Off-world Robotic Excavation for Large-scale Habitat Construction and Resource Extraction

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Abstract

This paper describes technologies we have developed to perform autonomous large-scale off-world excavation. A scale dragline excavator of size similar to that required for lunar excavation was made capable of autonomous control. Systems have been put in place to allow remote operation of the machine from anywhere in the world. Algorithms have been developed for complete autonomous digging and dumping of material taking into account machine and terrain constraints and regolith variability. Experimental results are presented showing the ability to autonomously excavate and move large amounts of regolith and accurately place it at a specified location.

Introduction

The realization of humans living and working off-world poses significant challenges. The key challenges for off-world habitation are the construction of living quarters prior to human settlement and the extraction of resources such as oxygen, water and various metalliferous minerals that can be used for life support, fuel and construction materials. This will require excavation of a scale of operation that to date has never been undertaken in any space exploration program.

Off-world habitat designs have been proposed for both above and below the surface (Heiken, Vaniman, & French 1991; Benaroya 2002). However, construction of these habitats poses significant challenges (Krishen 1998). To protect humans from the extreme environmental conditions that they will be exposed to on the lunar surface, a popular proposal is to bury living habitats beneath a layer of regolith (Benaroya 2002). Habitat construction will also involve the moving of large pieces of equipment and various excavation tasks. Additionally, resources to support planetary exploration have been found or believed to exist in small concentrations within the surface regolith (Heiken, Vaniman, & French 1991; Taylor & Martel 2003). Therefore, to achieve habitat construction and mineral extraction, large-scale surface and underground mining operations will be required.

To date, off-world excavation tasks have been for scientific discovery with the largest amount of material removal (approximately 382kg) being conducted during the six Apollo landings (Heiken, Vaniman, & French 1991). This was achieved by direct human involvement and collection. Today, typical excavation tasks are of much smaller scale (grams) such as the sampling conducted by the Mars robotic exploration rovers which have relatively small scoops (Bonitz, Nguyen, & Kim 2000). In order to realize off-world habitation, a major challenge is to extend excavation tasks from the gram and kilogram scale to the thousands of tonnes scale — a scale up by six orders of magnitude.

The constraints/challenges to be considered for larger-scale off-world excavation and habitation construction are:

- Habitats will likely be constructed prior to human settlement.
- Selecting suitable machines to undertake the excavation task in a low gravity, low atmosphere environment.
- Power for these machines.
- Remote operation of the machines since humans will not be present locally, at least initially.
- Remote operation in the presence of round-trip latencies for tele-operation (e.g. $\sim$2 seconds for the moon, $\sim$19 minutes for Mars).
- The machines will eventually be operating in the presence of humans and other robots for which safety and failure modes require careful consideration.

As there will initially be no direct human interaction with the machines, the systems will be robotic in nature with levels of autonomy ranging from shared to full autonomy. As operations become larger, more time consuming, and with greater round-trip latencies, the level of autonomy will need to increase.

This research focuses on the development and testing of algorithms for low-level machine control and high-level planning that allow reliable, safe and efficient large-scale excavation and planning operations given the above set of challenges. This paper presents our most recent concepts and experimental results for autonomous large-scale excavation with particular emphasis on:

- Operational issues for remote operation of large mining equipment.
- Novel excavation techniques for larger-scale operations and metrics for machine selection and design.

- Control and safety systems for reliable machine operation.
- The human-machine interface for high level task planning.
- Digital Terrain Mapping (DTM) and ‘click to dig’.
- New results for fully autonomous excavation using a 1/7 scale dragline.
- Concepts in machine design that allow for multi-use operation and transportability.

Large-scale Robotic Excavation

There have been many studies for off-world excavation on the smaller scale. Although these were not for bulk resource extraction, they provide valuable information into digging forces and control limitations for use off-world. For larger scale mining operations, concept designs have been proposed, but very little in the way of full-scale experimental results have been presented or demonstrated.

Mining Technologies for Space

Most of the proposed off-world mining methods have been based on current terrestrial open-cut and underground mining machines and operations. Early work by Gertsch (Gertsch 1983; Gertsch, L.E.Gertsch, & Kent 1990) evaluates these technologies for lunar excavation based on the lessons learnt from the Apollo missions. They also describe a new method of lunar surface mining and set design criteria based on environmental and mechanical considerations.

