Autonomous Mars ISRU Robotic Excavation: Characteristics and Performance Targets

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Abstract—**Characteristic hardware concepts and performance targets are described for a potential robotic excavation system that can operate and robotically maintain itself without regular human intervention. In-Situ Resource Utilization (ISRU) is the exploitation of available resources at the site of a landed spacecraft on the surface of another planetary body. This can include harvesting of atmosphere, regolith, or rock for direct use (e.g. as radiation or micrometeorite shielding) or for separation/purification (e.g. for propellant production). The objective of this study is to try to identify a potential ISRU architecture, specifically for extracting water from hydrated minerals identified from orbital multispectral imaging on Mars, which can be implemented in an affordable way. By its nature this architecture must incorporate not only all the conventional excavate / scoop / haul / dump / process functions of a terrestrial mining operation on Earth, but also the sorts of maintenance and repair capabilities which any terrestrial mining operation would require in order to stay operational for an extended duration. The early concepts described in this study are intended for Mars, but also can be adaptable to lunar and other solar system planetary bodies.**

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1. INTRODUCTION

Space exploration generally involves large changes in velocity at multiple points in reaching and achieving rendezvous with celestial objects, which is expensive in terms of propellant, so that the total mission cost is often directly proportional to the mass of the payload. If part of the mass needed to accomplish the mission can be harvested at the exploration site, this mass does not need to be brought from Earth, potentially greatly reducing mission cost. A figure-of-merit for ISRU systems is the time required for the ISRU system to generate its own mass in useful product. The ISRU system is highly advantageous if the ISRU system can generate many times its own mass during the nominal mission, thereby saving several times the mass of the ISRU system in launch mass.

For ISRU to be accepted as a mission-critical element of a mission architecture (e.g. ISRU is enabling for mission success or possibly even crew survival), it must be highly reliable. ISRU systems that harvest only atmosphere may be automated with conventional technologies, but ISRU systems that harvest regolith or rock and then process it into useful products must deal with significant uncertainty in the detailed form and properties of the source material as it is uncovered. This requires autonomy to make real-time judgments about how best to dig regolith, break rock, load buckets, traverse to the processing plant, dump ore, dispose of waste, and maintain and repair the whole ensemble of system components. For Mars or more distant destinations, the myriad decisions required moment-to-moment in each of these processes generally cannot afford a speed-of-light round-trip delay back to Earth for human decision-making in any sort of workable architecture. Such decisions must be made autonomously by the robotic ISRU system in such a way as to keep the process running smoothly and reliably. In particular, as Earth-based mining experience abundantly shows, maintenance and repair of the mining equipment is a critical element of any system that is expected to operate for an extended period and to process many times its own mass in raw materials.

Autonomous ISRU operations are required in the area of deciding which next place to excavate as the mining proceeds, which rocks or clods need crushing (or further crushing), what path to take between the excavation site and the ore processing site, what path to take from the ore processing site to the dump site, what path to take between the dump site and the excavation site, what preventive maintenance to perform, and fault detection, diagnosis, and repair. Each of these broad areas has many sub-topics, such as (for example) how to modify the transit ramp (or make a

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new ramp) into an open pit as the geometry of the pit changes, as part of the "what path to take between the excavation site and the ore processing site" broad topic area. Other topics that would generally be straightforward automation but may involve a bit of "autonomy" include how to ensure that a hauling vehicle becomes lined up properly for correct dumping into the intake hopper of the processing plant. Deciding when well-used roads need to be re-graded (or completely re-established along another route) is another topic for autonomy.

Some aspects of autonomy may be human-assisted, for those cases where the frequency of intervention is low and the round-trip speed-of-light latency is not large compared to the average time associated with the operation. An example might be in repair of a vehicle, where replacement of an actuator is under consideration. The human might review the diagnostic data and autonomy-generated diagnosis prior to the work proceeding, assuming this happens only occasionally.

While it might be possible to directly replicate the function of each human employee of a terrestrial mine with robotic systems on Mars, this study attempts to identify an architecture that simplifies the robotics and autonomy needs of the system to the point where a long-life and reliable system can be implemented in the near-term, and to elaborate a realistic approach to autonomy which can be prototyped within the scope of a realistic task.

2. Approach and Target Performance

On 4 December 2017, NASA released a Broad Area Announcement (BAA) entitled NextSTEP-2, which "seeks proposals to advance critical ISRU capabilities for producing oxygen, water, and methane fuel to TRL 5 or 6". That solicitation identified that the desired rate of excavation of hydrated minerals on Mars is 12.5 - 30kg/h if they are consolidated minerals (expected to be 5-12%wt water), or 50-100kg/h if they are granular soils (expected to be 1-3%wt water). Our focus here is on consolidated minerals, since that poses the more challenging case, the need for which cannot be established (or rejected) without a precursor mission to the Mars surface. An ISRU architecture for the case of granular soils is presumably a subset of that required for consolidated minerals which includes the scooping, hauling, dumping and processing of the ore, without the excavation and breaking of the consolidated rock into small particles.

Terrestrial mining experience can inform many aspects of the needed system. At Infomine.com is an economic model of an open-pit mine producing 5000 metric tons (t) of ore per day [1]. This model has the open-pit mine located an average hauling distance of 1532 meters from the processing site and another 1310m to the waste dump site. The mine operates two 10-hour shifts per day, 312 days per year.

The heavy equipment required for this operation is summarized in Table 1. In the seventh column we calculate the specific throughput of ore per unit mass of equipment in t/d/t, which gives a measure of how fast the equipment "pays" for itself in the sense of ISRU material processing versus ISRU delivered system mass. The centerpiece of the mine is a hydraulic shovel as shown in Figure 1, able to keep six 41t rear-dump trucks busy.

Using the fact that this mine processes 5000t/day of ore using this equipment, and looking up the mass of these items of heavy equipment, we calculate that the mine processes 1.30kg/hour of ore for each kg of heavy equipment.

Equipment	Qty	Size	Units	Mass (kg)	Extended	t/d/t	Example Reference
Hydraulic Shovel	1	3.4	m3	75,380	75,380	66.3	Komatsu PC800 mass from http://ritchiespecs.com/specification?type=&category=Hydraulic+Excavator&make=Komatsu&model=PC800-6&modelid=93092
Front-end Loader	1	3.8	m3	19,213	19,213	260.2	Caterpillar 950M mass from https://www.cat.com/en_US/products/new/equipment/wheel-loaders/medium-wheel-loaders/1000029161.html
Rear-dump Trucks	6	41	t	31,853	191,118	26.2	John Deere 410E mass from https://www.specguideonline.com/product/john-deere-410e
Bulldozers	3	60	kW	7,958	23,874	209.4	Caterpillar D3K2 mass from http://www.ritchiespecs.com/specification?type=Con&category=Crawler+Tractor&make=Caterpillar&model=D3K2+XL&modelid=108961
Grader	1	115	kW	13,720	13,720	364.4	Komatsu GD530 mass from http://www.ritchiespecs.com/specification?type=&category=Motor+Grader&make=Komatsu&model=GD530A-2C&modelid=91845

Table 1: Heavy equipment needed for 5,000t/d mine economic model from infomine.com

Recall that a key figure of merit for ISRU is the time for the ISRU plant to produce its own mass in useful product. We consider the production ratio of the mine as a potential high-level supply-side feasibility calculation starting point for ISRU system production targets.

Using the lower-bound of 5%wt water for the ore specified in the NASA NextSTEP-2 BAA described above, the time required for the heavy equipment of this mine to produce enough ore to "pay" its own mass in water would be 0.77 days. Obviously, this is very encouraging, since any time-to-replicate which is short compared to the total mission duration (presumably years) would be considered preferable.

Figure 1: Hydraulic shovel with 3.4m³ bucket, the centerpiece of a mine producing 5,000t/day of ore, keeping six 41t hauling trucks busy

One aspect of our conceptual ISRU operation that differs significantly from this terrestrial mining example is that we do not imagine drilling blast holes and using explosives to break the rock. Instead, hydraulic rock breakers [2] are advertised to break ~30 cubic yards per hour of medium limestone (harder than the expected hydrated mineral on Mars, which is gypsum) using a hydraulic breaker having a mass of 1455 kg on a carrier vehicle having a mass of about 20t. Each cubic yard of limestone is about 2t [3], so we conclude that this rock breaker and carrier processes about 3 times its own mass per hour in broken rock. This broken rock would then be transported to a rock crusher that produces the particle sizes needed for ore processing.

Figure 2 shows a plot of the advertised throughput of assorted commercial rock crushers as a function of their mass. Note the approximately linear relationship between the mass of the crusher and the throughput, with a slope of about 5t/h per t of crusher. So, once again, we have the mass of ore processed per day is many times the mass of the heavy equipment. Note also that there does not appear to be any consistent non-linear trend in the scatter, which would indicate, for example, a fall-off in t/h/t for very small crushers, at least over the scale of machines considered (>1 t dry mass).

Recall that the NextSTEP-2 BAA called for excavation rates up to 30 kg/h for consolidated minerals such as solid gypsum.

