Multi-Robot Hillside Excavation Strategies for Mars Settlement Construction

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Multi-robot earthmoving strategies were studied for the simulated excavation of a large hillside section. This could be the first construction phase of a permanent settlement on Mars, which would consist of masonry structures built in the dug-out area and buried under a regolith layer for protection. The robotic fleet consists of eight compact skid-steered wheel loaders and eight or more dump trucks. The basic strategy is to assign each loader its own workspace along the slope face, separated from neighbouring workspaces to avoid possible conflicts, and for two loaders to share the same dump truck for load transfer while extra trucks wait. The workspaces are arranged along a row which advances into the hillside after all material in the row is excavated, in an attempt to excavate the slope evenly. The strategies developed generate commands which nominally allow the robots to operate autonomously until job completion. Various parameters can be modified in the simulator, such as the workspace dimensions, dump truck location, and slope height. Several simulations were conducted in order to test the effect of these parameters on the excavation rate and amount of driving required by the machines. It was found that while the workspace dimensions could be adjusted to increase the excavation rate, larger advantages could be gained by positioning the machines favourably so as to decrease the driving needed for load transfer.

I. Introduction

BUILDING permanent settlements on other worlds will enhance the long-term survival of humanity. Not only will this insure against sudden planetary-scale threats, either natural or man-made, but by expanding the economy into deep space, it could also help to mitigate the gradual harmful effects of increasing industrial and economic activity on Earth's biosphere. This economic activity could include the development of physical resources in space, but also new inventions and culture developed by settlers on other worlds.

The best candidate location for the first permanent settlement beyond Earth is the planet Mars. Although the surface environment of Mars is extreme and hazardous to humans, some factors will help to make it a welcoming place. These include the nearly identical day length (24⅔ h), seasons due to the similar axis tilt (25.2°), and vistas analogous to Earth's arid regions.

The flight time to Mars is typically 5-10 months, and only possible every 2.14 years if using a minimum-energy Hohmann transfer. Another transportation constraint, due to launch costs, is the amount of cargo that can be brought from Earth. These challenges, however, may help to make a Martian settlement permanent, as the inhabitants will need to become self-sufficient, using local resources as much as possible.

One detailed plan for building a permanent, growing settlement on Mars is the Mars Homestead Project by Mackenzie et al.[1] The architectural design by Petrov[2] (see Figure 1) outlines the general construction plan. After a temporary outpost of habitat modules is established by the first manned missions, the excavation of a hillside section is initiated. This would measure 45 m wide by 30 m deep (horizontally), and once excavated, masonry structures would be built in the cavity using locally manufactured bricks. These would then be covered by a layer of regolith for protection against ionizing radiation, and also from micrometeorites. The process could then be repeated in adjacent sections to grow the settlement linearly as more settlers arrive.

Assuming a 30° slope, the initial hillside section to excavate corresponds to a volume of 11691 m^3, which would be even higher due to material collapsing in from the surrounding slope. Other earthmoving work which may be needed on site includes clearing and grading areas for setting up infrastructure and road construction, and building up blast-protection berms around launchpads. Regolith would also be harvested to mine useful chemicals and

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minerals (such as water for life support, and metals for construction and manufacturing), which could be combined with the hillside excavation.

This earthmoving work would involve repetitive and long duration operations in the Mars surface environment, which would be hazardous to humans due to radiation exposure and the risk of depressurization. To increase safety, this work would be better suited to robotic machines. While remote teleoperation of the robots may be possible if a human crew were on site, automating the machines as much as possible would be desirable to increase the limited man-hours available for other important tasks.

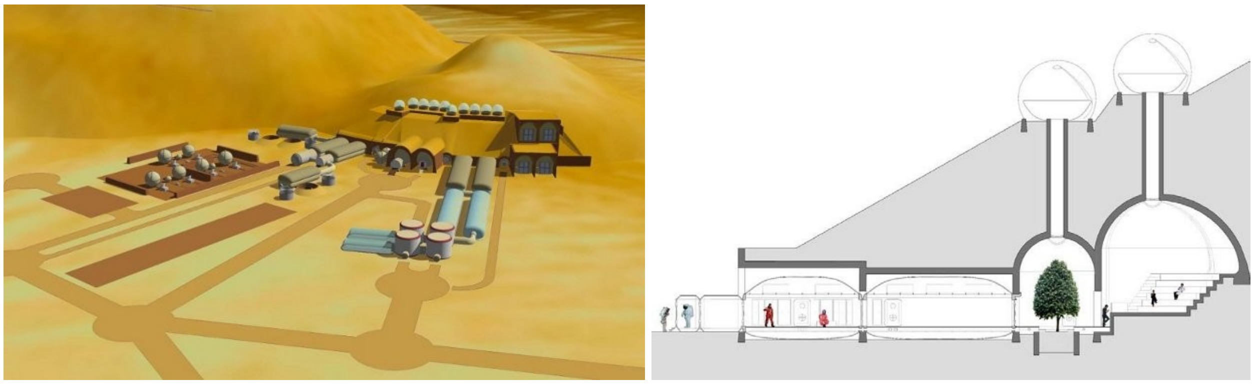

Figure 1. *(left)* Mars Hillside Settlement Phase I, for 24 settlers - initial outpost modules connected via inflatable greenhouses. *(right)* Section elevation - vaults near exterior encase inflatable modules; those further inside can be pressurized due to regolith overburden. Design by Georgi Petrov[2] (used with permission).