Recent work by Satish (Satish, Radziszewski, & Ouellet 2005) discusses and evaluates the design issues and challenges of various current and novel mining techniques for the Moon and Mars. The authors do not conclude which method would be most appropriate or provide experimental validation. However, they present a more comprehensive set of design criteria for off-world mining which includes:

- Low machine mass,
- Operational and design simplicity,
- Flexibility,
- Low energy requirement,
- Automation and teleoperation potential,
- Minimise the need for working fluids,
- Special attention to the tribology part of the design,
- Special shielding requirements,
- Availability of advanced fabrication materials,
- Long-term operation with minimal maintance.

These design criteria do not however, consider issues of large excavation properties such as slope stability and machine control, nor operation in low-gravity and vacuums. Other studies (Podnieks & Siekmeier 1992; 1993) also consider mining technology for lunar excavation, however, they disregard a significant proportion of traditional cabled mining equipment such as draglines stating that they are inflexible. This statement may not be the case if careful design is employed.

Consideration of the feasibility of large-scale lunar soil excavation has been widely undertaken by institutions such as the North Carolina State University[1]. Their research considers scale excavation of a lunar regolith simulant. They found that the high level of regolith compaction just below the lunar surface is very difficult to penetrate with traditional bucket designs. However, if blasted, regolith mining becomes significantly easier with reduced excavation forces required. It was demonstrated that shovel and dragline type machine configurations could then easily excavate the regolith. Although, blasting regolith has the potential for improving excavation, it requires other technologies such as drilling and charge loading machines.

Earth-Based Robotic Mining

Terrestrial robotic excavation has been investigated by a number of authors on different machine types. This research is primarily focused around digging, weight estimation, motion planning and health monitoring of traditional mining machines. Automation of these machines offers the potential to factor out or overcome issues of sub-optimal machine control and misuse that can often be the case with human operators. Further benefits accrue through less damage to the machine through “smarter” operation during the excavation task by eliminating overloads and collisions.

Singh (Singh 1998) provides a good review of the field and discusses state-of-the-art in sensing and machine/ground interaction models. He then uses a number of implemented systems as examples to illustrate different levels of autonomy: teleoperation, trajectory control, tactical and strategic planning.

A significant body of relevant work was conducted at Carnegie-Mellon University by Singh, Cannon, Rowe, Stentz and others in the 1990s. The work was sponsored by Caterpillar and resulted in a considerable number of patents related to automation, motion planning and terrain profiling of a backhoe type excavator which is digging a bench and loading dirt into a truck (Singh & Cannon 2000; University 2000; Rowe 2000).

In other related work, Singh (Singh 1995) describes early research on predicting excavation forces. Many other researchers have considered the excavation forces in more detail such as Hemami (Hemami & Goulet 1994; Hemami 1994), Bernold (Bernold 1993) and Shi (Shi, Wang, & Lever 1996). A more comprehensive evaluation of the autonomous excavation research and OEM systems with their benefits and limitations is presented in (Corke & Dunbabin 2004).

For the last decade, CSIRO’s Autonomous Systems Laboratory has been researching and implementing advanced robotic techniques to the task of large-scale mining machines for operational use in mines. Figure 1 shows some of these machines which have included an electric rope

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[1] Construction Automation and Robotics Laboratory (http://www2.ncsu.edu/CIL/CARL/Research/Space)

(a) Electric rope-shovel.

(b) LHD.

(c) 3500 tonne dragline.

Figure 1: Excavating machines with various levels of autonomy.

shovel, underground mobile excavator (LHD), vehicle and a dragline (the world's largest robot). These machines have varying levels of autonomy with swing assist algorithms for traded autonomy of a 3500 tonne dragline (Corke *et al.* 2003), to fully autonomous digging using an electric rope shovel (Corke & Dunbabin 2004), and autonomous navigation of an LHD (Roberts, Duff, & Corke 2002). In 2003, an experimental evaluation of the traded autonomy system on the dragline moved approximately 250,000 tonnes of overburden over a two week period (Corke *et al.* 2003).

The successes in earth-based robotic excavation has prompted the investigation of algorithms and machine designs that could realize larger-scale off-world excavation, well beyond the current scientific sampling capabilities of exploration robots.

