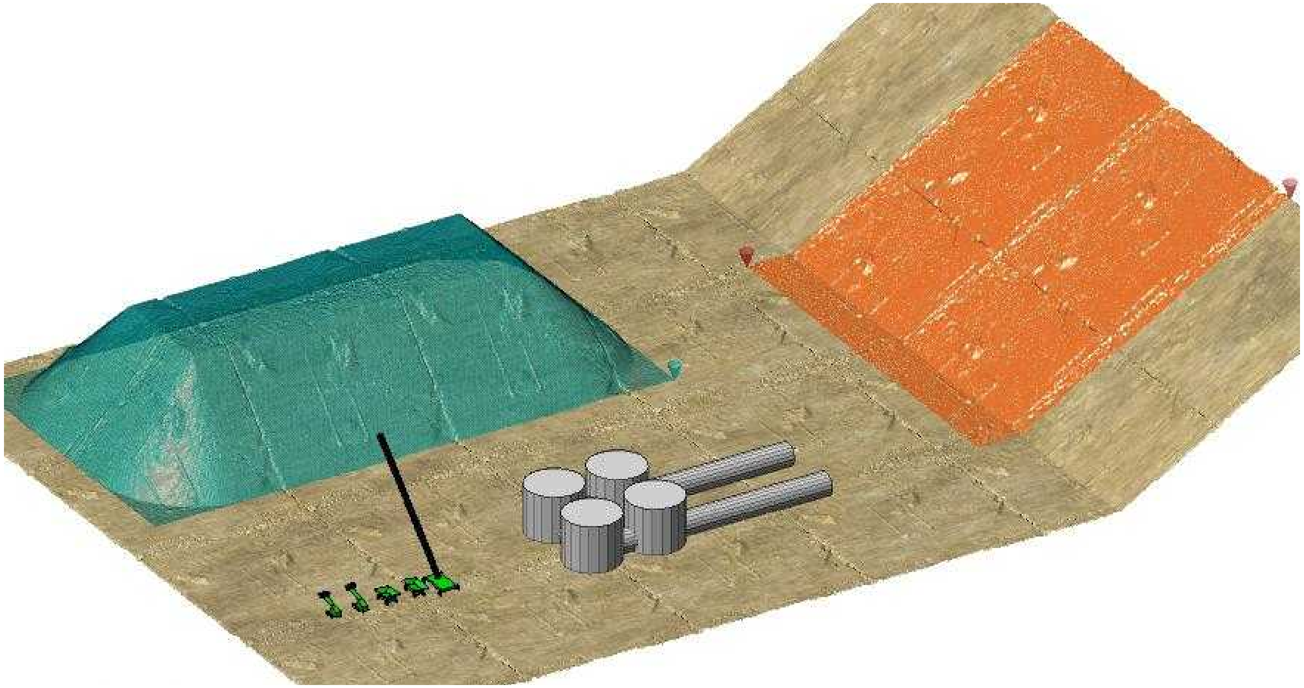
Simulation of Robotic Regolith Mining for Base Construction on Mars



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Motivation

Image: SpaceX

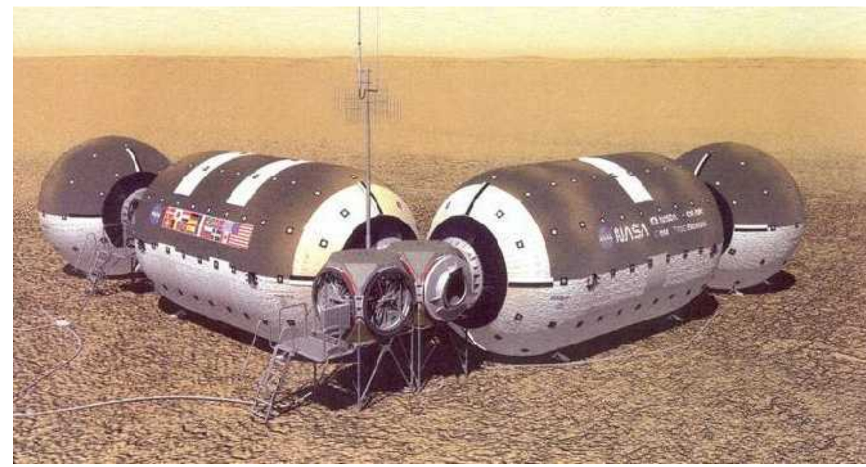


Image: James Cameron

Manned landings on Mars may soon be a reality. After initial outposts are established, the challenge will be to build permanent, growing settlements out of mostly local materials.