This paper makes a contribution to the goal of automated hillside excavation by presenting a general strategy for coordinating a fleet of robotic wheel loaders and dump trucks removing material along a slope face. This strategy is not necessarily specific for Mars applications, and might also be useful for lunar or terrestrial excavation. The main goal behind the strategy is that ideally, commands can be generated which allow the machines to operate for hours or days autonomously until job completion. This goal was motivated by the Mars Hillside Settlement construction plan, since full automation would present the possibility of monitoring the machines from Earth, where the long telecommunication time delay (4-20 min. one-way) makes direct teleoperation on Mars impossible.

This paper also presents the results of several simulations whereby changes are made to various parameters related to the workspace layout and job, in order to study the effect on the excavation rate. The simulation environment and coordination strategies are based on previous work by the author, which mostly focused on single-loader scenarios though included some early results related to multi-loader excavation strategies.[3-7]

The next section will begin by presenting related work in this field, followed by a description of the problem studied, simulation environment used and general coordination strategy in Section III. Simulation results comparing modifications to the strategy are then presented and discussed in Section IV. Section V contains the conclusion and discussion of areas for future work.

II. Related Work

Automated earthmoving has become an important research topic due to its application in the mining industry, where it can help to increase safety and reduce costs. Some sub-topics in this area include control of the excavation action,[8-12] and also deciding *where to dig* in a worksite.[13-21] The references given here are mostly related to wheel loaders rather than backhoe excavators, since this is the type of machine used here.

While most research focuses on the control of single machines, some related work in autonomous multi-robot excavation and earthmoving has also been found in the literature. Some of these concepts follow a bottom-up, behaviour-based approach, one example being the "blind bulldozing" strategy developed by C. Parker et al.[22] In this system up to four robots worked to clear an area of material by pushing in a random direction, stopping when the resistance became too high. The net result was a cleared circular "nest," with only indirect communication between the agents in the form of stigmergy through the environment and reacting to collisions with other robots.[22]

A similar task was simulated by Huntsberger et al.[23] and L. Parker et al.,[24] specifically with space applications in mind. These simulations were for multi-robot bulldozing to prepare for deploying solar arrays on the Martian surface. It was found that adding more agents initially sped up progress, but too many started to interfere with each other.[23,24] Another bottom-up solution for multi-robot excavation is the Artificial Neural Tissue (ANT) controller developed by Thangavelautham et al.[25] This was developed with Lunar applications in mind, with a system of autonomous excavation robots developing its own control strategy based on a single global fitness function.[25] The JPL Nanorover Outpost Project[26] envisioned a swarm of small-scale robots for earthmoving jobs on other planets, although possibly using a top-down hierarchical control strategy.

One example of a top-down control strategy for multi-robot applications is the conflict-free trajectory system developed by Pecora et al.[27] Though not specifically applied to excavation work, this allows a fleet of Autonomous Ground Vehicles (AGVs), such as in a warehouse or mine environment, to share the same workspace and avoid collisions with each other without needing to stop.[27]

In the literature no detailed top-down control strategy has been found specifically for multi-robot excavation jobs, therefore the work in this paper makes a step in this direction. Furthermore, the simulations show that the strategy allows full automation at timescales of at least 10-20 hours, while removing several thousand cubic metres of material. Insight is also provided into how modifying certain planning parameters affects the excavation rate.

Whether using a bottom-up or top-down control strategy, fully automated robots would ideally be available for earthmoving jobs to help build a permanent settlement on Mars, and might also allow work to begin before humans arrive. Even with a human crew located on site, however, most monitoring might be done from Earth, with local attention only needed for special situations and maintenance. Mishkin et al.[28] discuss these types of considerations for controlling robots remotely with a long time-delay, such as between Earth and Mars, and sharing control with a local crew.

III. Problem and Method

The problem studied here is the excavation of a slope section 45 m wide with a 30° slope, which follows the Mars Hillside Settlement construction plan[1] described in the Introduction. Figure 2 (at left) shows a concept of the initial site in the Matlab simulation environment used here, with the first habitat modules comprising the base and a small fleet of machines. These surface models have a grid resolution of 0.2 m.