Although most aspects of robotic mining have been addressed in some way, most research does not consider the integration of all the required components to achieve fully autonomous excavation missions. This research program is considering aspects of robotic mining to allow an excavator to autonomously plan and then move material based on an overall excavation requirement taking into account:

- Machine limitations.
- Minimum and desirable sensing requirements.
- Gross regolith characteristics.
- Failure analysis and decision making.
- Terrain and obstacle avoidance.
- Interaction with humans.

More recently we have worked on a telerobotic approach to large machine control as part of an MIT led project on autonomous manipulation in space environments. In particular we are considering the use of dragline (cabled) type excavators for large-scale regolith mining which can also be used for habitat construction.

Operational Issues for Remote Operation of Large Mining Equipment

The primary difference between earth-based and off-world mining operations is the time latency, the level of allowable/desirable autonomy, and the interaction with human operators and other personnel and equipment. In earth-based operations, latency and bandwidth is generally not an issue. Off-world, this is important as latencies over 2 seconds can make direct teleoperation difficult, if not impossible. For earth based operations, there is a general reluctance to adopt completely autonomous systems. However, for operation off-world, a greater reliance on autonomy is required. One important aspect of CSIRO's research has been the fact that there is generally interaction between the human, the machine and other equipment. The following sections discuss issues such as latency, teleoperation, force feedback and machine selection.

Latency

The issue of latency (or transport delay) in any controlled vehicle whether it be teleoperated or fully autonomous is a significant problem. Sources of latency are wide ranging and can be machine or human related. In teleoperated control, the significant sources of latency are:

- compression/decompression/packetization of information between the control station and vehicle.
- transmission delays due to distance.
- actuation of vehicle components (for example robotic arms, steering).
- all in addition to the human transfer function.

The magnitude of the latency ultimately limits the maximum operational speed of the vehicle for safe and effective control. The maximum bearable latency depends on the task. However, latency significantly increases the workload and concentration levels of the operator on teleoperated vehicles, and therefore must be kept to a minimum.

Teleoperation vs Autonomy

Fong and Thorpe (Fong & Thorpe 2001) present a taxonomy for teleoperation interfaces in which they define the following control classes to describe their functionality: direct, multimodal/multisensor, supervisory and novel.

A direct interface is appropriate when it is critical that human scene interpretation and decision making is "in the loop". It has strong requirement for high-bandwidth, low-latency and reliable communications for both the video uplink and the command downlink. It is well known that direct interfaces are problematic for several reasons. McGovern (McGovern 1990) discusses many of these issues from his extensive experimental study of teleoperated ground vehicles in off-road conditions. The key problematic areas identified are:

1. Loss of situational awareness.
2. Inaccurate attitude judgement.
3. Depth perception.
4. Failure to detect obstacles.
5. Over-control when the operator was introduced to the system.

Despite the number of disadvantages of direct control, it does have some key advantages such as:

- Human scene interpretation.
- Very versatile as operator is making all decisions.
- Proven an effective control technique over small and large distances.

Supervisory control interfaces are designed for high level command generation, monitoring and diagnosis. They must provide mechanisms for the operator and robot to exchange information at different levels of detail and abstraction. This concept was demonstrated with Sojourner on Mars (Cooper 1998) which operated with a 28 minute round trip delay and communications issues meant that the rover received a daily command upload and used onboard sensors and intelligence to execute them.

Teleoperation and Mining In 1996 CSIRO began to investigate the possibility of automating underground mining vehicles and a number of field trials at a mine in Queensland were conducted (Scheding *et al.* 1997) on an LHD vehicle.

Subsequent work generated a framework for various levels of autonomy for large mining equipment, especially as these machines are typical retrofit systems and operators may want direct control of the machine or humans may be in the vicinity. Therefore, a control architecture with various levels of autonomy and machine operation was devised (Roberts, Duff, & Corke 2002). This control architecture provides for a spectrum of control modes described as:

MANUAL, where the operator is physically moving the controls of the machine.

REMOTE, where the vehicle is controlled with a joystick via a teleoperation system.

DRIVE-BY-WIRE, introduces an "operational layer" which enables the operator to drive the vehicle at a more abstract level. In control systems terminology we would say that the operational layer accepts control set-points from the operator and hides the actual dynamics of the machine.

COPILOT, introduces a "tactical layer" which controls the vehicle so as to operate safely and automatically. The operator acts as a copilot and simply provides hints to the tactical layer such as: dig faster, dump material here, etc.

