

# SIMULATION OF ROBOTIC REGOLITH MINING FOR BASE CONSTRUCTION ON MARS

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## ABSTRACT

A simulated mining scenario on Mars is presented in which regolith is excavated from a hillside and stored nearby by a fleet of robotic machines, in the first phase of establishing a permanent human settlement. The simulation process shows how it can assist with several aspects of planning and robot control. These include high-level job and site planning, identifying machinery requirements and testing algorithms for automatic command generation and multi-machine coordination. It is also shown how a single remote human operator is able to plan and monitor the work by avoiding direct teleoperation of the machines and maintaining a supervisory level of control.

Key words: automation, excavation, construction, mining, robotics, earthmoving, human-machine interaction, supervisory control, Mars.

## 1. INTRODUCTION

Establishing a human presence beyond Earth will require the construction of permanent, growing settlements on other worlds. In our Solar System, the best candidate location for this development to first take place is the planet Mars. Although its surface conditions are extreme, with cold temperatures and low pressures, Mars is the most Earth-like planet in the Solar System. With an almost identical day-length, a similar axis tilt resulting in four seasons and surface vistas analogous to Earth's arid regions, Mars will also be a welcoming place for human settlers. With minimum-energy Hohmann transfers from Earth only possible every two years, the first settlers will need to attain a high level of self sufficiency, using local resources for life support, construction and manufacturing.

A detailed plan for establishing a permanent, growing settlement on Mars using local resources is the Mars Homestead Project (MHP) by Petrov and McKenzie [7], [6].

One of the main resources featured in this plan is the Martian regolith itself, which can be used for resource extraction (metals, chemicals, possibly water), manufacturing (bricks, glass) and shielding from radiation and the near vacuum (by burying inhabited spaces).

According to the design, following the initial establishment of a 12-person outpost consisting of habitat modules brought from Earth, the settlers proceed to excavate into a hillside. They then build masonry structures in the dug-out area using locally-manufactured bricks, covering them with a protective layer of regolith. The inhabited spaces are highly modular to protect against air leaks. Structures deep inside can be made to hold air pressure with a sufficient regolith overburden (>10m). Masonry vaults near the surface would contain and protect pressurized fibreglass modules, with thinner regolith layers (>1m) providing at least some radiation shielding. A concept of the first phase of this settlement for 24 settlers is shown in Figure 1.

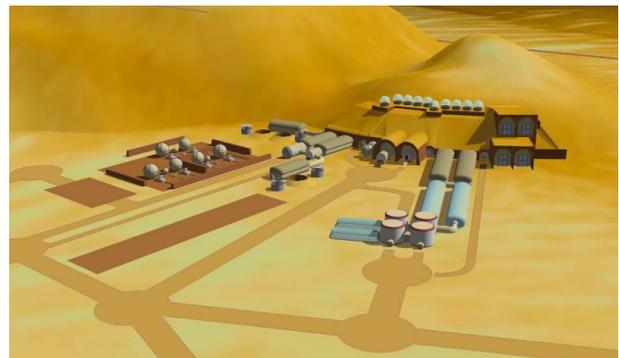


Figure 1. Mars Homestead Project [7].

This paper presents simulations of robotic regolith mining for the first construction phase of the Mars Homestead Project. This phase consists of excavating the slope section in which to build the masonry structures, as well as storing the regolith in an efficient manner so it can be used later as a resource.

It is assumed that robotic machinery should be used for

this work, with one main reason being to reduce the radiation exposure and risk of depressurization that human machine drivers would face. Various methods could be used to control the robotic machines. According to the scenario, since humans are already present in the initial outpost, direct teleoperation would be possible. If the controllers are far away, such as on Earth, the long time delay would only allow high-level supervisory control, and highly autonomous machines would be required. Even if teleoperation is possible however, supervisory control would be desirable to reduce operator workload and allow one human to oversee all the machines, freeing the rest of the crew for other tasks. Another possibility may be a hybrid approach, with operators on Earth doing as much as possible, sometimes relying on the crew members to intervene more directly.