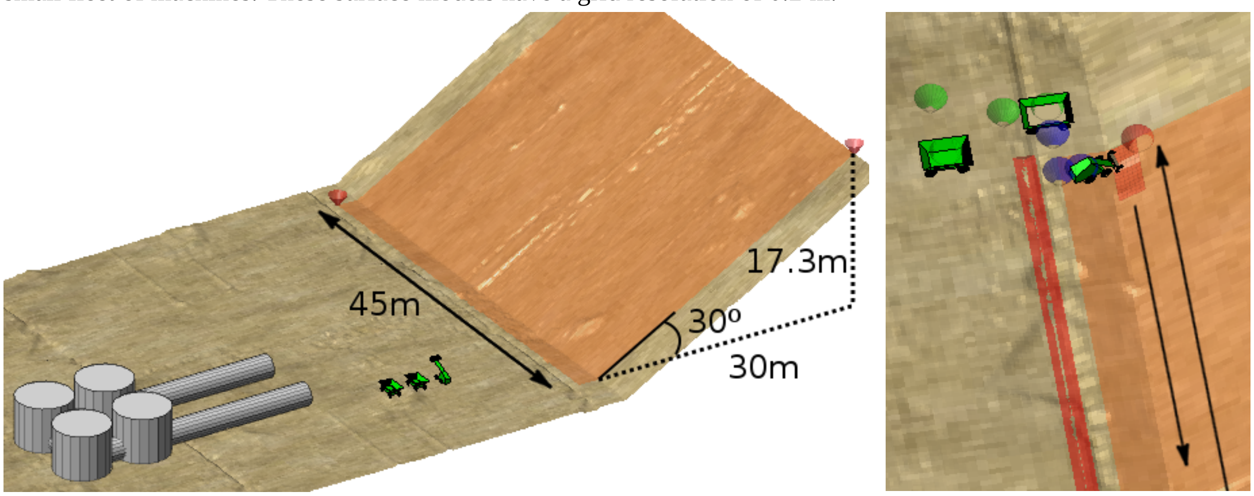

Figure 2. *(left)* Initial base and full slope section to excavate for Mars Hillside Settlement. *(right)* Single-loader strategy for dividing workspace with smaller rectangular Scoop Area, which scans for next location along rows from front to back, and stays at current location until all material cleared.

The site would have to be carefully surveyed and characterized beforehand. Many unknowns and potential challenges exist if these large-scale earthmoving operations would be attempted on Mars. The compactness of the ground material, and effects of extreme temperature gradients and possible ice deposits are some examples.[29] Here it is assumed that the material being loaded is loose and free-flowing, either naturally or due to periodic fragmentation by blasting or other means.

Traditionally, robotic planetary rovers have been designed as light as possible due to tight mass constraints and high launch costs from Earth. While some research in excavation with lightweight rovers for space applications has been done,[30] the low-mass requirement generally conflicts with the fact that machines for earthmoving and excavation should be heavy enough to exert the necessary forces on the ground. They should also be robust to the mechanical wear and tear they would be subject to. One possibility for increasing the weight of such machines in the reduced Martian gravity (0.38 g) could be by filling on-board containers with regolith for ballast. Modular design, and perhaps a common chassis and interchangeable parts between different machines such as loaders and dump trucks could ease maintenance.

In the low-gravity environment of Mars, different earthmoving machinery and processes may function more effectively than those used typically on Earth. These could include drag-line buckets which are tethered to exert higher forces on the ground, and ballistic regolith blowers which can transport material onto storage piles or cover habitat structures. In this paper, however, it is assumed that conventional wheel loaders and dump trucks are used. One advantage of a multi-robot approach is that a small number of machines can begin working after the first cargo flight arrives, with the work rate scaling up as more machinery arrives.

A. Simulation Environment

The kinematic simulation environment used here was developed previously by the author using Matlab, and allows for the basic simulation of excavation and earthmoving jobs by robotic machines.[3,4,7] The kinematic nature of the simulator means that no forces are modeled, however the total volume of ground material is conserved, as is a constant angle of repose in the X and Y directions. This simulates the collapse of material whenever ground heights are changed from removing or depositing material.

The wheel loaders in these simulations are modelled after the compact skid-steered Avant 320 (see Figure 3), one of which was previously available to the author for hardware experiments.[3] They are therefore able to turn on the spot, and have a bucket 0.8 m wide by 0.5 m long with a volume capacity set at 0.15 m^3. The dump trucks are not based on any machine which was available, but were designed for the simulator with space applications in mind, i.e. small-scale and with a similar chassis as the loaders. They are also skid-steered, and have a hopper capacity of 1 m^3.

Figure 3. Compact skid-steered Avant 320 wheel loader.

Power is a key issue. Such machines would likely be electric battery powered, recharging from the base grid. The ideal base power source may be a nuclear fission reactor, though solar panels are another possibility.

More analysis concerning vehicle size, mass and power requirements are beyond the scope of this paper. The main parameters which could be modified in the simulator are the wheel positions, bucket dimensions and volume, and kinematics of the bucket joints, though here they are kept constant.[4] These parameters can all have a significant effect on the excavation rate since they affect how much material can be removed in one scooping action, and also how many loaders can work simultaneously within the 45 m-wide workspace.

In the simulator it is assumed that the robotic wheel loaders are able to automatically control a scooping action given an approach vector, resulting in an average bucket filling ratio of 0.9. During a scooping action, the tool passes through the ground surface without any resistance, until the point at which the intersected volume capacity has surpassed the load capacity of the scoop. Meanwhile, the ground surface heights along the bucket path are lowered to account for the removed material. At this point, when the scoop has been filled, the loader stops the scooping action and extracts the scoop, while the surrounding ground heights are reset as required to maintain the maximum repose angle.