AUTONOMOUS, introduces a "strategic layer" which interprets a mission and generates the appropriate hints to the tactical layer, which in turn generates the appropriate vehicle demands to the operational layer. The vehicle is given a mission by the operator, who subsequently, has no influence over the vehicle's operating behaviour.

Having the highest level of abstraction in the autonomous mode allows the vehicle to operate independently and complete the desired mission by adapting to changing environments with dynamic obstacles typical of many mine sites.

Force Feedback

A particular concern with the operation of large mining equipment is the ease with which a machine can be damaged whilst digging. These machines typically have enough power to essentially destroy themselves if not operated correctly. As these machines provide little or no direct feedback to the machine operators, they generally use sound and "seat of the pants" perception of the machine to estimate its 'pain'.

Force feedback for direct control, or teleoperated control with negligible latencies, also allow an operator to 'feel' and control the stress the machine is undergoing. However, if the machine is operated with significant latencies (e.g. 2 seconds for round trip delays to the moon), force feedback in excavation tasks has little direct benefit. This is due to fact that by the time the operator's control signals reach the machine, it could already possibly be damaged. More recent advances in electronics and machine diagnostics has enabled the machine to monitor its own health and override any operator or control commands that could potentially damage the machine. This type of self-monitoring and control is considered essential for off-world excavation.

Machine Selection

As discussed previously, selecting appropriate machines for off-world excavation is difficult with many mechanical and environmental issues to consider. However, other considerations that need addressing are the stability of the machine on steep slopes (roll over), traction on potentially blasted regolith, the reachability of the machine and bucket size (material removal rates). Additionally, there are metrics such as the energy and number of machines required to move a certain mass to a certain location which need attention (e.g. is it better to have separate excavator and hauling vehicles to move the material from the pit, or a larger vehicle that can reach into the pit and deposit material at another location). All these issues affect machine choice.

In light of recent advances in machine design, control and self-monitoring, we have chosen to use a scale dragline excavator for evaluating the algorithms for autonomous off-world mining. The dragline was chosen as it is simple in operation, has very few moving parts, and its size enables material to be moved large distances. They can also excavate deep pits and keep the machine away from potential dangerous sides of the excavation. Its size also allows sensors to be mounted high up the boom to allow greater situational awareness. Additionally, using truss structures for the boom and body, the mass of the machine can be significantly reduced.

Another benefit of dragline excavators are that in addition to creating a hole, they can also be used as a crane to move habitats and other equipment, and then move the excavated material back to bury the habitat if required.

Remote Regolith Excavation Experiment

It is desired to demonstrate that a machine of a size capable of performing the required off-world habitat preparation and resource extraction could autonomously perform a large-scale excavation task. Therefore, the Remote Regolith Excavation Experiment was devised which consists of a 1/7th scale dragline excavator made capable of autonomous control and a communications link to a remote location to simulate robotic off-world excavation. The control system must be capable of performing complete autonomous excavation and consists of systems to perform:

- Terrain mapping.
- Digging and dumping of material.
- Path planning.
- Monitor machine condition and potential damage.
- Obstacle avoidance.
- Achieving a desired excavation plan.

The dragline excavator was located at a remote test mine in Brisbane, Australia. The following sections describe the machine and its capabilities, its control and communication systems.

Machine Overview

The experimental platform used in this project was a 1/7 scale model dragline and has a bucket capacity of approximately 0.1 cubic metres as shown in Figure 2.

Dragline operation is achieved via three primary control inputs; (1) drag, (2) hoist, and (3) slew, as shown in Figure 3. The drag and hoist ropes move the bucket horizontally and vertically in the plane made by the ropes and boom and perform the digging (filling) and dumping of the bucket. Slew rotates the entire machine about a vertical axis to allow the bucket to be placed at any point within a circle scribed by the outer reach of the machine. In addition to these three control actions, the vehicle is also capable of moving on its caterpillar tracks, although, this functionality was not computer controlled. The model dragline is driven by three Baldor Vector motors.

(a) Machine.

(b) Bucket.

Figure 2: 1/7th scale excavator used for autonomous excavation.