Motivation

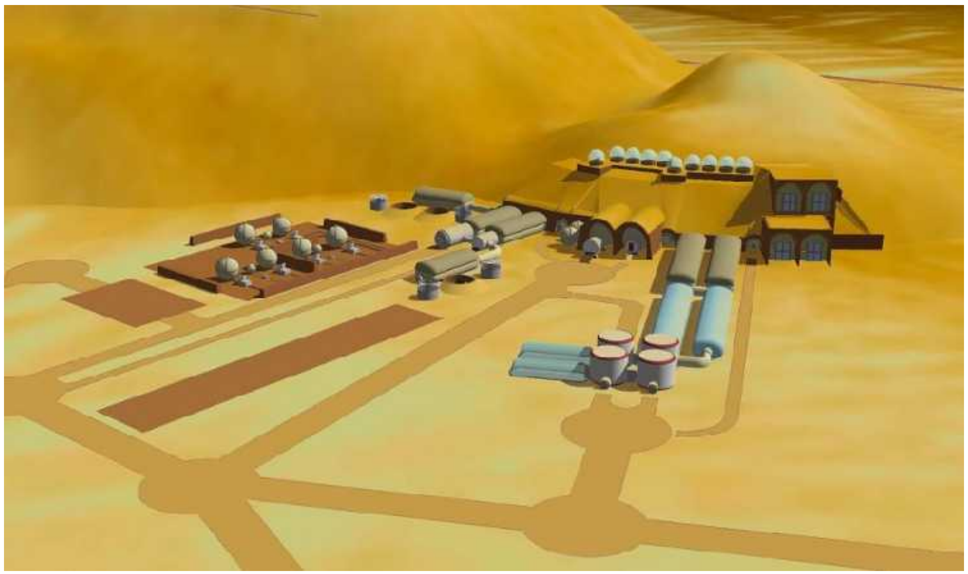
Images: Mars Foundation

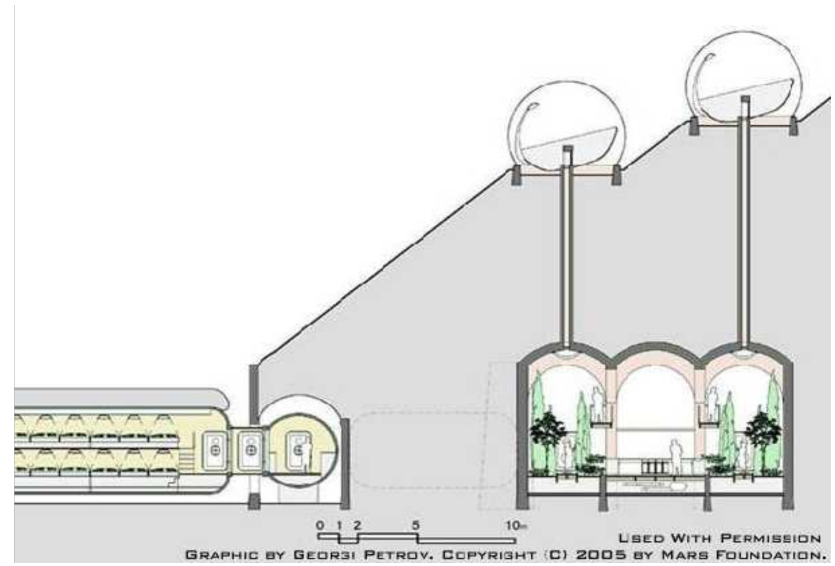
Mars Homestead Project (MHP) by the Mars Foundation: a detailed plan for a growing, permanent settlement using local resources.
Extensive use of regolith: locally manufactured bricks for masonry construction and burying inhabited spaces for radiation protection.

Mackenzie, B., Leahy, B., Petrov, G., and Fisher, G. (2006). The Mars Homestead: a Mars Base Constructed from Local Materials. In Space 2006.

Petrov, G. I. (2004). A Permanent Settlement on Mars: The First Cut in the Land of a New Frontier. Master's thesis, Massachusetts Institute of Technology.

Mars Homestead Project



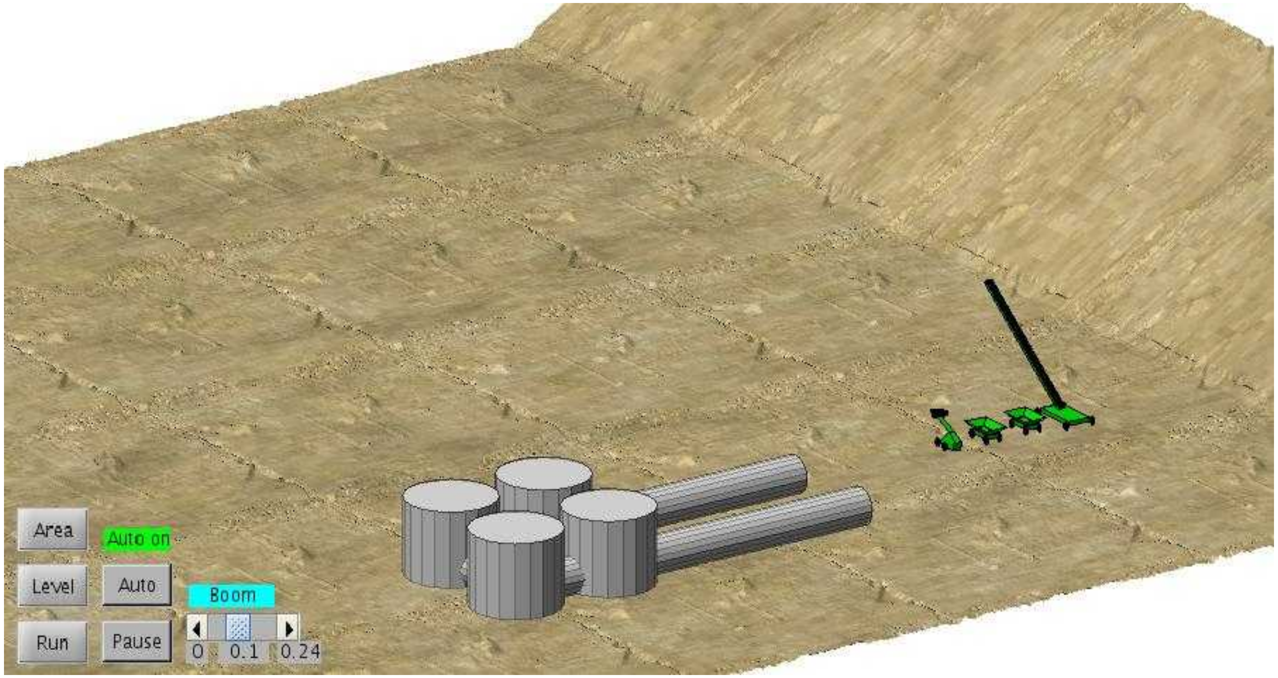


Images: Mars Foundation

First phase of construction: excavation into hillside 45 m wide, 30 m deep (laterally). Assumptions: slope angle 30 deg., debris apron with consistency of loose gravel – no fragmentation required.