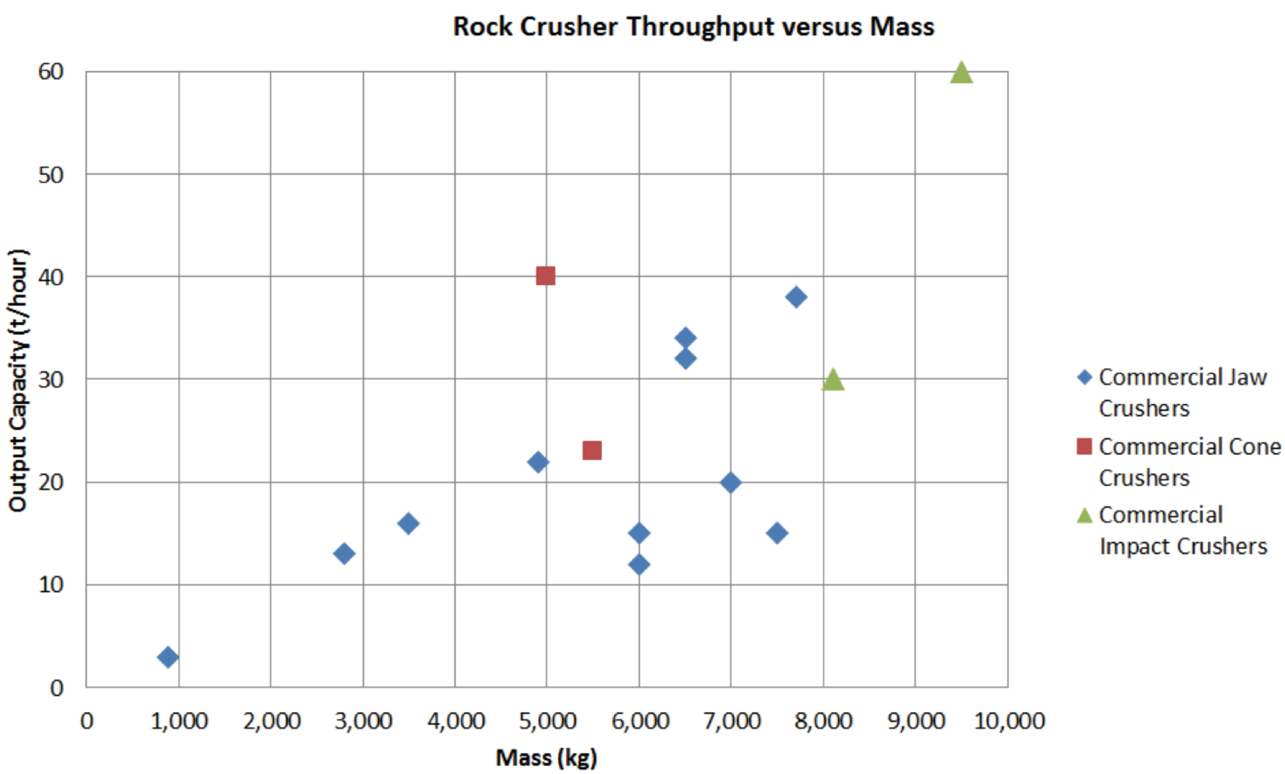

Figure 2: Throughbut of commercial rock crushers as a function of their mass

This is orders of magnitude less than the hundreds or thousands of tons per hour produced by a typical terrestrial mine. So it is natural to ask the question if the throughput of the mining equipment will remain linear over orders of magnitude on the low end of the scale. If the combined throughput per unit mass for all the equipment discussed so far (hydraulic shovel at 66kg/d/kg, front-end loader at 260kg/d/kg, rear-dump trucks at 25kg/d/kg, bulldozers at 209kg/d/kg, graders at 364kg/d/kg, rock breaker with carrier at 60kg/d/kg, and rock crusher at 100kg/d/kg, assuming 20 hour workdays), we get a combined throughput for the system of 11.0kg of ore per day per kg of equipment. If we assume the required 30kg/h of gypsum must be produced 10 hours per day on Mars (assuming the worst case of solar power and system hibernation during the cold nights), we require a total of 300kg of ore per day. So we would expect, assuming linear scaling, that the total amount of "heavy equipment" needed to deliver ore into the ISRU processing plant will be only 27.4kg. Obviously, this equipment isn't very heavy if linear scaling applies at these small scales. Each piece of equipment would be about the size of a child's toy if the terrestrial mine architecture were to be replicated.

Instead of replicating the heterogeneous vehicle fleet of a terrestrial mine architecture, we might consider a small fleet of identical vehicles, each in the shape of a mobile gantry crane (Figure 3).

Figure 3: Mobile gantry crane (photo credit: shuttlelift.com)

The back end of each vehicle might have a shorter distance between the wheels than the front end and also a shorter gantry, which would allow these vehicles to "nest" inside one another like a stack of Dixie Cups. This would allow a disabled vehicle to be retrieved by another similar vehicle that could approach from either end, embracing it over the small end or inserting itself by backing into the large end. The work platform at the top is able to move along the two top gantry rails and would have crane and latch elements to pick up larger tools like buckets and rock breakers. Each of the vertical posts could have sliding platforms hosting robot arms with interchangeable end-effectors that can perform any needed functions including maintenance and repair.

Considerations that lead us to this approach include the need for the system to be capable of self-maintenance and repair with a minimal set of specialized tools and repair parts. This suggests the following principles:

- All vehicles are identical
- Any vehicle can recover any other failed vehicle from the sorts of terrain geometries expected in and near a shallow open-pit mine (one scoop deep)
- All components come from a minimalist catalog representing all components used in the system
- All subsystems are affixed onto each vehicle where another identical vehicle can reach and replace it
- All methods of attachment are "robot friendly" in the sense of not being easily cross-threaded or otherwise prone to difficulty

Mining literature [4] is abundant with caution that maintenance and repair are of utmost importance.

3. ISRU Robotic Excavation System

The ISRU Excavation and Material Delivery System will need to function for long periods of time without human presence or intervention. In order to accomplish this, all elements will need to be robotically operated and maintained. Autonomy, especially for maintenance and repair, cannot be applied as an independent top-level control layer on any complex robotic system. In order for autonomy to be successfully applied and be successfully executed, the whole system needs to be designed and implemented with autonomy as an integral element. Therefore, the scope of the system development in this document covers all aspects of the development of the robotic excavation and material delivery system.

A set of conservative estimates of requirement, based on the Mars Design Reference Architecture (DRA) 5.0 developed in earlier studies and reported in [5, 6, 7], were derived for the development of our system. These are shown on Table 2.

In addition to the mission and operational requirements, a robotic ISRU/excavation system must satisfy environmental requirements such as those shown on Table 3.

The need for long-duration autonomous operation places a significant burden on the design of the robotic elements of a robotic ISRU/excavation system to meet requirements that are different from the low-mileage planetary exploration vehicles NASA has fielded on Mars.

Description	Specification
Regolith delivered per day (mass and volume)	1040 kg, 0.75 m^3
Delivered regolith particle size	0.001 – output from crusher
Duration of operations	300 days
Total traverse distance per round trip – 3 legs: excavation site to ISRU plant, ISRU plant to dump site, dump site to excavation site	1.5 km
Allowable mass for robotic ISRU/excavation system, including repair and maintenance system and spare parts	< 2000 kg - may be significantly less than this depending of architecture chosen
Energy available per day for robotics operations	< 5 kWh
Autonomy	No direct human intervention; robotic ISRU/ excavation system may have supervisory overview and intervention from Earth at multi-day frequency

[1] Kleinhenz, Julie, Aaron Paz, and Robert Mueller. "Benefits of Mars ISRU Regolith Water Processing: A Case Study for the NASA Evolvable Mars Campaign." (2016).

Table 2: Requirements for a robotic ISRU/excavation system

Description	Specification
Operating temperature range	-30 to 5 °C (day) and -90 to -60 °C (night)
Range of topography	Grade < 5%, traverse along cleared paths
Dust from weather and generated by operations (Conc. and size)	Four particles / cm^3 0.05 to 10 microns particle size 1 dust storm per 120 days
Regolith Material	Gypsum rock
Excavation rock hardness (Mohr scale)	2
Regolith density	2000 kg/m^3
Approx. day/night duration	~11 hrs / ~13 hrs
Operational hours per day	10 hrs

Table 3: Environmental constraints for a robotic ISRU/excavation system

While the Mars ISRU application is different from mining operations on Earth, there are enough similarities that terrestrial applications should help inform the development process for the robotic ISRU/excavation system. These are discussed in the System Concepts and Interfaces section below. In particular, two new capabilities not previously performed in exploration systems development -- 1) maintenance and repair of vehicles; and 2) site preparation -- will be included in the robotic ISRU/excavation system design and operations.

Design for Long-duration Operation

Every element in the robotic ISRU/excavation system will need to be robotically maintained for long-duration operation, including the maintenance system. Vehicles and other robotic elements will need to be designed in such a way that the parts that have the most potential to wear or malfunction can be easily separated and replaced. The maintenance system should be capable of separating those vulnerable parts and swapping in spares to allow the vehicle or element to continue functioning.

Modular Parts and Spare Parts Inventory and Storage

All elements of the system will need to consist of modular parts and actuators. Mechanical and electrical components should be manufactured in advance of launch, with assembly complexity encapsulated into discrete, robust, dust resistant part modules. Each part module should be designed with handles, grasping points, or gripping surfaces sufficient to enable simple robotic material handling and inventory management of individual parts. Autonomous search and retrieval storage systems can be designed for holding spares, and storing malfunctioning or worn parts that have been swapped out. The assumption is that malfunctioning parts could be held for a future time when additional maintenance systems or human crews arrive that have the means available to them to open up the part module casings and perform internal maintenance on them.