Some randomness is introduced in the bucket filling to account for the unpredictable effects of tool-ground interaction. This randomness is achieved by assuming a minimum fill ratio of 0.8 when the scoop has been "filled," with the rest of the capacity filled randomly and the remaining material deposited back on the ground.[3,4] Over many actions this results in an average fill ratio of 0.9.

The robotic machines are assumed to possess accurate positioning information and be capable of navigating autonomously between two given points. Since they are skid-steered, all driving paths consist of straight line segments connected with points where the heading can be adjusted. A current ground model is also assumed to be available, which could be made from several local ground models obtained via laser scanners on each machine, and/or from other site sensor systems. One possible challenge in using optical sensors could be clouds of dust at the worksite blocking the view to the ground surface, therefore breaks in the work cycle may be needed to make new scans. Martian dust storms may also pose a challenge if they hinder visibility.

B. Slope Excavation Strategy

In order to excavate a large rectangular hillside section, as in Figure 2 (at left), a strategy illustrated in Figure 2 (at right) was developed for a single loader with two dump trucks available. Assuming the workspace is rectangular, and one requirement is to excavate the slope face evenly, the workspace is broken down by working in a smaller rectangular part called the Scoop Area (SA), which searches for the next working area in a raster pattern, first along the front row, then one step back and along the next row, as the arrows indicate in the figure. If a location is found with ground heights a certain threshold above ground level (here 0.15 m), the loader works there until the SA is cleared. The search then continues for the next location.

To remove material, the loader begins all scooping actions from a stationary Stage point located in front of and in line with the middle of the SA. Here a simple "High Point" strategy is used to decide where to scoop next, by aiming towards the highest point in the SA.[3,4] As the slope collapses from material being removed, the highest point shifts and the loader ends up clearing the area using a fan-shaped pattern of approach drives. The driving points are represented by cones in Figure 2, as well as in Figures 4-6.

When a load is extracted, the loader reverses back to the Stage point, then reverses to a point in line with the middle of the dump truck. It then turns 90° and drives to the final load transfer point beside the dump truck. In some figures not all driving point cones are rendered, however they are shown in Figure 2 (at right) and Figure 4. The full hauling path of the dump trucks is not included here. When a full truck drives off to be replaced by the other one, its load is deleted and it continues to the waiting position.

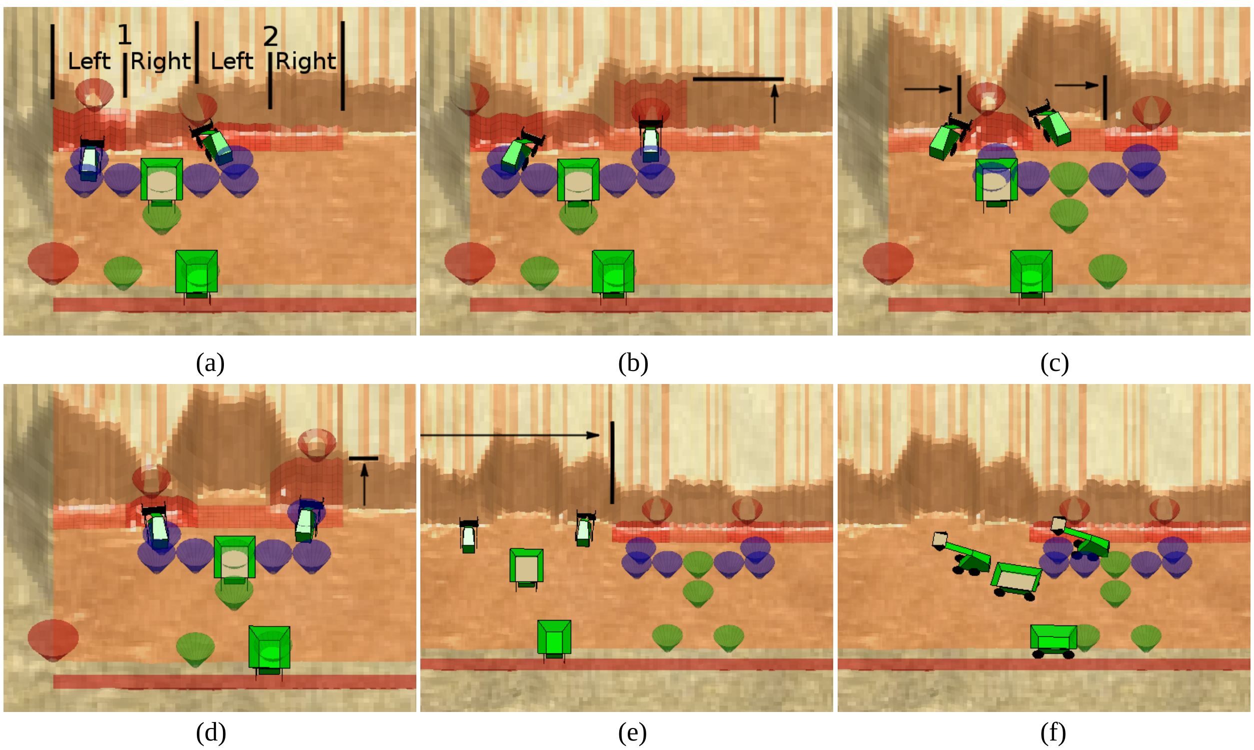

Figure 4. Workspace division for two loaders: a) Scoop Area divided into 4 Scoop Zones, loaders always separated by one zone to avoid conflicts; b) if zone completed, temporarily extended forward; c-d) when both zones complete, shift to neighbouring; e-f) when all four zones complete, Scoop Area shifts to next location.