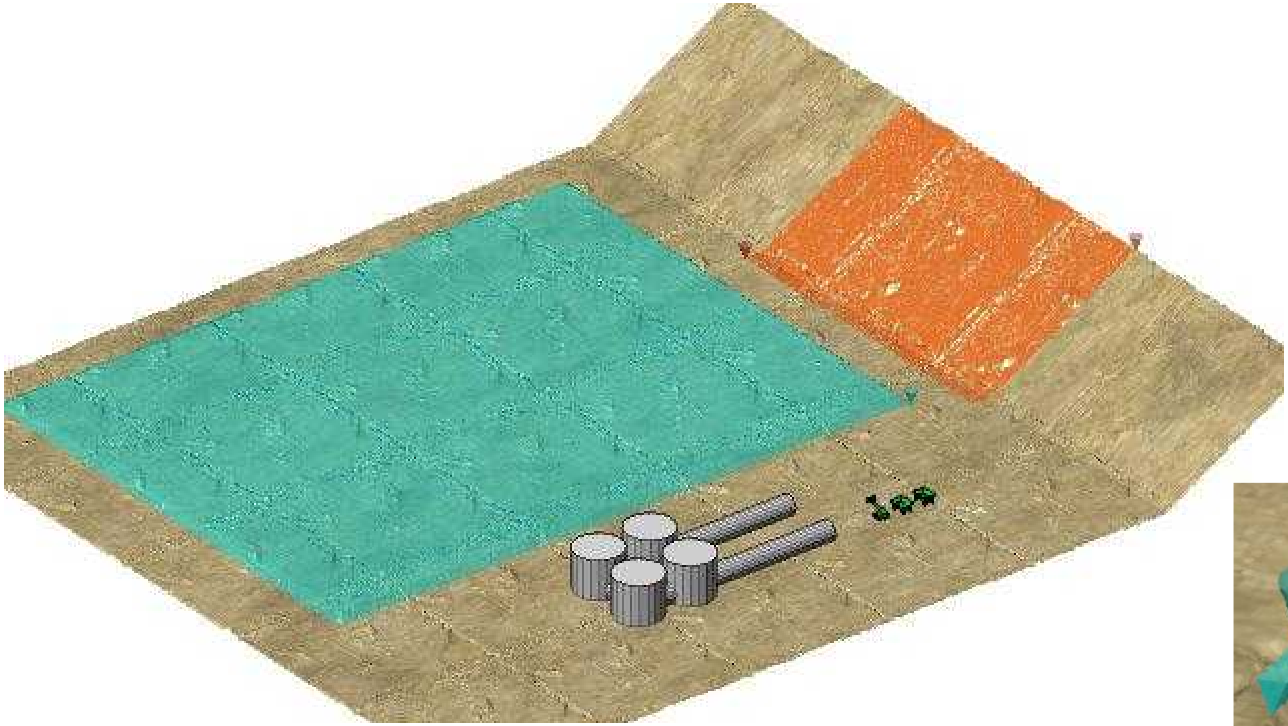
Assertion: robotic machinery should be used to increase safety. Direct teleoperation should be avoided to reduce operator workload, allow one operator to oversee fleet of machines and possibly allow long time-delay control from Earth.

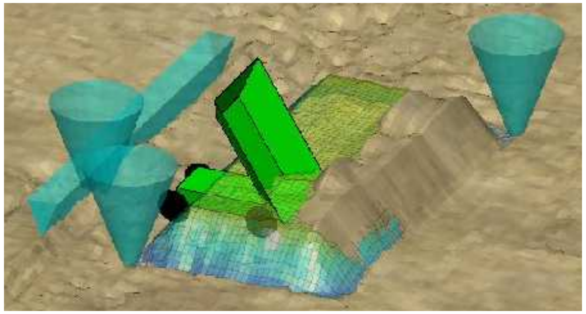
Simulated Worksite



Simulation of first MHP construction phase using Matlab-based simulator.
Purpose: develop and test high-level planning and control for robotic machines, investigate feasibility of job within reasonable time and without direct teleoperation.
1 Loader + 2 Dump Truck combination considered minimum requirement, to allow for continuous loader operation.