Simple Mechanical / Electrical Interfaces

All part modules will need to have structural, mechanical, and electrical interfaces designed for simple autonomous robotic connect and disconnect. When connected, mechanical and electrical interfaces must create a dust-resistant joint. When part modules are separated for swapping or cleaning, mechanical throughput and electrical contact interfaces should have built-in methods for protecting exposed mechanisms and contacts from dust.

Excavation Operation Functions

We have identified five functions that need to be performed for excavation and material delivery. These are:

- Breaking – The material to be delivered is assumed to be in rock deposits embedded in the ground. The rocks will have to be broken up into sizes small enough to be loaded and hauled to the ISRU plant. The breaking process will split chunks of rock from the embedded deposits and crack them up into the appropriate sizes for further processing.

- Scooping – The broken rock will be scooped up and loaded into the transport system for conveyance to the ISRU plant.

- Hauling – The material will be transported to the ISRU plant that is up to 500 meters from the excavation site. The hauling function also needs to be performed for moving processed material from the ISRU plant to the dump site up to 500 meters away.

- Dumping – The material will be dumped into the ISRU input hopper.

- Crushing – The material to be processed by the ISRU plant should be composed of fragments no larger than 3cm in size. The broken rock needs to processed to reduce the material size using a crusher. Crushing could occur immediately after the breaking function or immediately after the dumping function.

The overall scenario for these functions is illustrated on Figure 4 with the crushing function placed at the ISRU plant. Long-duration terrestrial mining operations have demonstrated that it is more economical to maintain and repair equipment that break-down or deteriorate in the field over a strategy of replacement of failed equipment. The performance metrics in an economic analysis for deployment and operation on Mars are quite different and should factor the cost of transporting equipment to the planetary surface from Earth, the unavailability of manual labor at the operations site, the technology readiness of autonomous operations and, of repair and maintenance, the mass of the repair system and spare parts, supporting infrastructure, etc. The costs of the architectural options, the configuration or range of configurations of the repair and maintenance system need to be determined for this application.

In order to integrate maintenance and repair into the ISRU excavation and material delivery system, a systems approach needs to be taken in designing all elements for long-duration operation. Among the considerations over and above excavation and material delivery functions include design for maintenance and repair, design of the maintenance and repair system, procedures for maintenance and repair operations, and site development and maintenance.

Performing autonomous maintenance and repair of complex machinery originally designed for servicing by human experts is an extremely challenging task that is unlikely to be achievable in the timeframe for the planned missions to Mars. The only alternative available for autonomous maintenance is to design the systems that can be assembled and serviced by robots using very simple procedures. The designs will have to be modular with mechanical, data and power interfaces that can be easily assembled and disassembled. The systems should be composed of a limited variety of parts, ideally with modular actuation and structural elements.

The maintenance and repair system itself should also follow the design principals outlined above. In addition, it will be beneficial for the repair and maintenance system to be dual-purpose and also perform some of the robotic ISRU/excavation systm functions like hauling and dumping. A comprehensive maintenance and repair program involves a number of strategies. These include: 1) taking proactive and preventive actions by integrating a health maintenance and monitoring system to perform regular inspection and servicing operations; 2) performing reactive actions in response to faults and failures like module replacement; 3) implementing approaches to reduce wear and tear on equipment, for example by preparing pathways, removing obstacles to minimize loads and drive distances, and improve safety; and 4) performing repair and maintenance of the repair system itself.

An additional critical element for autonomous ISRU material excavation and delivery is the autonomous preparation of the site for operations. This process could be highly supervised by operators on Earth. For example, ground operators will identify locations for the placement of assets on the surface and the mining site and plan paths between them using very high-resolution models of the surface. However, grading and clearing of obstacles and placement of instrumentation at the site and along pathways will have to be performed autonomously given the communication delay between Earth and Mars.

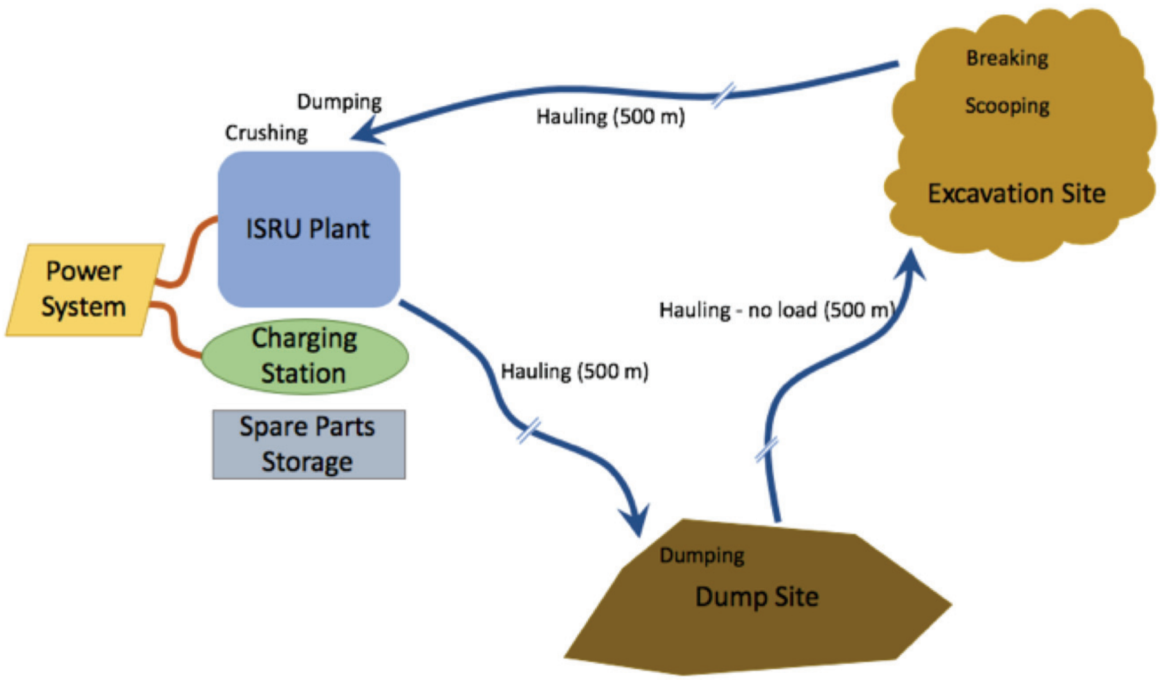

Figure 4: Overall ISRU excavation and material delivery scenario

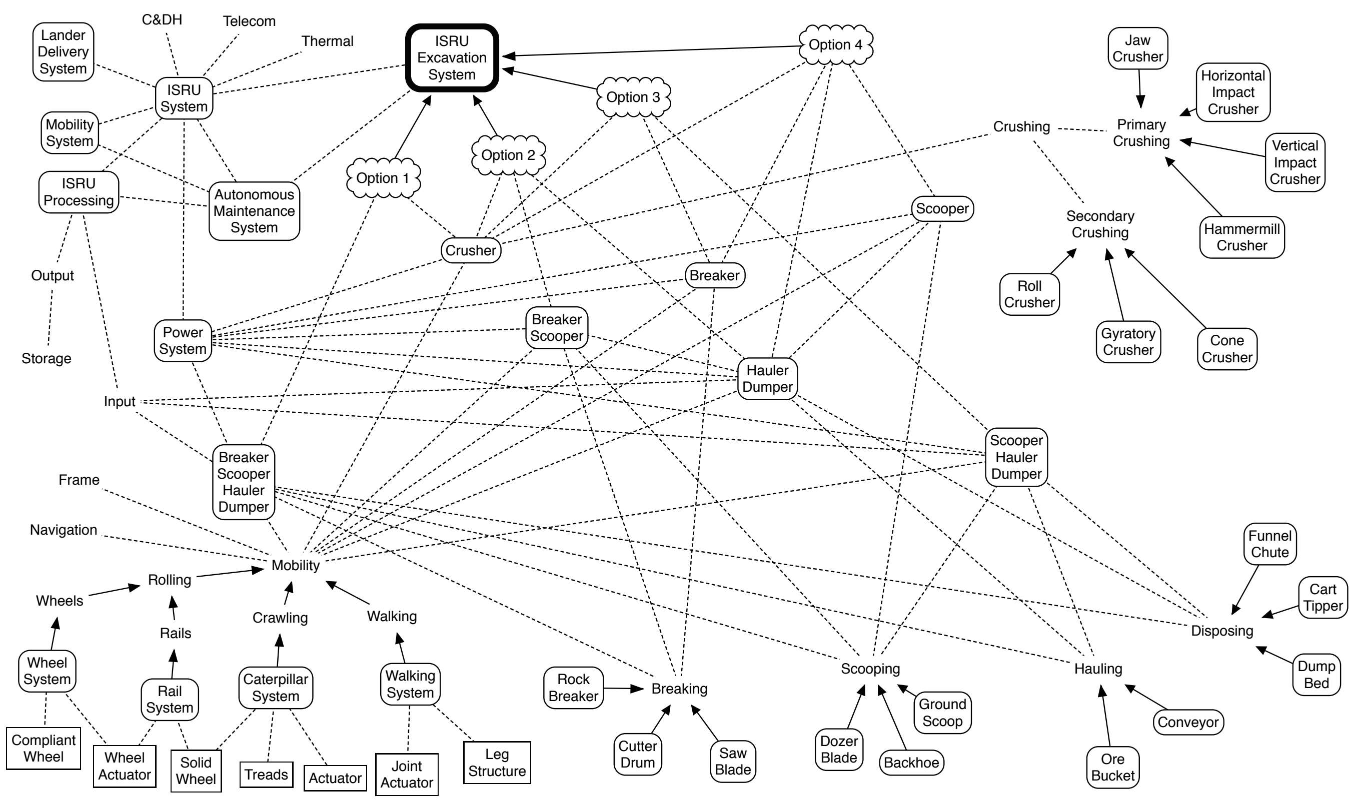

Figure 5: Autonomous ISRU/excavation system options and trades (see break-out diagrams for detailed descriptions)

4. System Concepts and Interfaces

The various tasks of breaking, crushing, loading, hauling, and dumping were explored using terrestrial commercial mining and excavating as examples. Grouping these functions together resulted in four options. The entire trade tree and system description can be seen in Figure 5.