The simulations presented here make use of a wheel loader for the excavation work. Previous work by the authors focused on job planning for a robotic skid-steered compact wheel loader [3]. Here, the concept is extended to include dump trucks for hauling and a conveyor belt spreader for depositing the regolith, increasing the overall capability. The machines are shown next to the outpost in Figure 2, with the hillside to the right. The slope is assumed to be a debris apron [7], which should be possible to excavate using a wheel loader. In case fragmentation is first required, a wheel loader will still be necessary afterwards.

The machines are deliberately kept small-scale (wheel-base approximately 1 m) due to the mass and volume constraints of transport to Mars. No detailed design has been done for the actual machines that would be needed on Mars, however it is assumed that they would be electrically powered with batteries, requiring recharging from the base fission reactor(s).

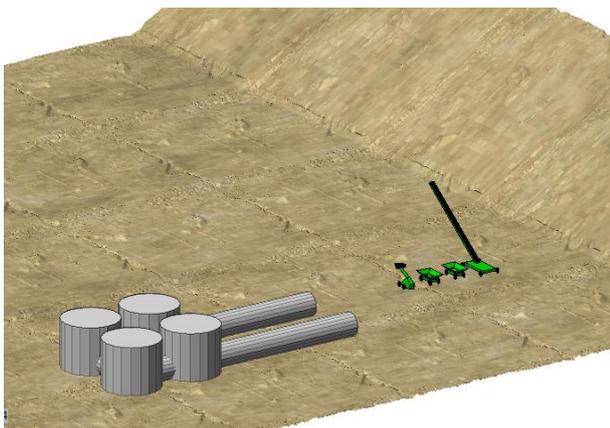


Figure 2. Initial outpost and fleet of machines at worksite.

This simulation environment was developed using Matlab and is based on a Master's thesis by the author [2]. It is purely kinematic, meaning forces are not considered. The ground is modeled as a digital elevation map, or 2D matrix of height values, with a 0.1 m resolution in the XY plane. Machine-ground interaction works by check-

ing for intersection of the wheel loader bucket with the ground, and adding ground volume and lowering ground heights accordingly. An ideal soil behaviour is assumed, which maintains a constant angle of repose in the X and Y directions at locations where heights have changed. The simulator conserves total ground volume and is sufficient for testing high-level earthmoving control strategies.

Job planning and supervisory control of the machines is made possible using interactive 3D graphical tools which are rendered over the worksite model [3]. In a real-world application, the ground model would be constructed using 3D ranging data, and would need to be frequently updated.

The overall goal is to show that it would be possible to excavate the large hillside section specified in the Mars Homestead Project using a fleet of small earthmoving machines. In addition, it will be shown how the job planning and supervisory control strategy will only require one remote human monitor at any given time, and how the overall simulation process can help with planning for large-scale robotic excavation work.

Section 2 will begin by giving a brief overview of research related to these simulations. Next, Section 3 will show how the high-level job plan is made and the effect this has on machinery requirements. Section 4 then shows how the plan is automatically interpreted to generate lower-level commands, and how the operator can modify these. The main simulation events are presented in Section 5, followed by the Results and Discussion in Sections 6 and 7. Finally, areas for future work are identified in Section 8.

## 2. RELATED WORK

### 2.1. Construction Simulation

Research for the terrestrial construction industry aims to use the simulation of construction processes to lower costs. This can be done by identifying scheduling and site layout problems and finding the right type of equipment to use, all before earth is broken. Kamat and Martinez have focused on the benefits of 3D graphical simulation, and shown how visualization of processes can enhance communication between participants with different expertise, as well as help identify production bottlenecks [4]. Shi and AbouRizk show how machinery combinations can be optimized by running simulations with backhoe excavators of varying bucket capacity and different numbers of dump trucks [9].

### 2.2. Automated Earthmoving

The Intelligent Excavation System being developed by Seo et al. generates commands for a backhoe excavator from a high-level site plan [8]. Intelligent navigation

strategies for this system by Kim et al. include automated path planning with obstacle avoidance, both within work areas and for transfer between them [5].

Singh and Cannon developed multi-resolution planners for both a backhoe excavator and wheel loader, which break down a workspace into regions and then decide individual scooping actions within those regions [10]. With space applications in mind, Dunbabin et al. demonstrated fully autonomous, long-duration operations by a dragline excavator, using a 3D Graphical User Interface for planning and monitoring the job [1].