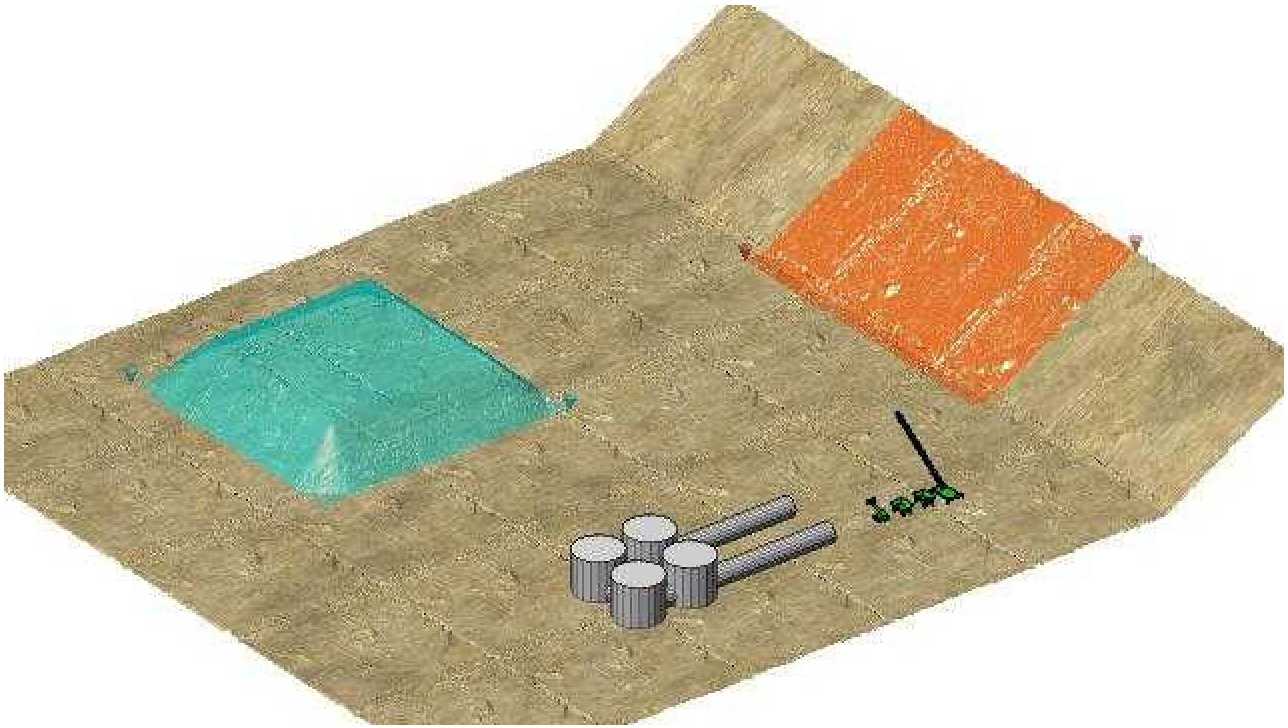
High-Level Plan

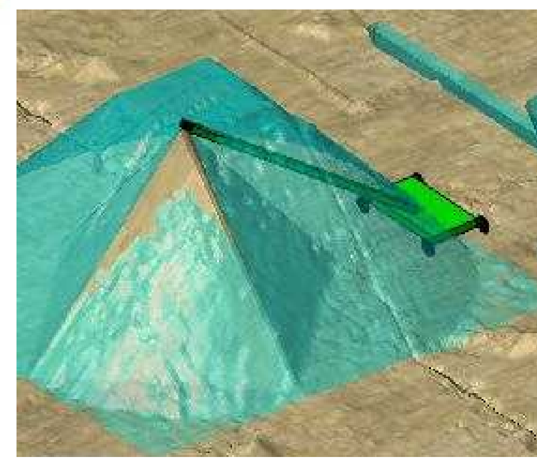




Interactive 3D graphical tools used to make high-level plan. Red slope surface: section to be excavated; blue virtual pile: where to dump material.
Low dump pile (1m) possible with dump trucks takes up large area, may hinder base construction and operations.
Requirement identified for machine capable of depositing material from higher above the ground.