The production rates planned for Mars ISRU operations are significantly lower than typical terrestrial mining operations. In order to use terrestrial mining as a model to estimate comparable quantities on Mars, appropriate scaling rules need to be developed. We have performed a 1st order analysis of scaling vehicle size by looking the capacities of commercially available vehicles across a range of sizes.

Crushing / Beneficiation

Several types of crushing functions in the terrestrial mining and excavation industry include primary crushing of larger rocks using jaw crushers, horizontal impact crushers, vertical impact crushers, and hammermill crushers. Tentatively jaw crusher technology using two opposing hardened plates has been selected for this effort due to its application to various scales and outputs (Figure 6). Secondary crushing methods could include similar methods commercially available as cone crushers, roll crushers, and gyratory crushers, which would take the output of the primary crusher as input.

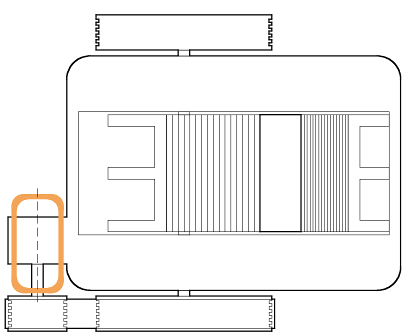

Figure 6: Mobile or stationary (relocated by mobile maintenance platform) primary jaw crusher

Tentatively cone crusher technology has been chosen for this effort (Figure 7), and it is expected that output particulates from the cone crusher would be acceptable as inputs for the ISRU processing plant. The jaw crusher and cone crusher units will consist of one actuator and two "part modules" each, for maintenance purposes.

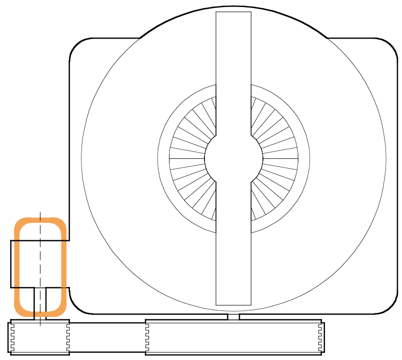

Figure 7: Mobile or stationary (relocated by mobile maintenance platform) secondary cone crusher

In excavation work, the equipment with the most mass and energy consumption may be the rock crusher, which can be grouped into primary and secondary crushing equipment. Primary crushing, such as jaw crushers, begins with larger feed size particulate input and outputs regular-sized particles that can then be further broken down with cone crushers or other secondary crushers or grinders.

In order to find an appropriate scale for crushers that could be economically carried out of Earth's gravity well and operated in a remote, low-energy planetary surface environment, we have attempted to find appropriate mathematical models to extract performance data. Our research so far has found detailed analysis of jaw crusher performance [8], cone crusher performance [9], and vertical shaft impactors [10]. We have identified commercial crushers with mass data available that would give us enough data points to produce a trending curve to allow us to make preliminary correlated output vs mass estimates. Figure 8 shows output vs mass, and Figure 9 shows output vs energy curves. Our data point samples originally included a larger number of commercial units, but we have arbitrarily set a mass ceiling of 10,000kg mass, assuming that it would not be practical to lift heavier units into space.

In addition to commercial approaches, lightweight, less energetic excavation and drilling technology based on ultrasonics/sonic and piezoelectric percussive systems researched by Honeybee Robotics and Jet Propulsion Laboratory [11, 12, 13] may be adapted to rock crushing to bring down the mass and energy needs of a space-based system. Percussive excavation systems specifically designed for the moon or Mars [14] may also provide inspiration for a percussive space rock crusher.

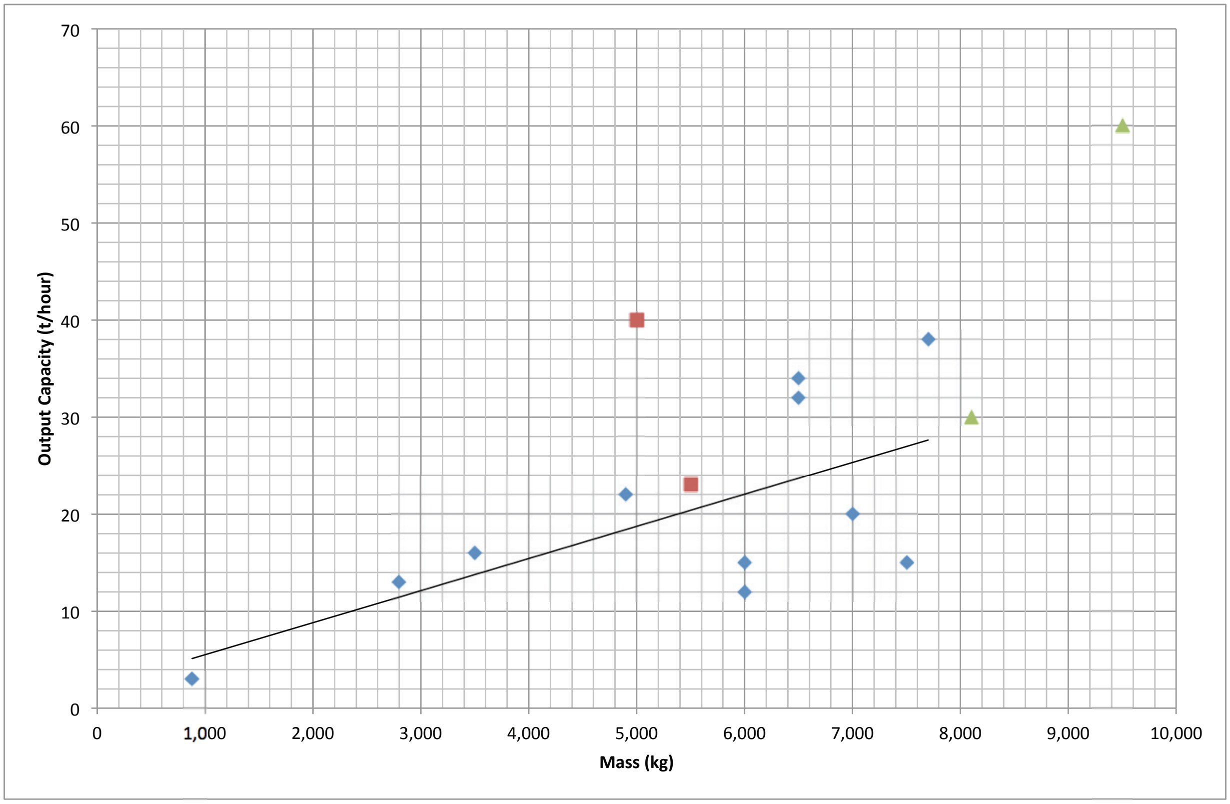

Figure 8: Commercial crushers output vs mass. Blue diamonds are jaw crushers, red squares are cone crushers, and green triangles are impact crushers