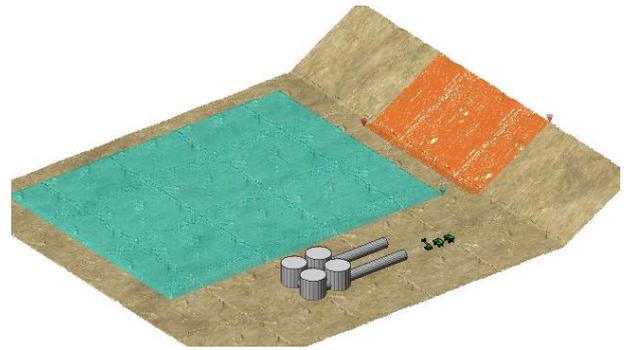
An analysis of multi-agent coordination for general resource collection and delivery tasks was made by the authors, with special attention paid to the problem of priority among agents when driving, collecting and unloading material [11].

### 3. HIGH-LEVEL PLANNING AND MACHINERY REQUIREMENTS

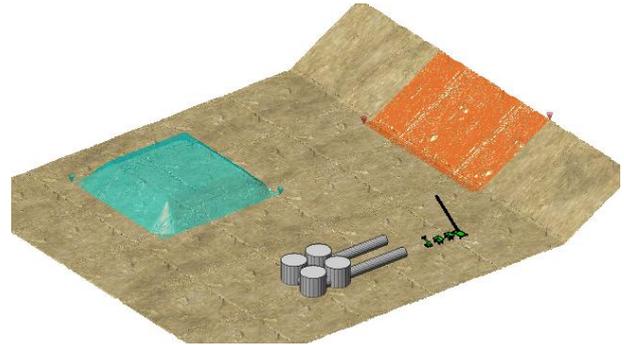
According to the MHP design, the initial slope segment to be excavated should be 45 m wide and 30 m deep (horizontally), with an assumed slope angle of 30 degrees. Figure 3 shows how 3D graphical job planning tools developed previously by the authors are used to make a high-level plan [3]. In this figure, the total ground area is approximately 100 m wide and 120 m long. The red rectangular surface on the slope is used to specify the portion of the slope (here 40 m wide and 20 m deep [horizontally]) we wish to excavate. The blue surface is used to specify a dump pile for storing the regolith. This “virtual pile” has a volume equal to that specified on the slope. This is an approximation, however, as the volume specified by the red slope surface is only of the ground material directly underneath, and does not include the additional regolith that would collapse in from the sides and further uphill.

When this plan was initially analyzed, the available machines were limited to a wheel loader and dump trucks. Figure 3(a) shows the large-area pile, only about 1 m high, that would be possible to deposit using the dump trucks. It is evident that this low pile would take up an exorbitant amount of space. This led to the machinery requirement for a conveyor belt spreader capable of depositing regolith from high above the ground, to create space-efficient storage piles, as in Figure 3(b), about 6 m high. This type of machine would also be required later in the construction process for burying structures with protective layers of regolith.

Another alternative for storing the material would be to have dump trucks capable of driving over the regolith they deposit. They could then build up a ramp that increases in height with the volume dumped. For covering structures later however, a conveyor belt spreader would likely still be required.



(a) Low storage pile (1 m) possible with dump trucks makes inefficient use of space.



(b) High storage pile (6 m) possible with conveyor belt spreader allows storing regolith more efficiently.

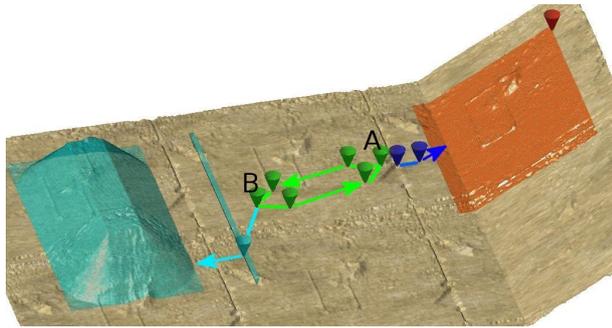
Figure 3. Effect of site plan on machinery requirements.