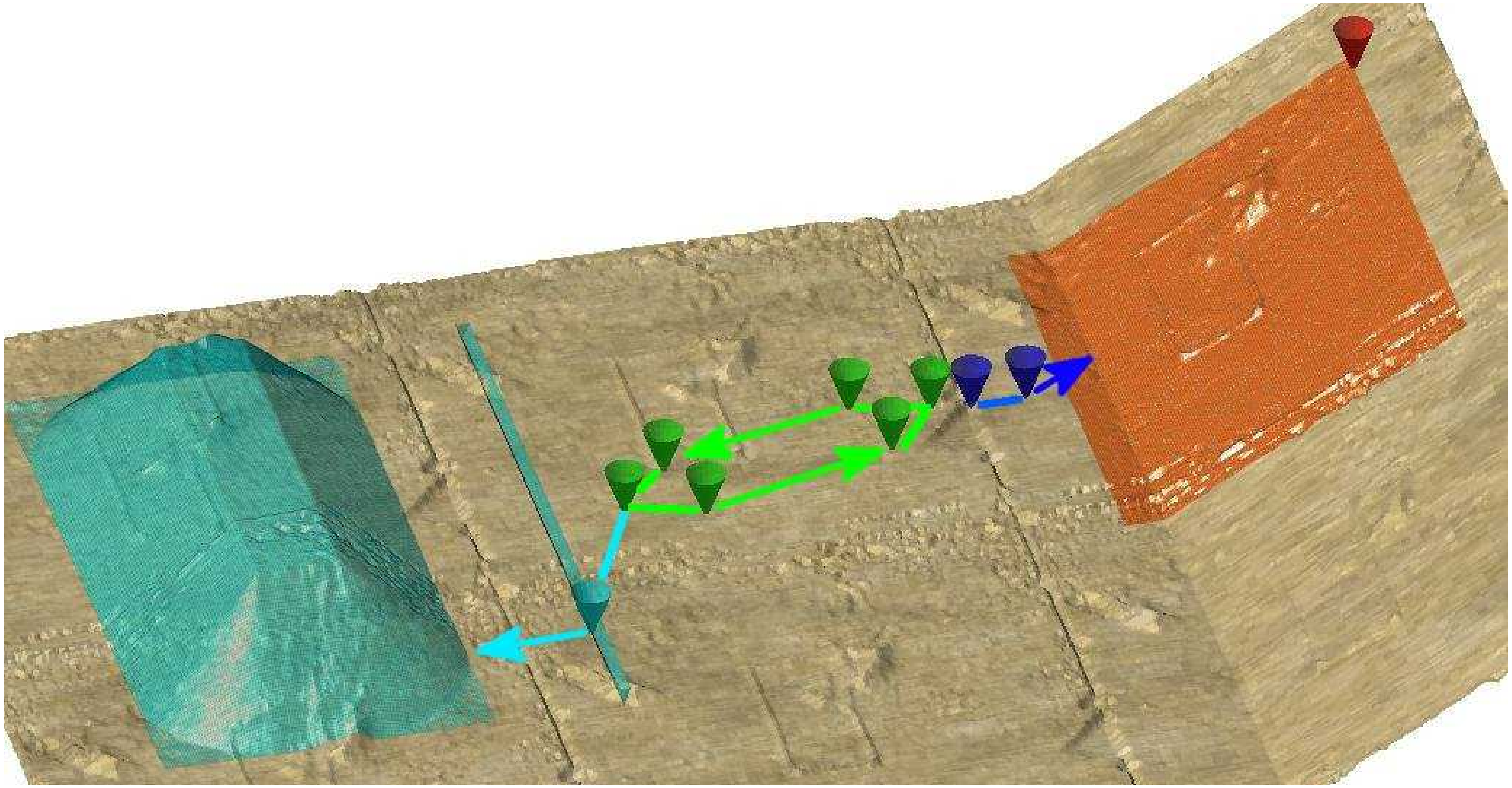
High-Level Plan





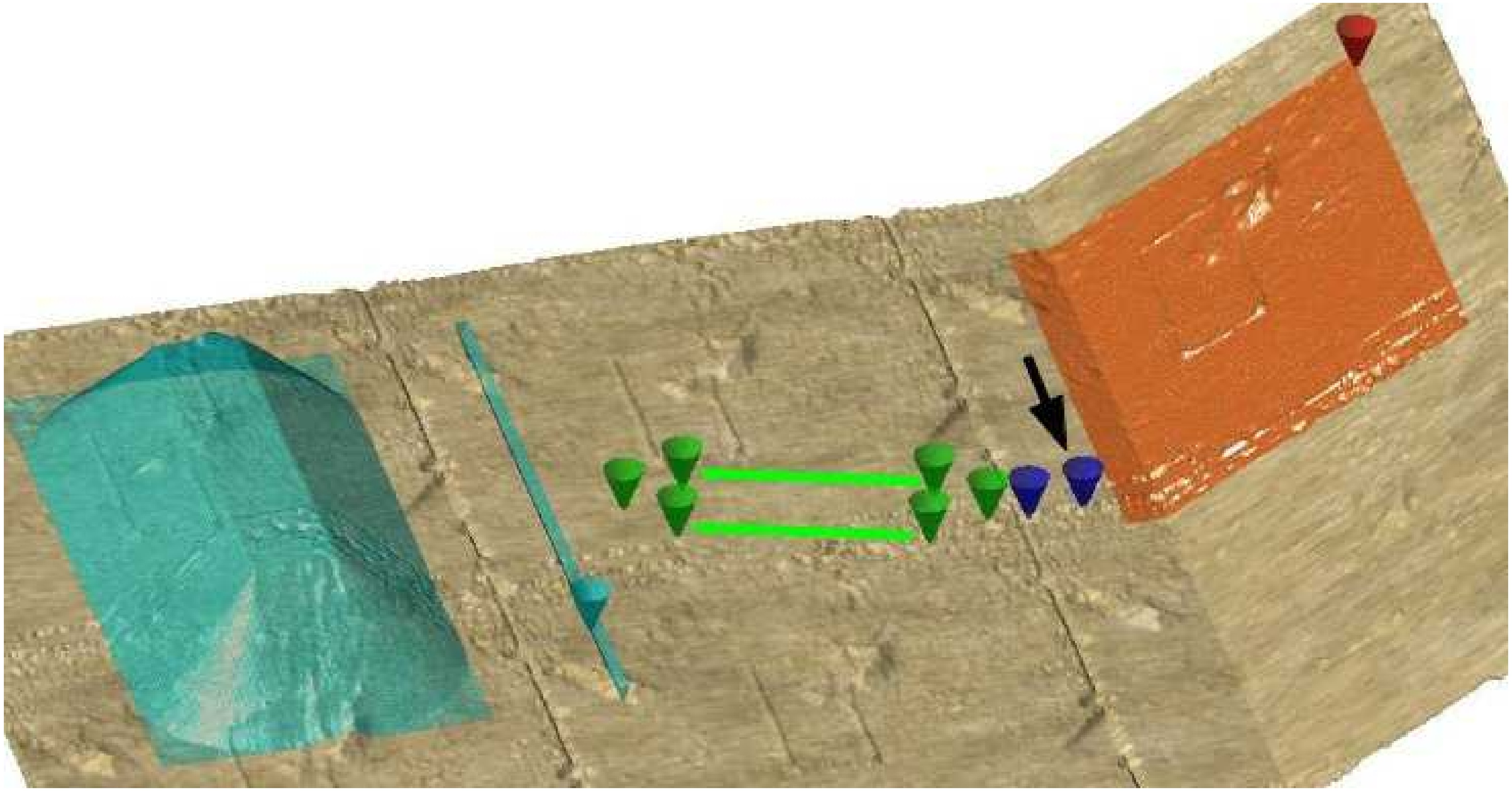
High storage pile (6m) possible with conveyor belt spreader stores material more efficiently.

Automatic Plan Interpretation



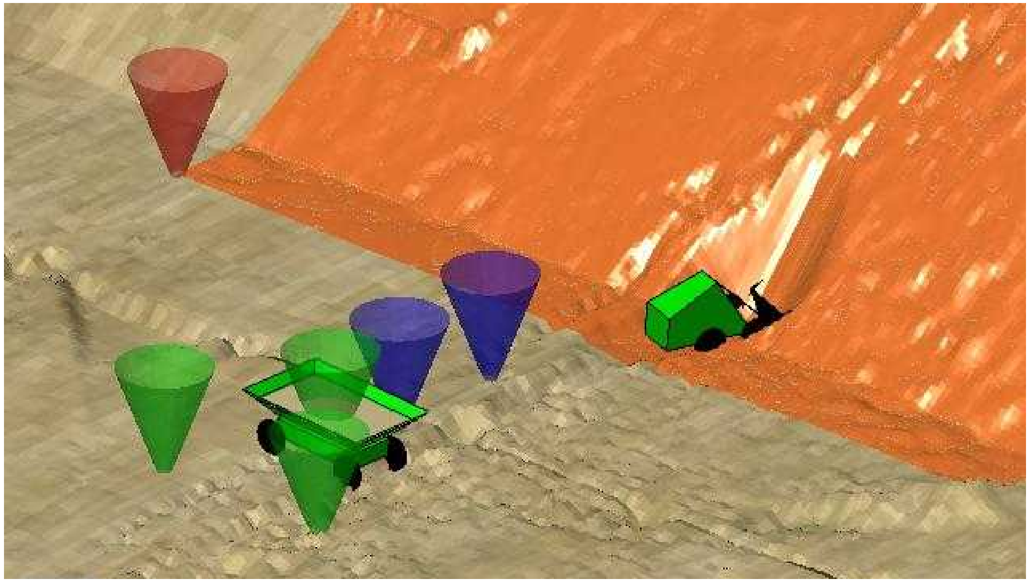
High-level plan automatically interpreted: points for scooping, hauling and dumping generated and represented by cones.