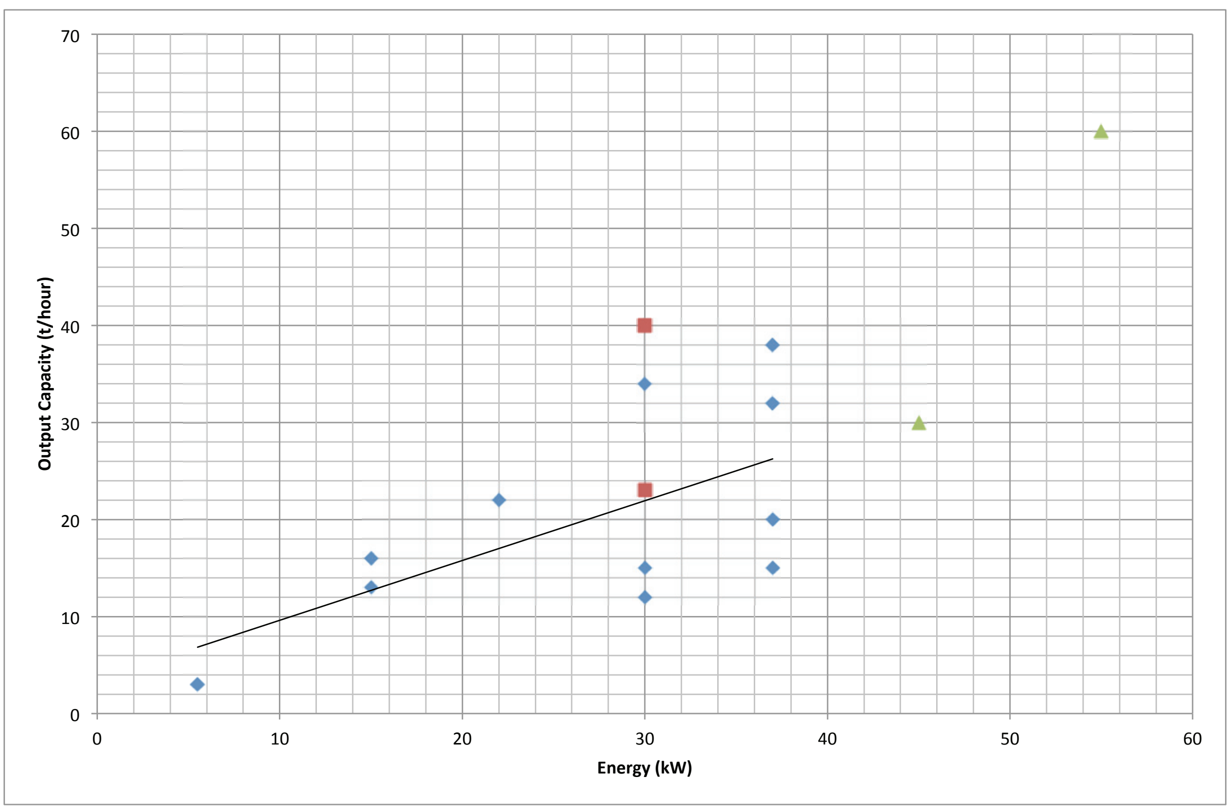

Figure 9: Commercial crushers output vs energy. Blue diamonds are jaw crushers, red squares are cone crushers, and green triangles are impact crushers

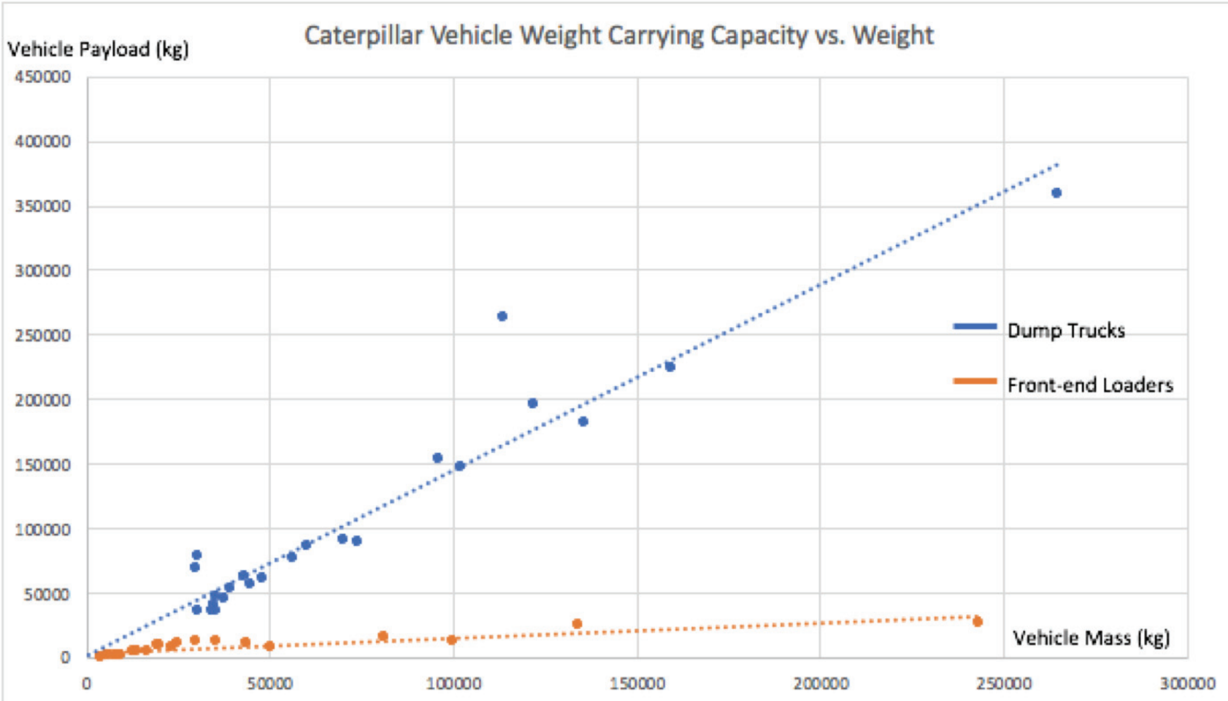

Figure 10: Dump truck (blue) and front-end loader (orange) load carrying performance

Dump Trucks

Caterpillar Model	Weight without load - kg	Payload - kg
797B	265000	358690
793D	159662	224087
793C	113510	262980
789C	135670	181845
789	121922	195538
785C	102150	147330
785	96353	153080
777F	73976	89317
777D	70307	90723
777B	60055	86911
777	56428	77112
775F	48004	61766
775E	30391	78018
775D	43227	63367
773F	44594	56104
773E	30164	69173
773B	39396	53138
773	37800	45370
772	35450	46650
771D	34750	40950
770	34242	36972
769D	35420	35980
769C	30675	36911

Table 4: Caterpillar dump trucks and carrying capacity (Source: http://speceps.com/weight/mining-11994/caterpiller.html)

Wheel Front-end Loaders

Caterpillar Model	Weight without load - kg	Bucket Capacity - kg*
903C2	4118	1100
903D	4279	1100
906M	5612	1320
907M	5762	1320
908M	6378	1650
910M	8133	2090
914M	8780	2090
918M	9508	2090
926M	13077	5500
930M	14036	5500
938M	16462	5500
950M	19255	10120
962M	20269	10120
966M	23262	8140
972M	24941	10934
980M	30153	13420
982M	35637	13200
986H	43809	11330
988H	50250	8470
990K	81144	16390
994K	243115	26950
992K	100040	13530
993K	133949	26070

* assume density of loaded material kg/m3 1100

Table 5: Caterpillar front-end loader weight and lifting capacity (Source: https://www.cat.com/en-US/products/new/equipment/wheel-loaders.html)

Loading

Scooping methods available commercially include dozer blades, backhoe buckets, and ground scoops. These methods are useful for loading varying amounts of material, and receiving ore buckets must be designed to accommodate the flow of material from the buckets. We have performed a 1st order analysis of scaling vehicle size [15, 16] by looking the capacities of commercially available vehicles across a range of sizes. In particular, Table 5 shows the mass and payload of front-end loaders from Caterpillar. The data is plotted on Figure 10. The data show that commercial front-end loaders can lift about 0.3 times their mass with each load across the range of vehicle sizes. As a 1st order estimate, we will assume that these scaling rules can be applied across the spectrum of functions that need to be performed for Mars ISRU excavation and delivery operations. These estimates will be applied for excavation and delivery operations as well as for maintenance and repair.

Hauling

Hauling trades could include the use of an ore bucket, conveyor, or combination thereof. For this effort ore bucket has been chosen as a preferred means, due to the compact size. Table 4 shows the mass and payload of a series of dump trucks from Caterpillar. The data show that commercial dump trucks can generally carry approximately 1.45 times their mass.

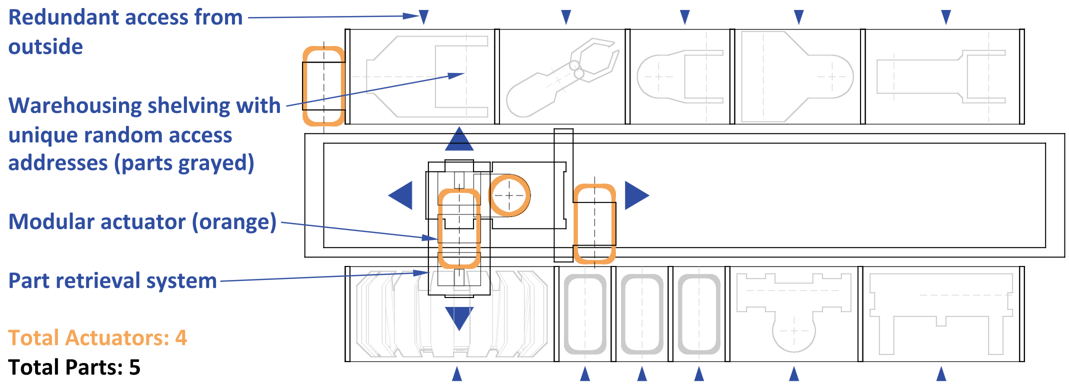

Figure 11: Autonomous warehousing and storage

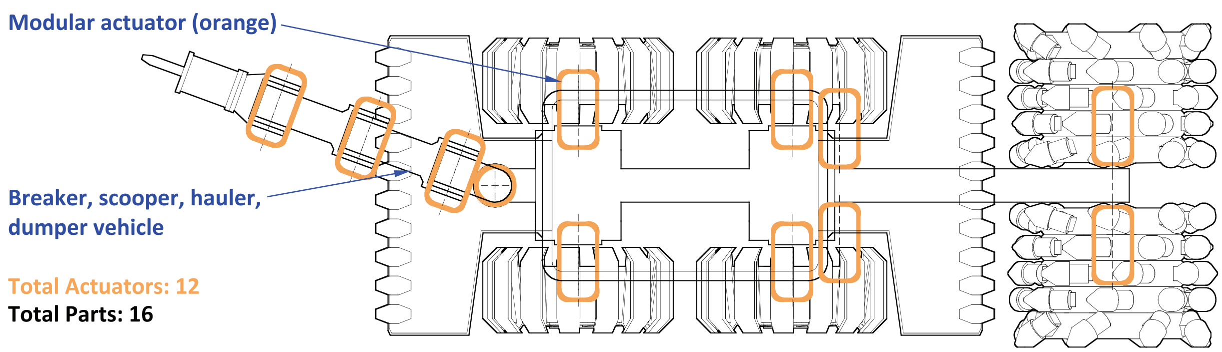

Figure 12: Breaker-scooper-hauler-dumper vehicle. Vehicles used in various options will be similar to this, using alternative modular implements and tools as required.