A general trend exists in the optimal SA dimensions, which is that a smaller SA has the benefit of being cleared faster, helping to speed up the job. Because it is finished sooner, however, it must reposition more often, requiring the machines to also reposition more often, thus slowing down the job. A larger SA, conversely, requires more driving to be cleared, however requires less repositioning. In the previous work several simulations, mostly for single-loader cases, were conducted to find the optimal SA dimensions which balance this trade-off.[3,4]

Figure 4 shows how the workspace division strategy is extended for two loaders. The SA is divided into twice the number of loaders, thus here into four parts, or "Scoop Zones (SZs)." The two zones on the left are assigned to one loader, and the two on the right to the other (see Figure 4(a)). Each loader begins by working at its own respective left zone. If one of these is cleared before the other, it is temporarily extended one step forward so that the loader can continue working while the other finishes its initial zone (see Figure 4(b)). When both initial zones are cleared of material, both loaders switch to their respective right zones, as in Figure 4(c). In Figure 4(d) the right loader has again cleared its zone first, thus it is temporarily extended forward again. When all four initial zones are clear, then the entire SA is clear and it continues searching in the raster pattern for the next location (Figure 4(e)), with the machines repositioning themselves there (Figure 4(f)). In this way, workspace separation is maintained in order to avoid conflicts between the loaders.

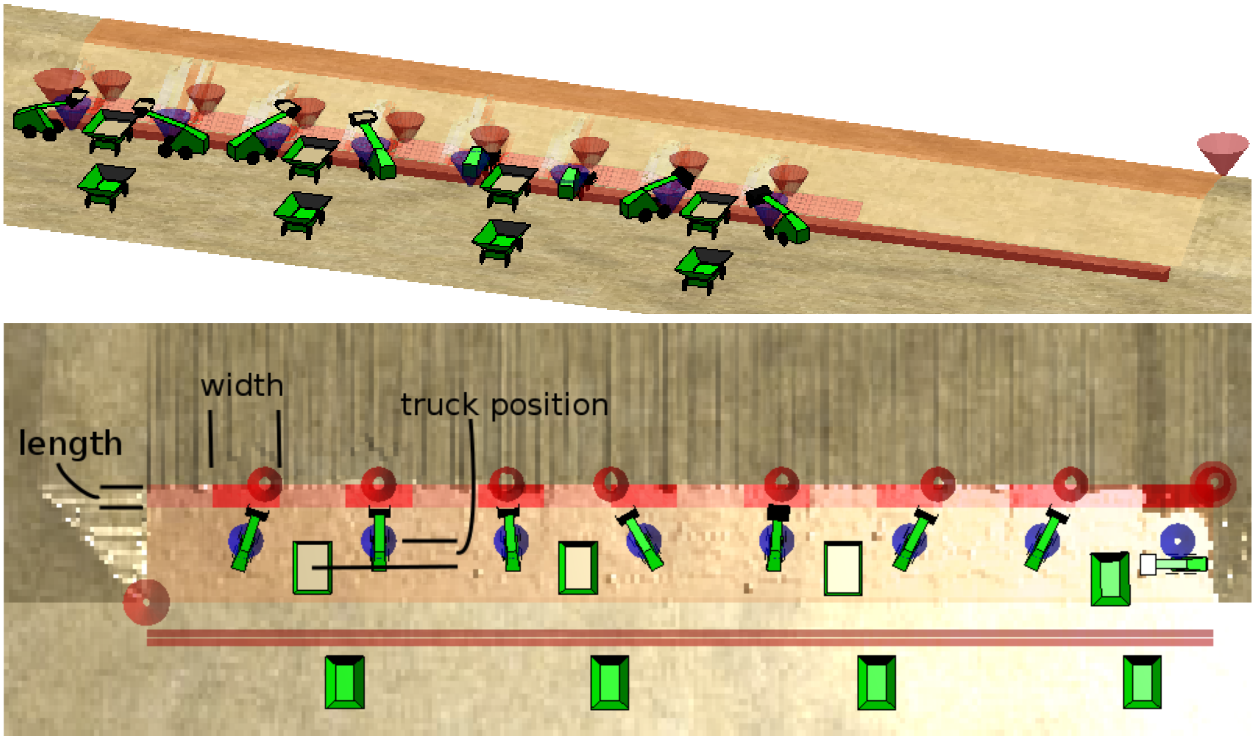

Figure 5. ***(top)*** **"Low slope" version of job, with 1.73 m-high plateau.** ***(bottom)*** **Overhead view of workspace division, with 3 parameters labelled: Scoop Zone "length" and "width", and "truck position."**

This strategy can be scaled to any number of loaders, with the only limitation being the maximum number that could fit within a certain width. If the SZs are made too narrow, there may not be enough space for maneuvering and collisions could occur, such as between a loader and dump truck when turning to load the truck. If there is an odd number of loaders, a loader at one end would have its own dump truck to load. The simulations presented in the next section make use of eight loaders, as this was the maximum number which would fit along the workspace for the range of SZ widths used.