Plan Modification by User

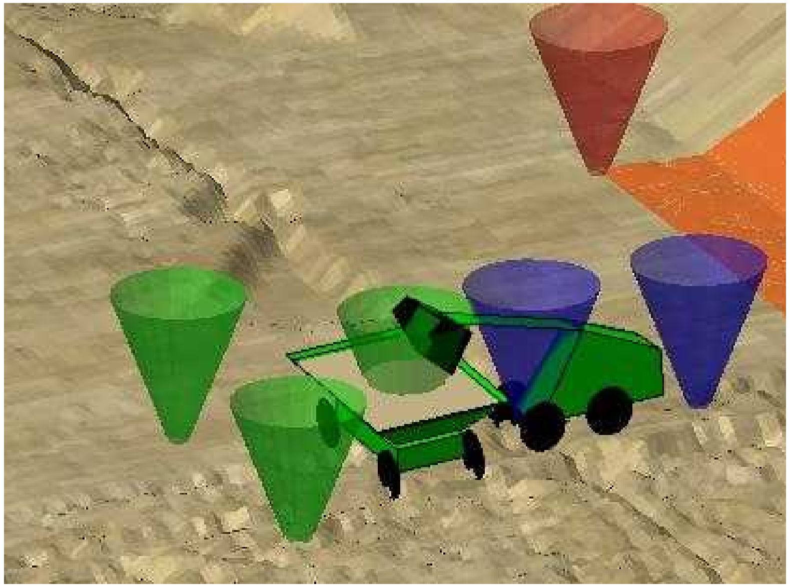


User can modify plan by clicking and dragging a point. Attached and associated points adjusted automatically.