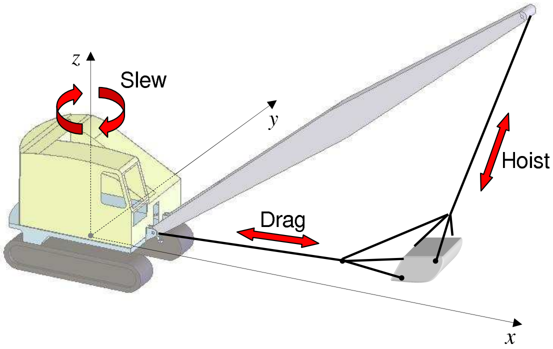


Figure 3: Dragline operational degrees of freedom.

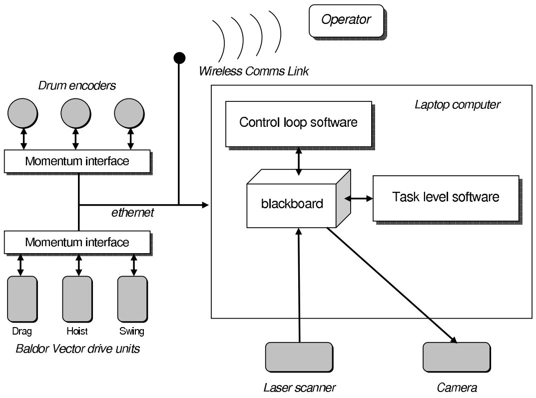


Figure 4: Dragline control system architecture.

Sensors

In previous investigations into dragline and shovel automation (Corke & Dunbabin 2004) it has been found that laser scanners located towards the tip of the boom scanning along the machine's x-axis are capable of providing high-resolution digital terrain maps as the machine rotates, as well as scan the dig face for bucket trajectory planning and obstacle avoidance. In this investigation only a limited number of sensors were utilised for providing feedback to the control software. These sensor inputs were provided by:

- SICK LMS laser scanner.
- Drag, hoist and slew encoder values.
- Drag, hoist and slew motor current and scaled velocity.

A digital camera was also installed to allow remote viewing of the dragline operation, however, this information was not used by the dragline controller.

Dragline control structure

The control structure for the dragline consists of a central computer which reads all drive encoders, selectable analog inputs and safety card logic. It provides control signals to the three Baldor motor drive controllers which are connected to the computer via Modicon Momentum data acquisition modules and the onboard local area network. This control structure is represented diagrammatically in Figure 4.

The control computer is a laptop running Fedora Linux. Controlling the dragline to perform autonomous swing cycles requires two programs: controller and task planner. The purpose of each program is:

- *Controller*: ensures that the drag and hoist lengths as well as swing achieve the desired value. It also updates drive states (lengths, current, voltage) on the blackboard at a rate of 10Hz.
- *Task (motion) planner*: uses information from the blackboard to plan the path that the bucket should follow as well as the desired drive velocities at a rate of 10Hz. These are then used by the controller program.

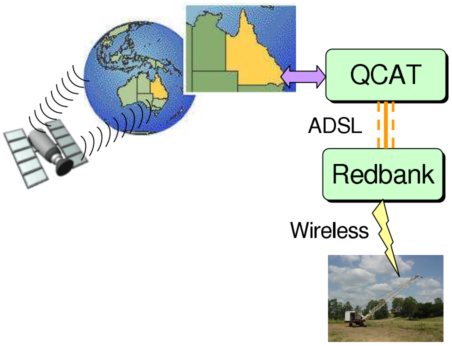


Figure 5: Communcation layout for Remote Regolith Excavation Experiment.

The task planner considers inputs from the mission parameters supplied by the operator, as well as its current situational awareness of its surroundings to control the machine within the changing environment.

All programs are connected by a custom "blackboard" data structure called DDX (Corke *et al.* 2004) through which they share information, with the ability to log any control, demand and response variable for post processing.

Communications

A dedicated communication link was installed which was capable of simulating an off-world communications scenario (see Figure 5). The architecture allows remote operation of the machine from essentially anywhere in the world via a secure network from our laboratories at the Queensland Centre for Advanced Technologies (QCAT).

The system consists of a wireless link from the dragline to hardware located in a shed at the mine site. This hardware is capable of producing pure transmission delays and packet loss to simulate large round trip latencies. There is a 512kB/s ADSL link from the mine to QCAT which then allows secure access to the dragline from anywhere in the world via satellite or cable.