IV. Simulation Results

The full hillside section to excavate, illustrated in Figure 2, would be 30 m into the slope horizontally, which corresponds to a height of 17.32 m at the rear of the section. Simulating the whole job multiple times to test different strategies and parameters would have been too demanding computationally, so two smaller versions of the job were used. These were both 45 m-wide hillside sections with 30° slopes.

The first job, shown at the top of Figure 5, has a slope or plateau height of only 1.73 m. This version was created because in the previous work, a job was needed which could be repeated many times to get average results on account of the randomness introduced in the bucket filling.[3] The reason for including it here is so that comparisons can be made with full 17.3 m-high slope excavations, to see how the slope height affects the excavation rates and optimal parameter values. The low slope simulations were terminated when a total of 100 m^3 of material had been removed. This was before any loaders had reached the back of the 5 m-long workspace, so that the recorded excavation rate would correspond to all the machines working continuously.

The 2nd version simulated was the full 17.3 m-high slope, but only excavated to a horizontal depth of 5 m. Simulations of each job were repeated while modifying certain workspace planning parameters (see bottom of Figure 5). These include the Scoop Zone "length" and "width," modified for both job versions, and the "truck position," only modified once for the full-height version.

The top of Figure 6 shows two images from the beginning of a full-height simulation. These illustrate how the slope collapse allows the machines to excavate into the hillside by working along the bottom contour. The bottom of Figure 6 shows a case near the end of a full-height simulation, excavating 5 m horizontally into the slope. Here it is assumed that a plateau with a constant height of 17.3 m is being excavated, but another possibility could be a higher slope, which would then take longer to excavate due to more material collapsing from uphill.