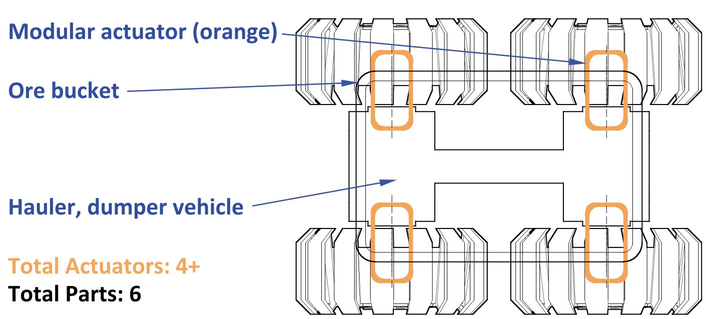

Figure 13: Hauler-dumper vehicle.

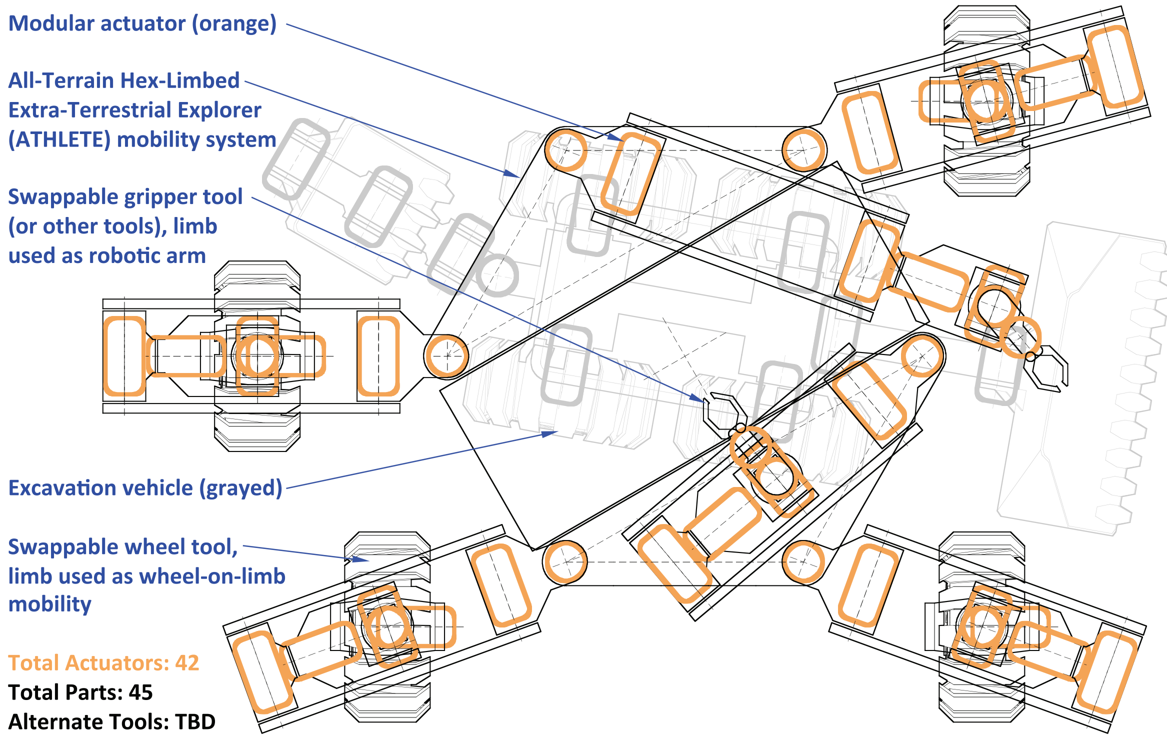

Figure 14: ATHLETE-based mobile maintenance platform (Alternative A), with swappable wheels and tools -- limbs can be used for both leg-on-limb mobility or as a robotic arm -- platform straddles vehicle to be repaired

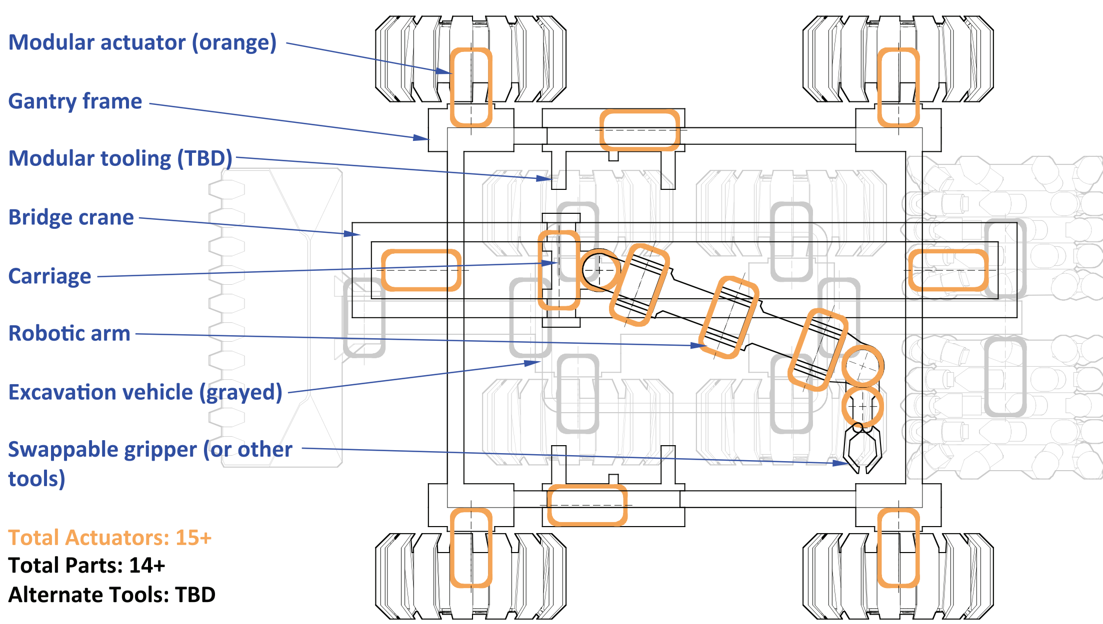

Figure 15: Gantry-based mobile maintenance platform (Alternative B), gantry with bridge crane and swappable tools straddles vehicle to be repaired

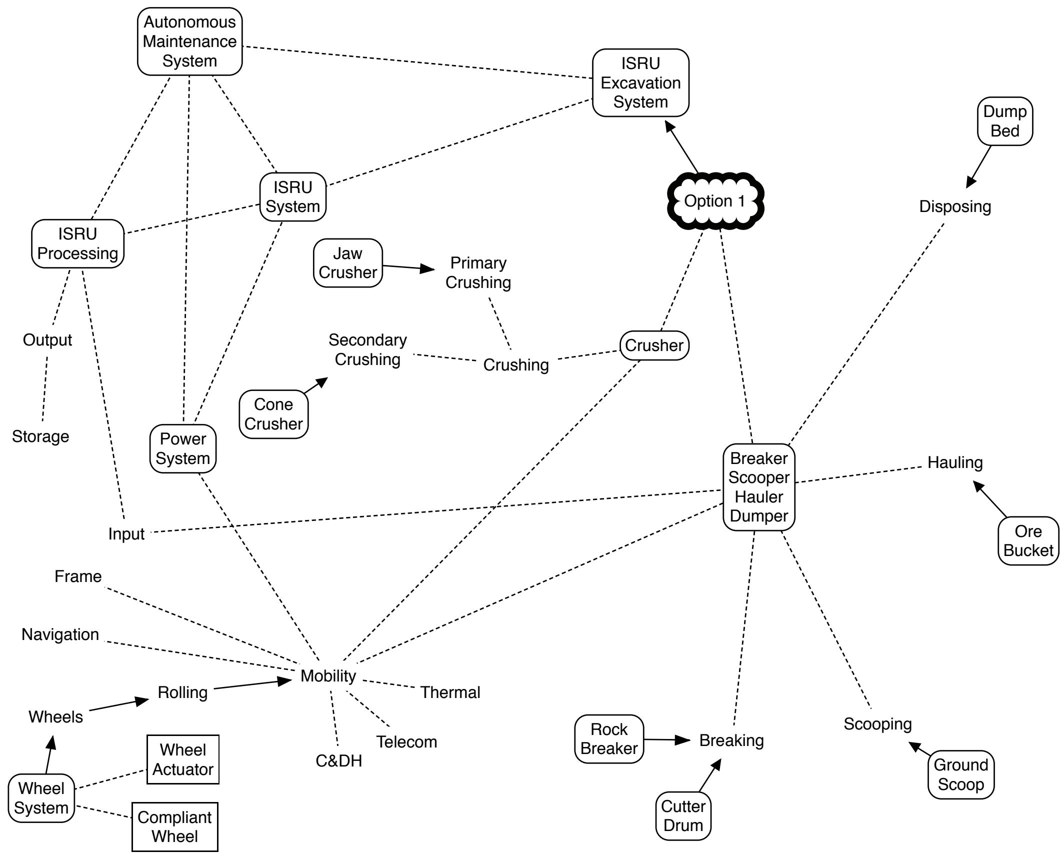

Figure 16: Option 1 system description, with mobile or stationary crusher and all-in-one breaker-scooper-hauler-dumper vehicle