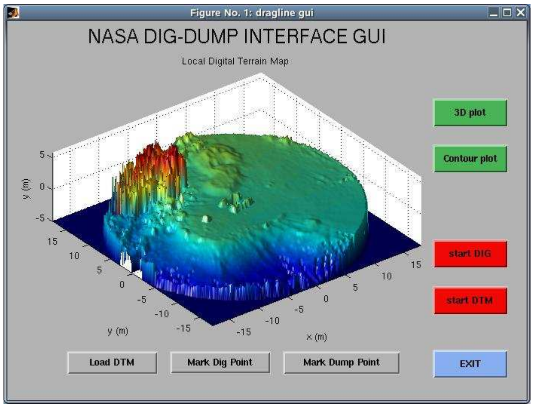
Although this communications link does not meet that described by Hanson (Hanson & Markley 1993) for off-world communications, it is a conservative solution to demonstrate the feasibility of remote operation of a large excavation machinery with high latencies and low bandwidth.

Graphical User Interface

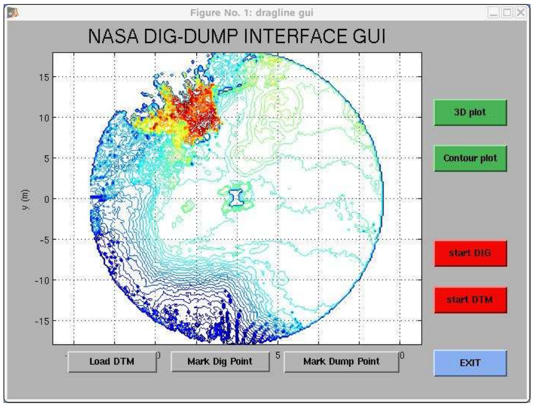
The Graphical User Interface (GUI) enables a remote operator to specify the type of task that is desired and to view the results of the task. There are currently two primary tasks that the operator can specify to the dragline from the GUI:

1. Collect a Digital Terrain Map (DTM) of the local vicinity.
2. Specify an autonomous excavation task.

In addition to task initiation, the operator can request the upload of past or present DTMs as well as specify the desire dig region and dump points within the terrain map. Figure 6 shows snapshots of the current GUI with a measured DTM



(a) GUI showing DTM.



(b) GUI showing DTM contour plot.

Figure 6: Graphical User Interface for remote operation of dragline.

and a contour plot of the DTM. The contour plot was added as it is simpler to mark dig and dump locations on a 2D rather than a 3D surface.

The GUI communicates via the wireless link to the dragline's task planner though the DDX middleware (Corke *et al.* 2004) as shown in Figure 4. The only information exchanged from the operator to the dragline is the task ID, the coordinates of the dig and dump regions, the number of autonomous digs to perform and a task activation flag. The only information supplied from the dragline to the operator is a data file containing the DTM (only when requested by the operator) and a live video feed to another window.

Experimental Results

An experimental investigation to evaluate the entire system was conducted. Here the dragline was instructed by a remote operator via the GUI to perform 50 completely autonomous cycles from a 4m long 15 degree wedge centred at $(x\ ,\ y)$ = (-9.5 , -5.0) and dump the material at coordinates $(x\ ,\ y)$ = (11.0 , -2.0). A total of 50 cycles was chosen as the dig and dump locations will significantly change in geometry over this time.

Only these coordinates and number of digs were specified to the dragline's on-board controller, with digging and bucket swing trajectories path planning and obstacle avoidance required continuously as significant terrain changes occur over the duration of mission.

The system successfully completed 50 consecutive cycles without any intervention by the operator. The average cycle time was approximately 63 seconds with the entire mission taking 52 minutes to complete. The following sections describe some of the results of the experiment.

Digging

At the commencement of each dig task, the profile of the terrain in the dig plane is measured with the laser scanner and the motion of the bucket through the soil is determined to achieve complete bucket filling at the disengage point.

Throughout the mission, each dig was indexed one bucket width back and forth within the wedge to ensure complete coverage. Newer algorithms will specify a desired excavation depth and adjust successive dig engage points to achieve this goal.

Optimal Path Planning

An optimal (shortest) path planning strategy was adopted for swinging the bucket from the dig to the dump locations. This strategy involved measuring the terrain height directly below the bucket using the laser scanner as the dragline swings from the dig to dump locations.