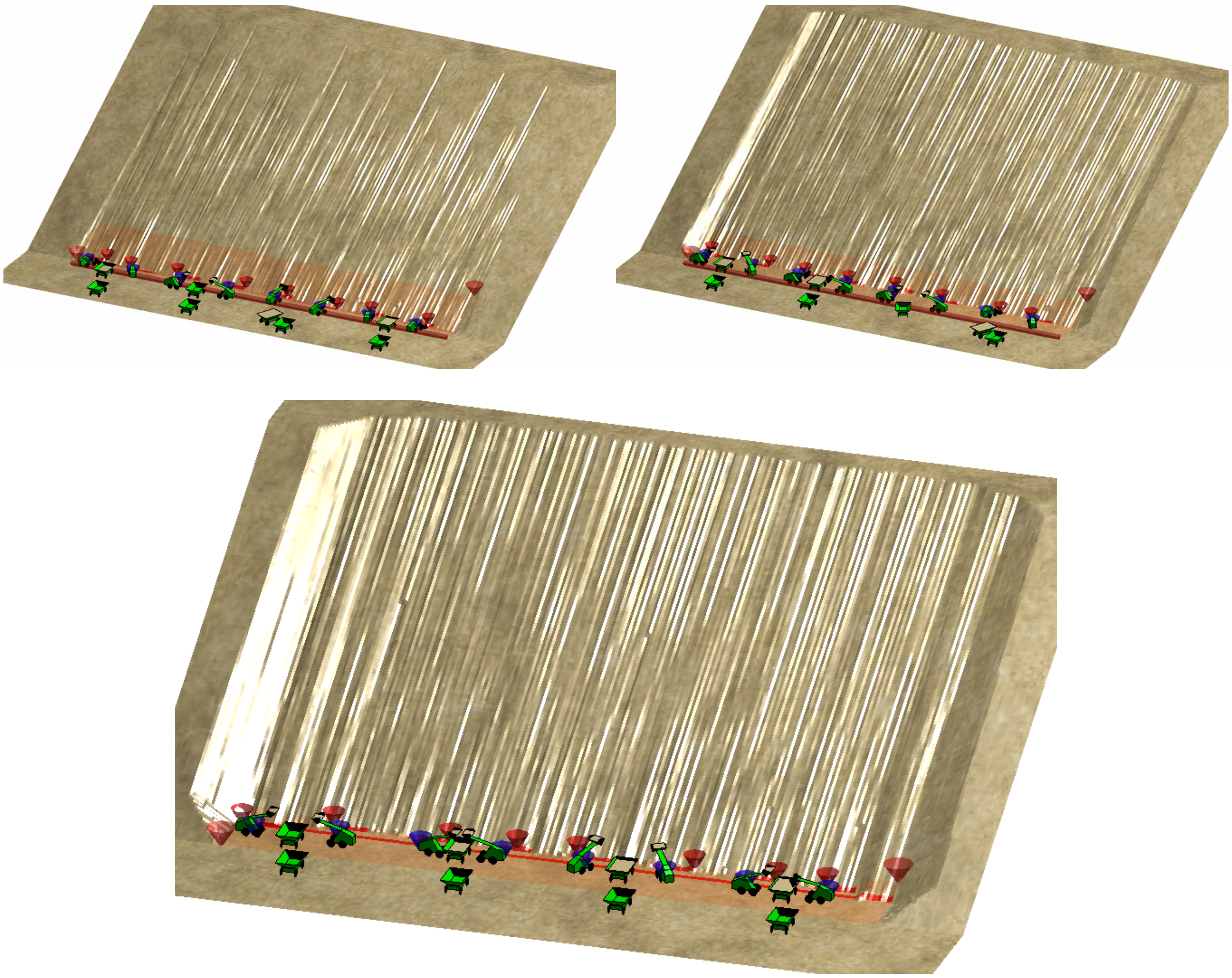

Figure 6. Full-height excavation simulations with 17.3 m-high 30° slope. *(top)* Early stages illustrate slope collapse and progression into slope. *(bottom)* Near end of job to clear 5 m into slope. Thin red line is Scoop Area - most Scoop Zones are extended ahead since Scoop Area remains in line with zones at ends. These end zones take longer to clear due to slope collapse from sides.

In Figure 7 the total volume of material excavated over time is plotted for three different simulations. All of these were with the full slope height of 17.3 m, excavating 5 m horizontally into the slope. It can be seen that each line starts with a straight portion, corresponding to a fairly constant excavation rate. The straight trend then ends when some loaders reach the back of the workspace and stop excavating. The loaders at the ends tend to keep working due to additional slope collapse from the sides, but the overall excavation rate decreases. The solid red line and dotted black line reached this effect after about 18 hours, while the dashed blue line reached it later at about 21 hours. The red line represents a narrow 2.4 m SZ, which makes forward progress rapidly, however overall the job becomes slower because more material is left in the corners for one loader to dig at a time. The fastest rate (dotted black line) is achieved with the case with zero "truck position," since the reduced driving required for load transfer to the trucks evidently results in significant time savings. The different lengths of the three lines plotted correspond to how long each simulations was run. Simulations were usually ended before all material was cleared, but after some loaders had reached the back of the workspace. The excavation times presented here were from non-stop operation, however in a real scenario work may frequently be interrupted by slope fragmentation (if required) and vehicle replacement due to battery charging and maintenance.

The results of all the simulations are summarized in Table 1. The rates which are given in the last two columns correspond to the "steady state" situation during the first part of the job, before any loaders reach the back of the specified workspace and stop contributing to the volume excavated. As Figure 7 showed, the rate during this part of the job tends to be fairly constant. Aside from the standard excavation "Rate" in the 2nd last column, which measures the volume excavated per time, another measure used to compare the results is the *volume per combined drive time*, abbreviated as Vol/t_{CD} in the last column of Table 1, also with the units of m^3/h. This measure attempts to consider the case where excavating as quickly as possible may not be the most important goal. In case energy is limited, for example, it may be more desirable to minimize energy use during the job even if it takes longer.

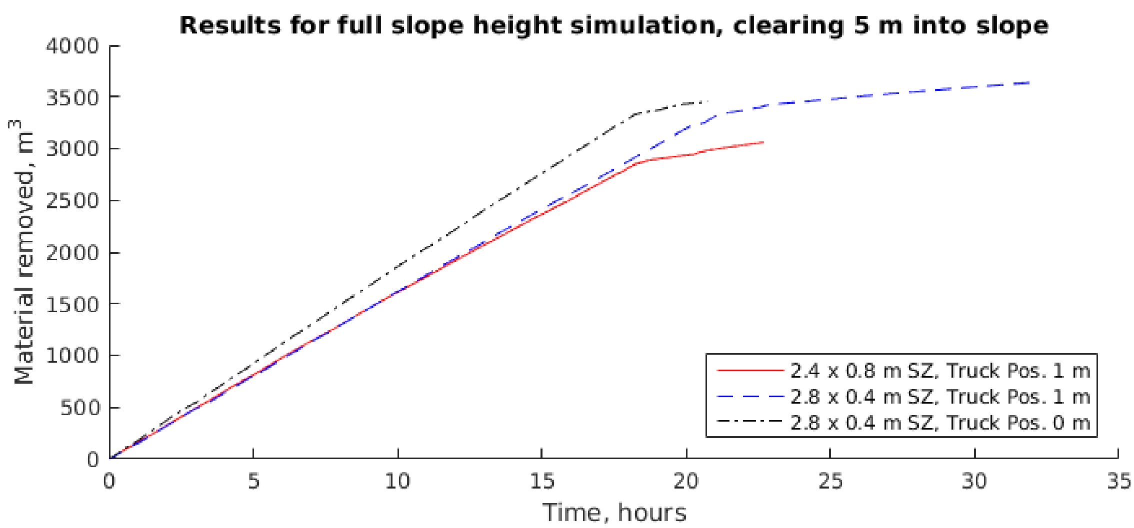

Figure 7. Comparison of material removal rate for three simulations of full height slope excavation.