The need for a minimum of two dump trucks comes from a simple efficiency analysis. First of all, as dump trucks generally have a bucket volume several times than a loader, the 1 Loader + 1 Dump Truck combination is more efficient at transporting loads than one loader alone, even for short hauling distances. This is because the hauling distance covered by the dump truck would have to be traversed  $N$  times by a loader to haul the same amount of material, where  $N$  is the number of scoop loads needed to fill the dump truck. With only one dump truck however, the loader stands idle during the hauling cycle, thus to ensure continuous operation by the loader, a minimum of two dump trucks are required.

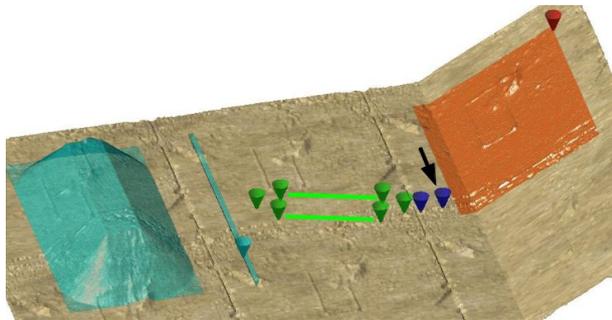
### 4. AUTOMATIC PLAN INTERPRETATION AND USER MODIFICATION

After the slope segment and dump pile are specified, lower-level plans are generated automatically and displayed back to the operator. These include all the driving waypoints for the machines to follow, as well as points defining the scooping actions into the slope, dumping location for the spreader, and points for load transfer between the loader and dump truck, and dump truck and spreader. These points are represented by inverted cones and rendered onto the world model, allowing the operator to see exactly how the machines intend to execute

the job and where they will be driving (see Figure 4). The machines are all skid-steered and therefore capable of turning-on-the-spot.



(a) Driving points for loader, dump trucks and spreader generated automatically.



(b) Click and drag one point, other affected points automatically repositioned.

*Figure 4. Automatic command generation with user modification.*

Scooping into the slope begins from the dark blue cone at the base of the hill and heads along the blue arrow in Figure 4(a) towards the highest point in the slope target area, represented by the red cone at the top of the hill. The machine stops before the scoop overflows, extracts the scoop, then reverses, turns and transfers the load to the waiting dump truck. Hauling between the loading area and dumping area happens along the 2-lane road represented by the green cones between the surfaces.

The dumping location is determined by scanning along a line in the virtual pile, from left to right and back to front (when facing the virtual pile), and comparing the desired heights with the actual corresponding ground heights. The light blue arrow pointing towards the virtual pile in Figure 4(a) indicates the lateral position of the first dumping location. The dump truck drives along this vector, transfers the load to the spreader and returns to the loading area.

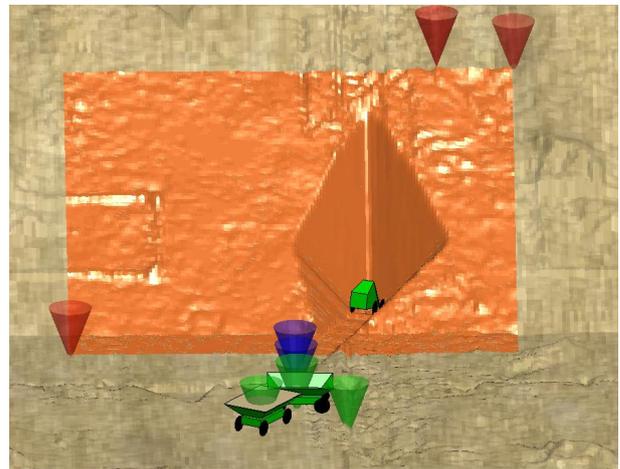
If necessary, the operator may modify the automatically-generated plan by clicking and dragging the necessary points with the mouse. If a point is moved, then other points dependent on it or connected to it are moved automatically. This is shown in Figure 4(b). Here, the staging point for scooping actions is moved, causing the transfer points and road hauling points to be moved automatically.

After a plan is finalized and approved by the remote operator, work may proceed.