Once the bucket reaches the desired dumping location, a desired height safety margin is added to the measured terrain profile and a shortest bucket height trajectory between the dig and dump determined whilst ensuring the safety height constraint is not violated.

At the end of each dig and dump cycle, the shortest path is re-evaluated to allow for changing terrain profile within the workspace.

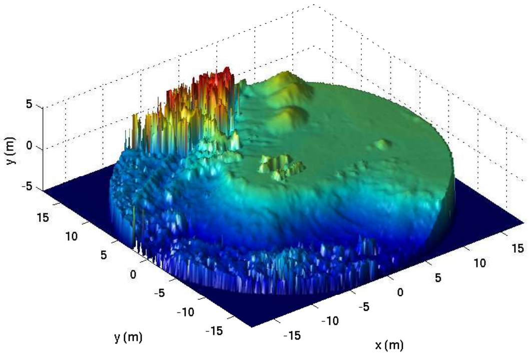
Terrain Mapping

Digital Terrain Maps were obtained at the commencement and end of the mission to evaluate the change in landscape. These terrain maps are shown in Figure 7. In Figure 7(b), the spoil pile is clearly visible at the dump location. The change in landscape at the dig site is less prominent due to the large surface area excavated.

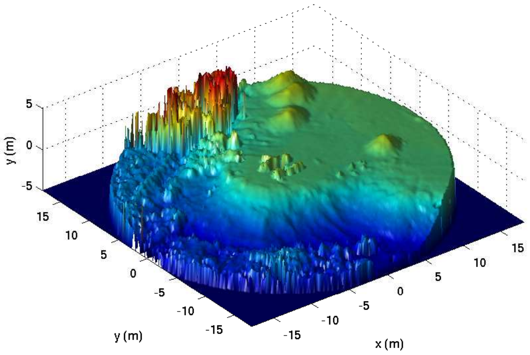
Taking a difference between the before and after DTMs, it was determined that approximately 5.1 cubic metres of material was moved during the 50 autonomous cycles. Figure 8 shows an image of the spoil pile generated at the dump location after 50 cycles.

Discussion

The system described in this paper has been used for a preliminary study into the feasibility of using a dragline type excavator for large-scale off-world robotic excavation. It has also enabled valuable insight into the development of autonomous control strategies that allow the machine to perform a mission without any human intervention. However, despite the success of this research, there are areas which require further investigation.



(a) Before.



(b) After.

Figure 7: Digital Terrain Maps before and after 50 continuous fully autonomous excavation cycles.

Figure 8: Photo of spoil pile after 50 autonomous cycles with the scale dragline in the background.

The most obvious is to repeat these experiments using a lunar regolith simulant. Although not reported here, preliminary investigations into flat digging compacted material has shown that bucket design is critical to penetrate the soil whilst dragging the bucket. Therefore, different bucket designs need to be evaluated in a lunar regolith simulant.

The final area for investigation is the concept design and construction of a more realistic lunar dragline excavator. The current dragline configuration only allows dumping at a radius close to the boom tip. Therefore, a lunar dragline may take the form of the newer “Universal Dig-Dump (UDD)” type machines that allow dumping anywhere in the work envelop, or a more novel multi-cable array robotic systems (Usher *et al.* 2005).

Conclusions

This paper has described current research into developing autonomous systems for realising large-scale off-world excavation for habitat preparation and construction as well as regolith mining for resource extraction. The current state of robotic excavation and the operational issues and design constraints for regolith mining have been discussed.

An experimental investigation was conducted to evaluate the performance of control strategies to perform autonomous excavation using a machine of similar size to that required to perform off-world excavation tasks. The results show that the machine is capable of taking high level commands from a remote operator and operating autonomously within a changing environment. A total of 50 consecutive autonomous cycles were conducted moving approximately 5.1 cubic metres of material.

Acknowledgments

The authors would like to thank the rest of the CSIRO Mining Robotics team for their valued contribution in hardware and software support: Les Overs, Stephen Brosnan, Pavan Sikka, Elliot Duff and Polly Alexander.

Preliminary dragline and rope shovel research has been conducted with the support of the Australian Coal Association Research Program (ACARP) through projects C3007, C5003, C9028,C13040, C12030, and NASA project 62442132.

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