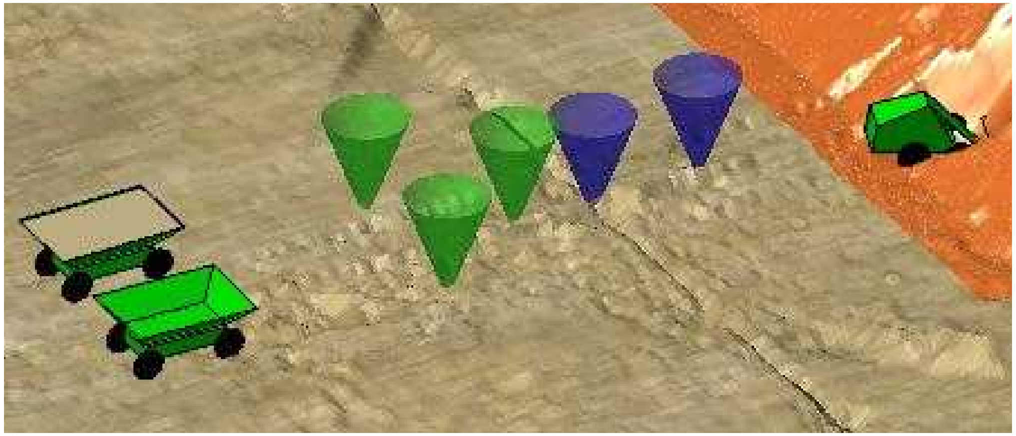
Work Cycle



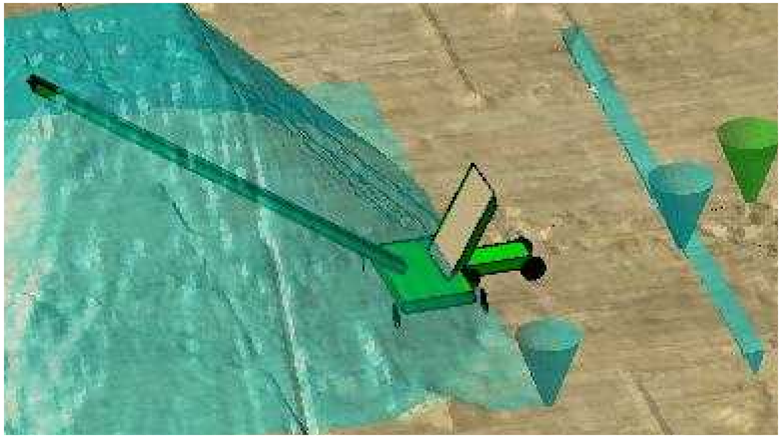
1. Scooping



2. Loading dump truck

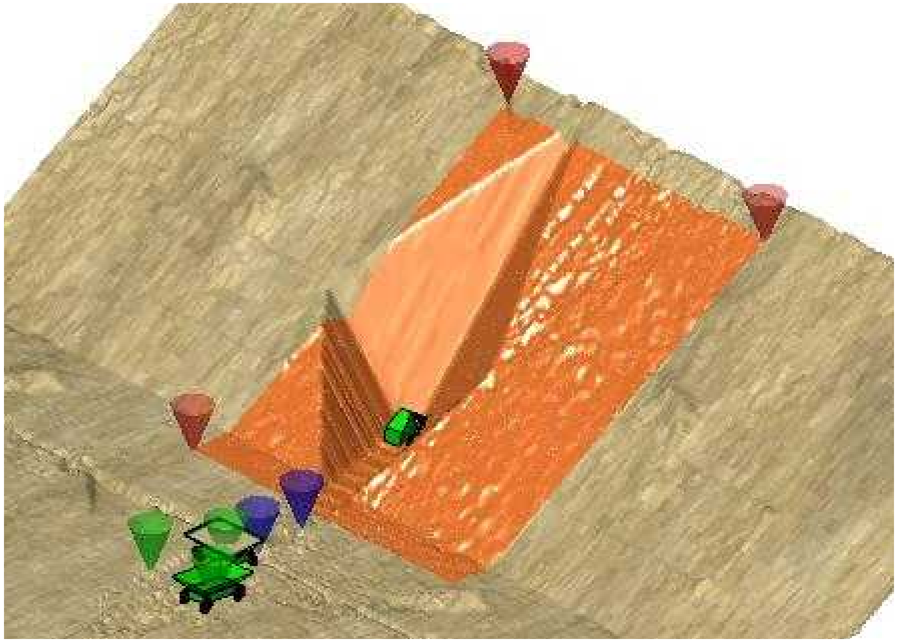


3. Hauling and driving back



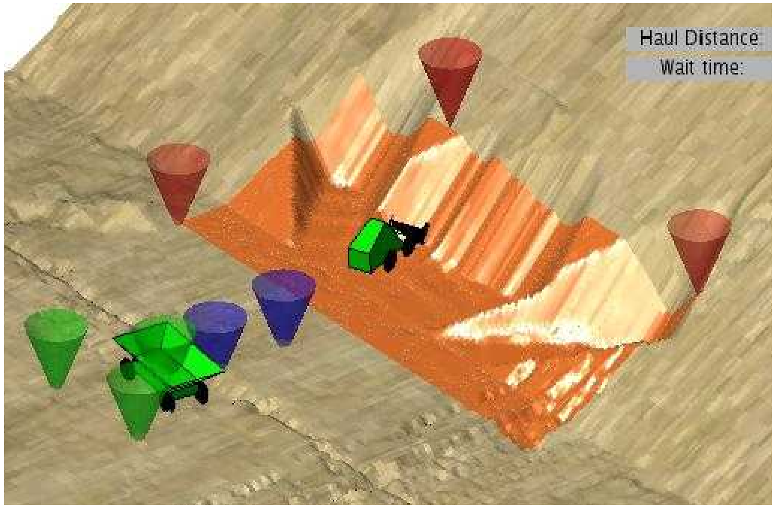
4. Unloading at the spreader

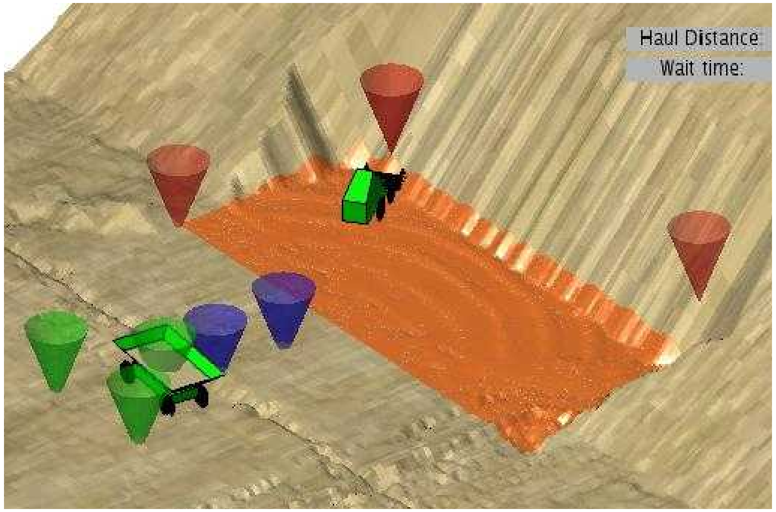
Scooping Strategy



Automated scooping approach is towards highest point in specified area. With large area, this tends to result in persistent scooping in same direction – likely an unwise strategy with inefficient bucket penetration and risk of loader getting stuck or tipping over.

Scooping Strategy

1.


2.


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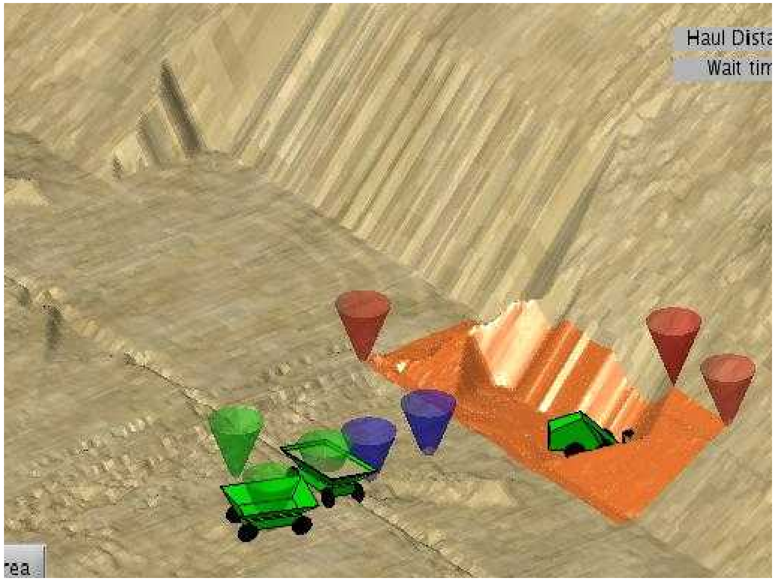
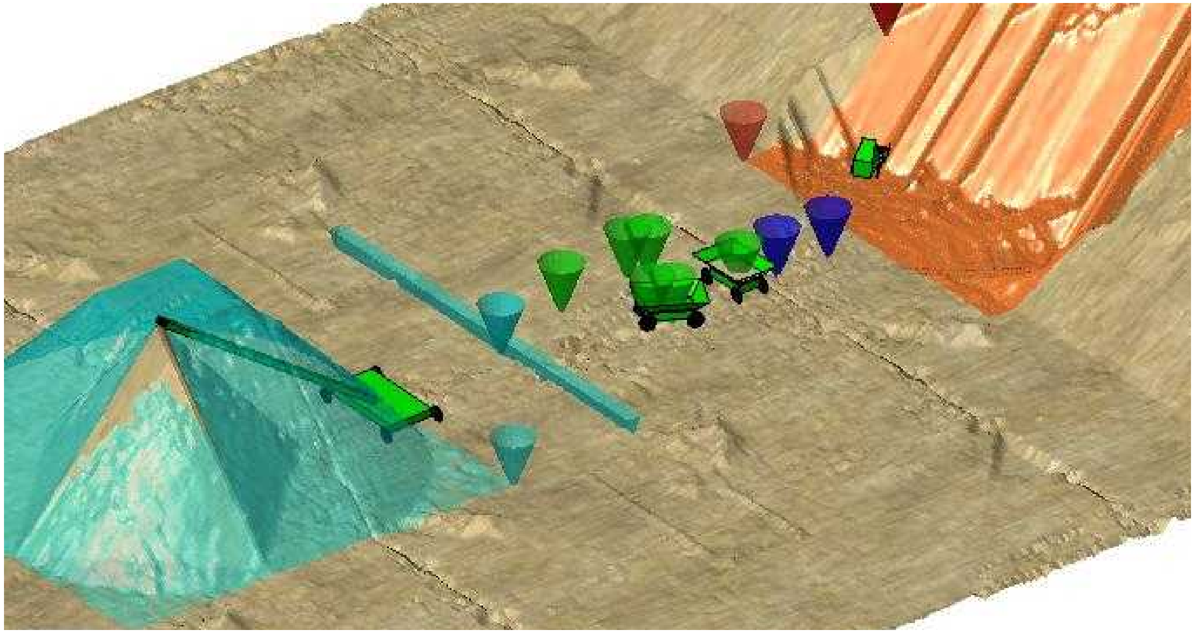
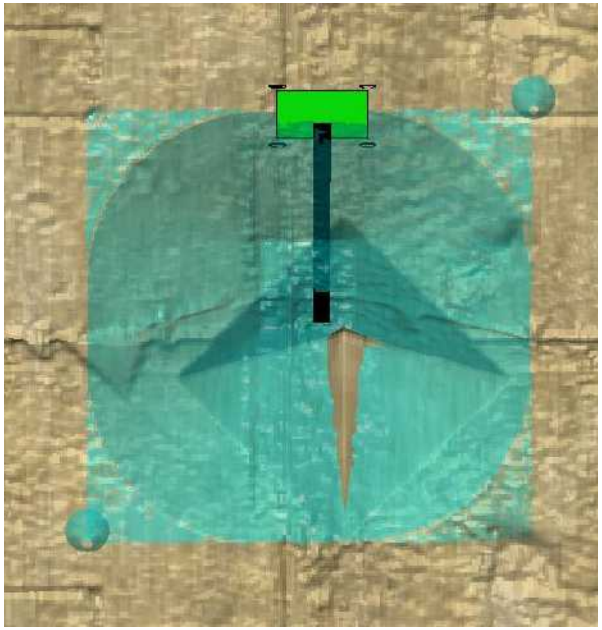