The volume per combined drive time is the volume excavated divided by the total time spent by all machines (loaders and trucks) driving and turning during the job. It would be expected that the maximum volume per combined drive time would be achieved using SZ dimensions that are larger than for the maximum regular excavation rate. This is due to the trade-off discussed in Section III.B, i.e. since smaller SZs are cleared more quickly, new SAs must be found more frequently, which involves all the machines repositioning themselves at the new SA location. Since repositioning involves all the machines driving and turning, including the dump trucks, SA repositioning would incur a higher penalty than with the regular excavation rate.

The rates in rows 1-6 are the average values from running each simulation 10 times, which was possible due to the smaller total amount of material to remove and faster simulation time. The remaining simulations only had one instance.

The "truck position" parameter was only modified for one simulation, in row 13 of Table 1. This was originally set at 1 m in order to place the trucks a small distance further back from the excavation areas, to avoid any chance of collisions. Since there is enough space, however, this 1 m spacing is perhaps too conservative, and also contributes to the distance the loaders must drive each cycle, therefore it was shortened to 0 m. This positions the dump trucks in line with the Stage points from which the loaders scoop (see Figure 5). In row 13 of Table 1, it is clear that this one modification had a significant effect on the excavation rate for the 2.8 x 0.4 m SZ case, raising it from 160.3 m^3/h to 184.1 m^3/h. These correspond to rates of approximately 20.04 m^3/h and 23.01 m^3/h per loader.

Comparing rows 10 and 11, it is seen that a higher volume per combined drive time is achieved with a larger SZ. As explained earlier, larger zones have the advantage that they result in less frequent repositioning of the machines simply because these zones contain more material to load. The highest standard excavation rate for the full slope height simulations, with the standard 1 m truck position, was with SZ dimensions of 2.8 x 0.4 m.

Comparing the first 6 rows, from the low 1.73 m slope, with the next 6 rows, the rates are comparable, therefore the slope height does not seem to have a big effect on the rates themselves. The maximum excavation rate for the low-slope job, however, is achieved with a longer 2.8 x 0.8 m SZ compared with the high-slope version.

V. Conclusion and Future Work

A general observation from the excavation simulations presented in this paper was that the loaders at each end or corner of the workspace have more material to remove due to slope collapse from the sides. Consequently, the loaders in the middle make faster forward progress into the hillside. The goal of excavating the slope evenly may then be difficult to achieve, as a concave contour tends to form over time.

Another workspace division strategy, which was first presented in earlier work[3,5] but not included here, would be to divide the workspace into separate SAs for each two-loader team. Some teams could then excavate deeper into the hillside if they make faster progress in the middle of the slope face, for example, as usually happens. In the Mars Hillside Settlement construction scenario, it may be desirable to reach the back of the 30 m area as soon as possible in order to begin masonry construction, while the corners of the space may take longer to excavate.

The simulation results presented in Table 1 showed that the SZ dimensions being used have an effect on the excavation rates, however changing the truck position from 1 m to 0 m resulted in a much more significant advantage. An area for future work could be to attempt further increasing the excavation rate by modifying the workspace planning strategy and parameters. One example could be dividing the SA with two different SZ widths: since the hauling distance to the truck has a big effect on the excavation rate, making the SZ corresponding to the dump truck locations narrower should speed up the excavation rate.

Due to the large number of possible parameters to adjust, the number of further simulations that could be conducted would only be limited by available time and computing power. Longer-term effects could be investigated by simulating the full 30 m excavation into the hillside, rather than just 5 m which was done here.

Finally, another area for future work could be to include the full hauling paths of the dump trucks, and to develop coordination techniques to avoid collisions between them. An important parameter may be the number of dump trucks needed, depending on how far away they need to bring the material. In a full dump truck scenario, each loader team would likely not have its own two trucks, but returning empty trucks would simply go where they are required. One problem would then be to determine how many trucks are needed to keep the loaders operating continuously.

Table 1: Excavation rates achieved with various job and plan parameters. Common parameters include eight loaders, 30° slope and 45 m-wide slope face.

	Slope height (m)	Truck position (m)	SZ width (m)	SZ length (m)	Rate (m^3/h)	Vol/t_{CD} (m^3/h)
1	1.73	1	2.4	0.4	156.4	17.29
2	1.73	1	2.4	0.8	158.6	17.82
3	1.73	1	2.4	1.2	155.5	17.44
4	1.73	1	2.8	0.4	156.8	17.36
5	1.73	1	**2.8**	**0.8**	**160.1**	**17.94**
6	1.73	1	2.8	1.2	155.5	17.24
7	17.3	1	2.4	0.4	156.6	17.50
8	17.3	1	2.4	0.8	156.6	18.49
9	17.3	1	2.4	1.2	152.0	17.19
10	17.3	1	**2.8**	**0.4**	**160.3**	18.32
11	17.3	1	2.8	0.8	159.0	**18.60**
12	17.3	1	2.8	1.2	154.8	17.64
13	17.3	0	**2.8**	**0.4**	**184.1**	**21.89**

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