such a characterization would facilitate automated reasoning, coordination, and planning at highest levels.

## 6.0 References

URLs current as of 2001-May-06.

- [1] “Arc Second”, corporate homepage, <http://www.arcsecond.com>
- [2] Bullock, Apte, Oppenheim, “For and Geometry Constraints in Robot Excavation”, Proceedings of Space 90, ASCE, Albuquerque, New Mexico. pg. 960-969. April 22-26, 1990.
- [3] Buddington, “Manifesting for a Lunarc, Robotic, Oxygen-Producing Base”, Proceedings of Space 90, ASCE, Albuquerque, New Mexico. pg. 1005-1014. April 22-26, 1990.
- [4] Cannon, “Extended Earthmoving with an Autonomous Excavator”, MS Thesis, Carnegie Mellon University, CMU Technical Report # CMU-RI-TR-99-10, 1999.
- [5] “Technology Products – CAES”, [http://www.cat.com/products/shared/technology\\_products/01\\_products/\\_products\\_caes.html](http://www.cat.com/products/shared/technology_products/01_products/_products_caes.html)

[6] Cheok, et al. "NIST Construction Automation Program Report No. 4: Non-Intrusive Scanning Technology for Construction Status Determination", NISTIR 6457, January 2000.

[7] Choset, Pignon, "Coverage Path Planning: the Boustrophedon Decomposition", In Proceedings of the International Conference on Field and Service Robots, Canbarra, Australia, December 1997.

[8] "The FastNav Project", <http://www.frc.ri.cmu.edu/~ssingh/fastnav.html>

[9] Nichols, Day, "Moving the Earth: The Workbook of Excavation", fourth edition, McGraw-Hill, 1999.

[10] Romero-Lois, Hendrickson, "A Strategic Planning and Monitoring System for a Machine Excavation Process", CMU Technical Report # R-88-175, 1988.

[11] "Technology Products - MineStar", [http://www.cat.com/products/shared/technology\\_products/01\\_products/\\_products\\_minestar.html](http://www.cat.com/products/shared/technology_products/01_products/_products_minestar.html)

[12] Okumura, Ueno, Ohashi, "Regolith Covering Method for Habitation Module in an Early Phase of Lunar Base Construction", Proceedings of Space 98, ASCE, Albuquerque, New Mexico. pg. 617-621. April 26-30, 1998.

[13] Lawrence E Pfeffer, DeWitt T Latimer IV, "Toward Open Network Data-Exchange Protocols For Construction Metrology and Automation: LiveView", 16<sup>th</sup> International Symposium on Automation and Robotics in Construction, Madrid, Spain, Sep. 22-24, 1999

[14] Rowe, "Adaptive Motion Planning for Autonomous Mass Excavation", PhD Thesis, Carnegie Mellon University, CMU Technical Report # CMU-RI-TR-99-09, 1999.

[15] Sherwood, "Lunar Base Elements Designed for Robotic Operations", Proceedings of Space 90, ASCE, Albuquerque, New Mexico. pg. 994-1004. April 22-26, 1990.

[16] R. Simmons and D. Apfelbaum, "A Task Description Language for Robot Control",

Proceedings of Conference on Intelligent Robotics and Systems, Vancouver Canada, October 1998.

[17] R. Simmons, S. Singh, D. Hershberger, J. Ramos, and T. Smith. (2000). "Coordination of heterogeneous robots for large-scale assembly". In Proceedings of the 7<sup>th</sup> International Symposium on Experimental Robotics (ISER). Springer-Verlag, Berlin

[18] "Trimble Product Guide: SiteVision GPS", <http://www.trimble.com/products/catalog/constr/sitevis.htm>