User can reduce target area, resulting in more balanced scooping approaches. Requires occasional updates when moving target area to new location.

Long-Term Simulation

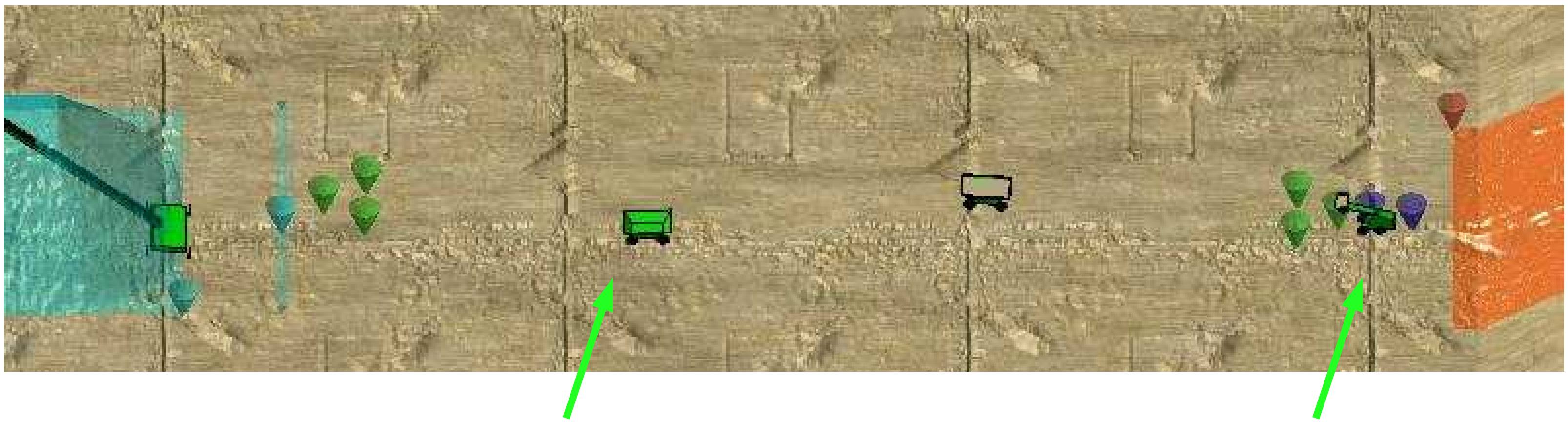




Long duration simulation with growing dump pile. 128 cubic metres of regolith moved in 6 hours of simulated time. Driving speed is 0.5 m/s, loader bucket capacity 0.31 cubic metres.

Automatically-updated dumping location: spreader has shifted to the left.

Hauling Distance Trade-Off



empty truck still returning

loader ready, standing idle

With increased hauling distance, the loader must sometimes wait for the next empty dump truck, standing idle and lowering productivity.

A long hauling distance may however be necessary, to avoid storing the material too close to the base and potentially disrupting operations.

The maximum hauling distance with no waiting time for a particular simulation was found by adjusting the position of the blue virtual pile until it was observed for several cycles that the loader did not need to wait.

Trade-Off Analysis

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^3)	Truck Capacity (m^3)	Average Scoop Load (m^3)	Average Loads per Truck	Max. Haul Dist. (m)	Work Rate (m^3/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

Larger loader scoop capacity increased work rate, as expected.

Mars Homestead Project excavation requirement: 30 degree slope segment, 45 m wide, 30 m deep = 11691 cubic metres. At 8 hours/day:
Work Rate A: 132 days (18.8 weeks)
Work Rate B: 59 days (8.4 weeks).

Ratio of dump truck capacity to loader scoop capacity affects maximum hauling distance at which loader will operate without interruptions, i.e. not having to wait for an empty truck.

Future Work

- Further investigate conflicting requirements of cost (smaller machines/buckets, fewer machines) and work rate (larger machines/buckets, more machines)
- Add more loaders, see if remote operator workload becomes saturated
- Add more dump trucks, see how many can share one spreader

Conclusion

- High-level planning identified machinery requirement for conveyor belt spreader to store material more efficiently
- Combination of 1 loader and 2 haulers allowed for reasonable work rates and hauling capabilities
- Trade-off between bucket ratio and maximum hauling distance was identified and analyzed
- All simulations were conducted without direct teleoperation, i.e. one remote operator could monitor all machines and provide high-level direction
- Simulation was shown to be useful for comparing machinery specifications and site plans