## 5. SIMULATION EVENTS

### 5.1. Scooping

As mentioned in Section 4, the automatic strategy being used for updating the scooping direction is to guide the loader towards the highest point in the slope target area. If a large slope section is specified, then the highest point will often remain in the same location for a long time, causing the loader to scoop repeatedly in the same direction and create a narrow passage for itself, as in Figure 5(a). This should be avoided, since in a dynamic real-world situation greater friction would likely be encountered acting on the sides of the scoop. This could reduce scooping effectiveness and increase the risk of getting stuck in the passageway. There would also be the risk of the loader driving up one side and tipping over.



(a) Persistent scooping in same direction with big target area.

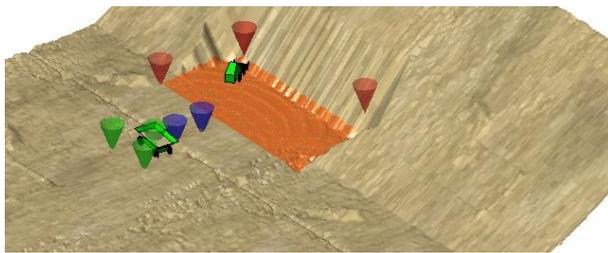


(b) Balanced scooping with smaller target area.

*Figure 5. Scooping strategy.*

This problem can be remedied by shrinking the slope target area after making the initial high-level plan. When this area is only a few metres deep, as in Figure 5(b), then the highest point will change more frequently, resulting in a more balanced set of scooping approaches into the slope. When this smaller area becomes level, it can be

moved to a new location by clicking and dragging with the mouse, as in Figure 6. Note that in this figure the corresponding cones have also been moved by the operator.



(a) First target area leveled.



(b) Target area moved to new location.

Figure 6. Moving smaller target area for scooping.

Another potential problem is that a preset scoop position (governing height above the ground) is used for scooping actions. If this preset position is too low, the loader tends to dig too deep, creating a downhill path over time. If positioned too high, the loader ends up driving up the slope, sometimes leaning heavily right or left, which in a dynamic environment would cause it to slip and/or tip over.

The remote operator can avoid this problem by adjusting the scoop height used for scooping actions via a slider control button on the screen. Occasional monitoring and updates are therefore required, however this still remains above the level of direct teleoperation and the system can usually be left alone for some time (several minutes real time, dozens of minutes to hours simulated time).

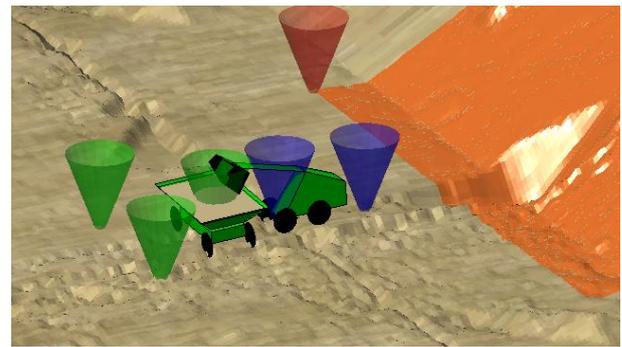
## 5.2. Load Transfer

Figure 7 shows load transfer operations at both the dump truck and spreader.

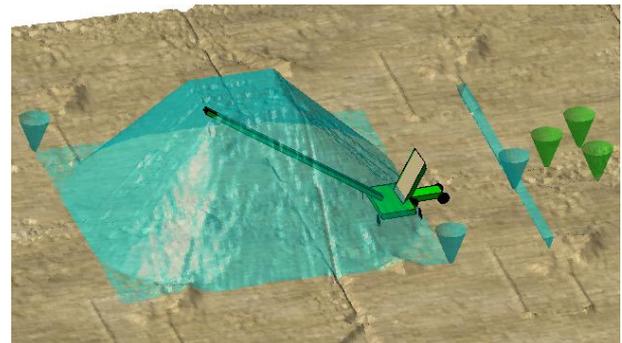
## 6. RESULTS

### 6.1. Hauling Distance

A basic trade-off exists in making the initial high-level plan, i.e. the placement of the virtual pile for regolith storage. It should be sufficiently far away so as not to obstruct settlement construction and development, yet also



(a) Loading of dump truck.



(b) Unloading at the spreader.