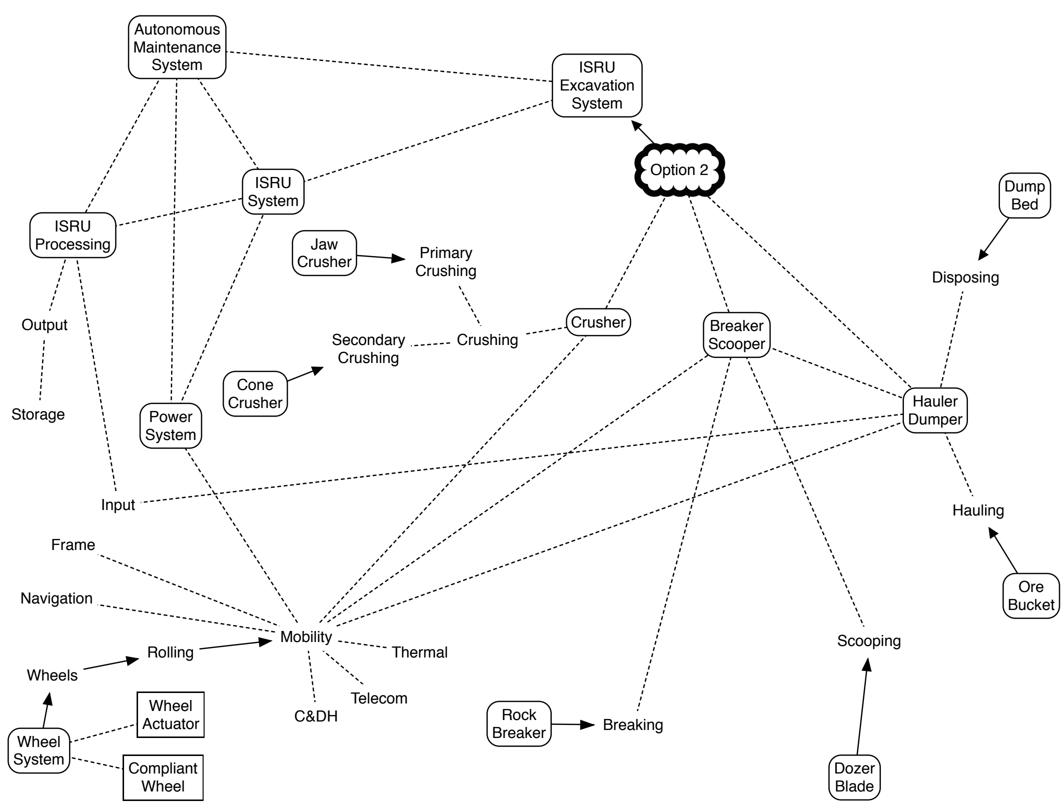

Figure 17: Option 2 system description with mobile or stationary crusher, breaker-scooper vehicle, and hauler-dumper vehicle

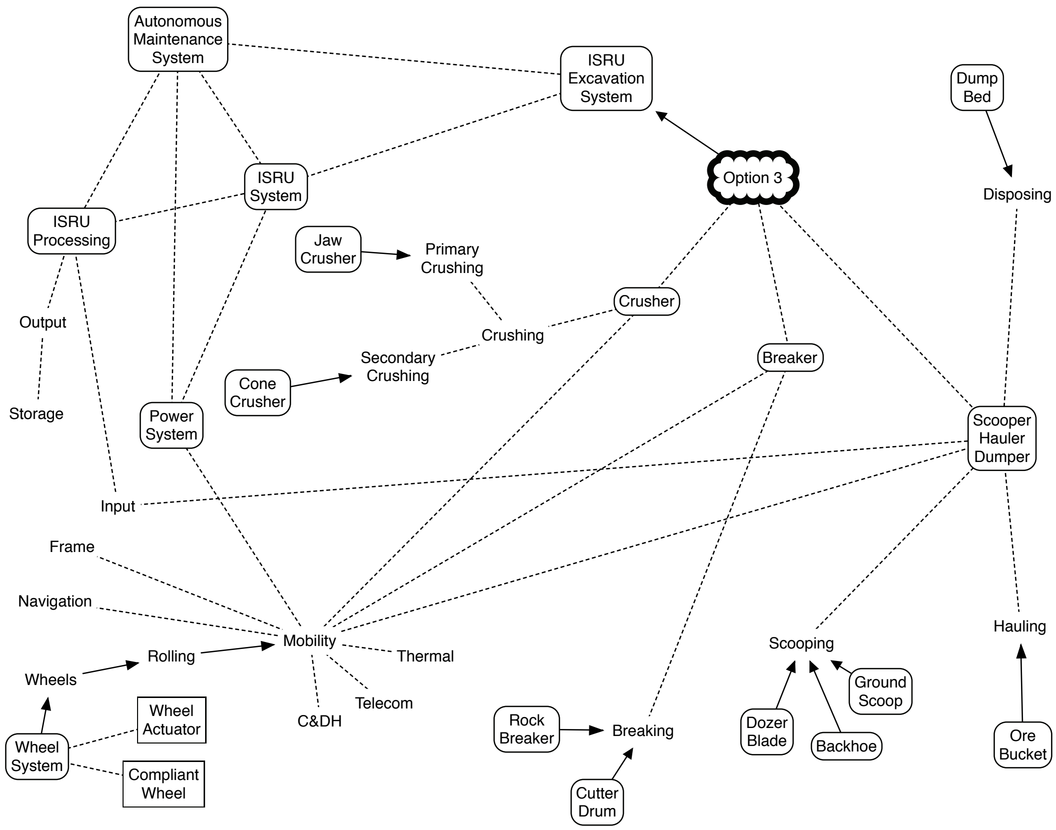

Figure 18: Option 3 system description, with mobile or stationary crusher, breaker vehicle, and scooper-hauler-dumper vehicle

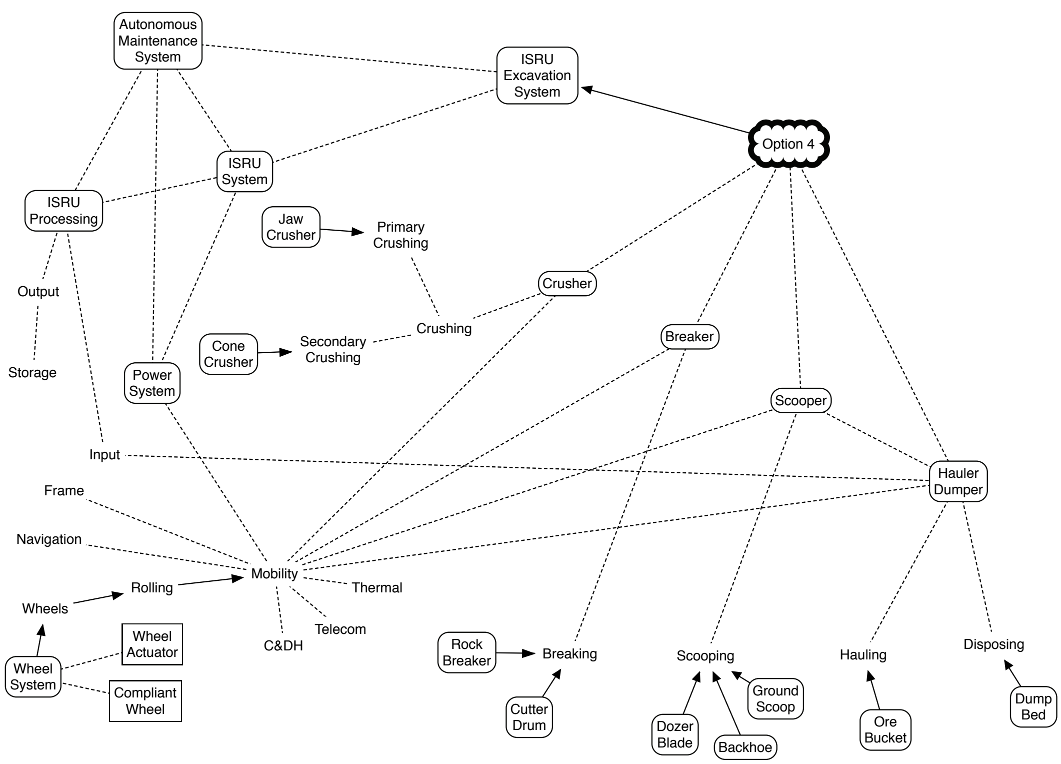

Figure 19: Option 4 system description, with mobile or stationary crusher, breaker vehicle, scooper vehicle, and hauler-dumper vehicle

Dumping

Dumping methods can include cart tipper, dump bed, or funnel chute. The latter two require extra actuators to tip the ore bucket or open the chute door, whereas the former requires additional hardware to cause the entire ore cart to flip over and right itself again.