Figure 7. Simulation transfer events.

be close enough to the building site and processing equipment to reduce hauling time. This is the case both during excavation and after, when the regolith will be used as a resource. If the hauling distance is too great, two dump trucks are not sufficient to keep the loader operating continuously. This situation is illustrated in Figure 8, in which the empty truck is still on its way back after the other one has already been filled.



Figure 8. Two dump trucks insufficient for long hauling distance - loader stands idle while waiting for empty truck.

The threshold distance at which a third truck would be required can be estimated by comparing the time needed to load a truck with the time needed for a complete hauling cycle. Loading time is difficult to estimate, however,

because the distance from the scoop staging point to the next load of regolith is constantly changing and unpredictable. Furthermore, the scoop does not fill up completely every time, causing the number of scoop loads needed to fill a truck to vary. One benefit of simulation is therefore being able to measure average times for various phases of the work cycle, which can then assist with planning.

Assuming we are limited to two dump trucks, one useful value to find out then is the maximum hauling distance which still keeps the loader operating continuously. Hauling distance here means the distance between cones A and B in Figure 4(a), basically the length of the two-lane hauling road.

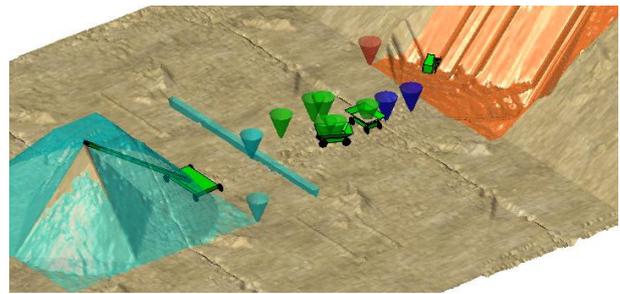
## 6.2. Excavation Rate

Besides hauling distance and the impact it has on site planning, another, perhaps more crucial parameter is the excavation rate. A higher excavation rate is obviously desirable for speeding up construction. One way to achieve this is simply to have all the machines drive faster. With a given driving speed, limited perhaps by energy consumption, another way to increase the rate would be to increase the volume capacity of the loader bucket. This, however, then affects the hauling distance - assuming the dump truck capacity remains the same, a larger loader bucket will fill the dump trucks more quickly and shorten the permissible hauling distance.

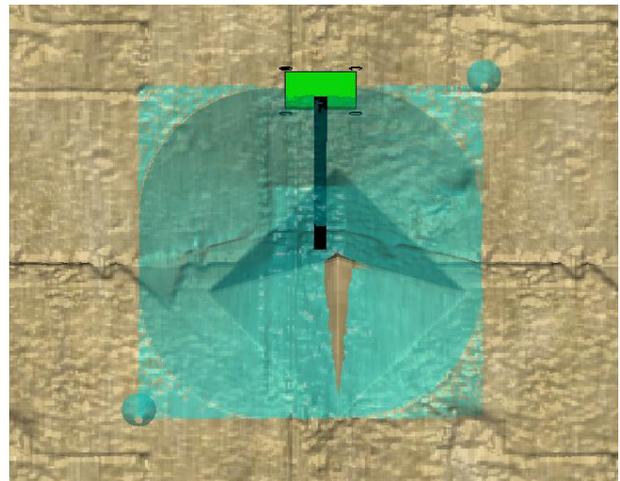
Two simulations were carried out which compare the effect of loader bucket capacity on the hauling distance and excavation rate. Table 1 shows the results. Both simulations (A and B) involved the 1 Loader + 2 Dump Truck combination. The first scoop capacity was  $0.15 \text{ m}^3$ , while the second was doubled with  $0.3 \text{ m}^3$ . Truck capacity was kept constant at  $1.0 \text{ m}^3$ . As the scoop does not fill completely when loading, the average scoop loads are shown, together with the average number of loads needed to fill a truck. "Max. Haul Dist." refers to the approximate maximum hauling distance which still allowed for continuous loading operations. As expected, Simulation B, with a loader capacity twice that of A, fills a truck roughly twice as fast, has roughly twice the excavation rate yet half the available hauling distance.

## 6.3. Long Simulation

Figure 9 shows some aspects of long-duration simulation. Here the scale of the workspace has been reduced, i.e. the entire 45 m-wide slope section is not specified, in order to simplify the simulation. In Figure 9(a), 128 cubic metres of regolith has been moved after 6 hours of simulated time, and the dump pile is starting to grow higher than the virtual pile. In Figure 9(b) the dumping location has been automatically updated, with the spreader having moved to the left.



(a) Long duration simulation, with growing dump pile.



(b) Automatically-updated dumping location - spreader has moved to the left.

Figure 9. Long duration simulation.

## 7. DISCUSSION

The volume of the full MHP slope section to excavate (45 m wide, 30 m deep, with a 30 degree slope) equals  $11691 \text{ m}^3$ . With the rate achieved in Simulation B from Table 1, 472 hours would be needed to excavate it. At 8 hours/day, for example, the full volume could be reached in 59 days, a reasonable time. This is of course a very rough estimate, and many factors could prolong the excavation period, such as difficult regolith properties, the need for drilling and blasting and machinery breakdown and repair.

The analysis in Table 1 shows that a balance will have to be found between transport range and excavation rate when planning robotic excavation operations on Mars. Minimizing construction time is a primary concern, yet this goes hand-in-hand with proper site planning and flexibility. Hasty decisions on the construction site could lead to longer delays down the road, which could be avoided with enough simulation and contingency planning. Aside from just construction plans, conflicts must also be checked with other base operations such as science sorties, greenhouse deployment and plant/manufacturing setup.

The nature of this job - repeated transfer of regolith in the abrasive dust and extreme cold of Mars - means that

Table 1. Comparison of simulation results with different loader scoop capacity. Driving speed is 0.5 m/s.

Sim.	Loaders	Dump Trucks	Scoop Capacity (m <sup>3</sup> )	Truck Capacity (m <sup>3</sup> )	Average Scoop Load (m <sup>3</sup> )	Average Loads per Truck	Max. Haul Dist. (m)	Work Rate (m <sup>3</sup> /h)
A	1	2	0.15	1.0	0.100	10.5	~55	11.11
B	1	2	0.30	1.0	0.238	4.69	~20	24.78

mechanical breakdown is inevitable. Fault tolerance dictates having extra machines and parts. Another balance will have to be found between the mass (robustness) and number of machines. Parts commonality would be an asset - perhaps with the loaders and dump trucks sharing the same chassis. Extra machines arriving with periodic cargo flights could allow the production rate to ramp up over time.

## 8. FUTURE WORK

One improvement would be to implement a scooping controller which would automatically adjust the scoop height based on the pitch of the loader. If pitched downwards when extracting the scoop, the loader is digging too deep, while being pitched upwards would indicate that the scoop is positioned too high, causing the loader to drive up the slope. This should reduce the amount of operator input needed, which leads to another area for further investigation, i.e. operator workload.

A second loader could be first be added, which could be utilized in two ways. One way would be to use it at a new location, which would require twice as many dump trucks. The second way would be to place it near the first loader, with both of them loading the same dump truck. This would fill the truck faster and require extra dump trucks, perhaps also twice as many if they are getting filled up twice as fast.

More loaders could then be added, still requiring monitoring and possible updates, to find out at what point the operator's workload becomes saturated. Another limit that could be tested is the amount of time delay the system can handle, to investigate the scenario of monitoring the fleet from Earth.

## 9. CONCLUSION

Simulations of a mining scenario on Mars were carried out in which regolith was excavated from a hillside section and stored nearby by a fleet of robotic machines. The simulations showed that a fleet consisting of one wheel loader, two dump trucks and a spreader should be able to

excavate the slope segment required for MHP settlement construction in a reasonable amount of time (59 days).

The benefits of construction simulation were demonstrated by the identification of a machinery requirement when making the high-level site plan. It was concluded that a conveyor belt spreader would be needed to store regolith in a space-efficient manner. Another aspect that was studied was the relationship between loader bucket capacity, excavation rate and the maximum hauling distance which still allows for continuous loader operation.

The simulations also allowed for the testing of automatic control algorithms which interpret the high-level plan and generate commands for the fleet of machines to follow. This allows work to proceed without the need for direct human teleoperation - one remote operator is able to monitor the fleet and remain in a supervisory capacity, occasionally providing input such as an updated scoop setting or target area.

## ACKNOWLEDGMENTS

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