ISRU Input Hopper interface

This is a component of the overall system that needs to be defined in coordination with the ISRU Plant design team. The interface should include specifications on geometry, storage capacity, interaction loads, rate of material transfer, acceptable material particle sizes, instrumentation for autonomous operation and monitoring, and dust management procedures.

Maintenance and Repair System

The maintenance and repair system will consist of an autonomous warehousing and storage unit (Figure 11) and two identical mobile maintenance platforms, either ATHLETE-based (Figure 14) or gantry-based (Figure 15). These systems will consist of modular parts as described earlier. Since all complexity of the robotic elements will be encapsulated into "part modules", a discrete number of part modules and actuators are needed for each system. The autonomous warehousing and storage unit will consist of only four actuators and five part modules (a horizontal part carriage, vertical part carriage, horizontal frame, retrieval manipulator, and random access shelving). The Alternative A ATHLETE-based maintenance platform will consist of 42 actuators, 45 part modules (including wheels), and a TBD number of additional swappable tools.

The Alternative B gantry-based maintenance platform (Figure 15) will consist of fifteen actuators, fourteen part modules, and a TBD number of additional swappable tools.

All of the autonomous warehousing and storage unit and mobile maintenance platform concepts utilize the "part module" concept because they will also be subject to self-maintenance by the system. Additional autonomous warehousing and storage units can be provided as needed for redundancy, and the mobile maintenance platforms can also retrieve parts in a random access manner as backup.

Option 1

The Option 1 scenario (Figure 16) will utilize the crusher units (Figure 6, Figure 7), autonomous warehousing and storage unit (Figure 11), mobile maintenance platform (Figure 14 or Figure 15), and will group all the functions of breaking, scooping, hauling, and dumping into a single vehicle (Figure 12). In addition to the actuators and part modules required for the supporting systems, the breaker-scooper-hauler-dumper vehicle will require twelve actuators and sixteen part modules.

Option 2

The Option 2 scenario (Figure 17) will utilize the crusher units (Figure 6, Figure 7), autonomous warehousing and storage unit (Figure 11), mobile maintenance platform (Figure 14 or Figure 15), a breaker-scooper vehicle (similar to Figure 12 with alternate modular implements and tools), and will group hauling and dumping into a separate platform (Figure 13). The breaker-scooper vehicle will require ten actuators and eleven part modules, and the hauler-dumper vehicle will require 4+ actuators and six part modules.

Option 3

The Option 3 scenario (Figure 18) will utilize the crusher units (Figure 6, Figure 7), autonomous warehousing and storage unit (Figure 11), mobile maintenance platform (Figure 14 or Figure 15), a breaker vehicle (similar to Figure 12 with alternate modular implements and tools, with eleven actuators and twelve part modules), and a scooper-hauler dumper vehicle (similar to Figure 12 with 10+ actuators and eleven part modules).

Option 4

The Option 4 scenario (Figure 19) will utilize the crusher units (Figure 6, Figure 7), autonomous warehousing and storage unit (Figure 11), mobile maintenance platform (Figure 14 or Figure 15), a breaker vehicle (similar to Figure 12 with alternate modular implements and tools, with eleven actuators and twelve part modules), scooper vehicle (similar to Figure 12 with ten actuators and eleven part modules), and hauler-dumper vehicle (Figure 13, with 4+ actuators and six part modules).

5. AUTONOMY IN LONG DURATION OPERATIONS

Autonomous Site Preparation Operations

Prior to the robotic ISRU/excavation system operations, the mining site should be surveyed and a high-resolution topographical model should be developed and analyzed. The ISRU plant location and the excavation region should be identified and paths between them planned. Path planning should minimize traverse distance, limit slope and slope changes, ensure adequate path width for vehicles with additional space for repair operations without disrupting operations, ensure ground load capacity and stability with either absence of, or ability to clear obstacles. During the site set-up operations, the paths should be prepared by grading to meet slope and width requirements and clearing of obstacles. Grading and obstacle clearance could be performed by the scooping vehicle. These procedures may additionally need to be performed repeatedly during the operations phase if path conditions deteriorate. The operational area should also be instrumented with placement of beacons and perception sensors at the excavation region, the ISRU plant and at regular intervals along its paths to aid in navigation, inspection and maintenance. Note that these beacons and perception sensors could be self-deploying (from compact packages placed on the ground) solar powered towers for a distributed wireless network. A 1st order estimate of the mass of material that needs to be processed in preparing the site is about 30 times the daily production rate (see Table 2), i.e. 30,000kg of regolith and will require approximately 30 days of activity assuming direct human supervision. It is likely that performing these operations semi-autonomously under the communication delays between Earth and Mars, it will require a factor of 2-3 times longer.

Autonomous Material Excavation and Delivery Operations

In addition to a vehicle capable of performing the physical operation, autonomous excavation operations will need a high-resolution map of the excavation site with continuous updates as the excavation operation occurs. Beacons and navigation aids placed around the excavation site will greatly ease the situational awareness of the vehicle. The vehicle should have visual and navigation sensors and a Simultaneous Localization and Mapping (SLAM) algorithm running on-board to localize itself in the environment. The execution of the excavation process could follow a pre-designed plan developed by human geologists and operators on Earth. During excavation, terrain interaction sensors will be needed to monitor and control the process. In addition, health monitoring sensors (for example temperature and vibration on actuators) should also be used to monitor and manage the health of the vehicle.

The process for transfer of material from an excavator to the transport vehicle should be designed to be mechanically automated to reduce complexity and risk. Autonomous transport of excavated material from the excavation site to the ISRU plant will primarily be an autonomous navigation task. The path is expected to be pre-defined and periodically lined with beacons and navigation aids so this task should be relatively straightforward. The primary challenge in this process is to detect any deterioration in the path conditions and respond accordingly (as discussed in the site preparation section above).

A centralized planning and scheduling system overseeing the entire operation should be used to optimally manage resources and schedule operations in situ. It should have access to sensor data collected on all vehicles and beacon sites in order to monitor and re-plan operations if needed. An integrated system health management module within this centralized executive should monitor and schedule preventative maintenance procedures.

Autonomous Maintenance and Repair

Integrated system health management: Continuous monitoring and scheduled maintenance servicing will greatly improve reliability and duration and reduce equipment failure [17]. A comprehensive approach that incorporates a knowledge base of the equipment and its operational states, reasoning on interactions between sub-systems, models of nominal and off-nominal behavior, monitoring of equipment performance and trends in performance using embedded sensors, continuous analysis of streaming sensory data, detection of new and emergent dynamic behavior, and forecasting expected equipment behavior will greatly enhance the ability to detect anomalies and perform preventative servicing before catastrophic failures.

Parts management, storage, and material handling: All in-situ maintenance will comprise of swapping part modules as required – worn or malfunctioning parts will be swapped with spare versions using the mobile maintenance platform (Figure 14 or Figure 15). An automated warehousing and storage unit will provide storage for spare part modules that are most susceptible to wear and tear or malfunction. The automated warehousing and storage unit will provide random access cells that include a single part module stored at each unique address, that can be accessed and retrieved on demand. The vacated cell is then available for the storage of worn or replaced parts. The automated warehousing and storage unit will be designed in such a way that minimizes the distance a single part module must be carried during retrieval (may be a separate system, or use mobile aspects of the repair station, or a combination of both).

Instrumentation and sensing: External sensors placed in the environment and on the equipment (for example stereo vision to accurately locate all elements spatially) and embedded internal sensors within the equipment (for example temperature or vibration sensors to determine the operational state of the respective equipment) will be needed to provide thorough monitoring of the state of operations. These will be needed in order to conduct autonomous operations as well as for maintenance and repair operations. To reduce communication and data processing overload, a hierarchical distributed sensor data processing system could be used with each module processing its data to determine its state but also sharing the summarized module state with the higher-levels of the sub-systems and systems. The hierarchy would integrate a parallel fault-reporting framework to either resolve problems locally or report to a higher-level for resolution if the problem cannot be resolved locally.

Repair station design: The repair station will consist of two mobile platforms (each will be capable of repairing each other) with the capacity to: 1) remove, swap, and replace defective or worn part modules for every vehicle or element in the ISRU Excavation System (including itself for a limited extent or its counterpart); 2) retrieve spare parts from automated warehousing and storage unit; 3) carry defective parts back to automated warehousing and storage unit; 4) "cannibalizing" one vehicle for the benefit of repairing another; and on last resort 5) lift and carry malfunctioning vehicles to an offsite location for disposal, recycle, or dismemberment. The mobile repair platform may include robotic arms, gantries, cranes, etc and make use of swappable tooling such as grippers, wheels, drills, wrenches, or other tools.

Repair operations: Mobile repair platforms will be capable of remaining stationary while ISRU Excavation vehicles arrive and position themselves underneath. Alternatively, the mobile repair platform will be able to traverse over to where a stalled vehicle is waiting in the field. Repairs then will consist of: 1) diagnosis of malfunctioning vehicle; 2) advance retrieval of a replacement part from the automated warehousing and storage unit (if defective part is known); 3) waiting for vehicle to arrive (or traversing to vehicle if it is inoperational); 4) lifting the vehicle into an elevated repair position (and performing diagnosis if problem is not known in advance); 5) swapping out the defective parts; 6) another trip to the automated warehousing and storage unit for a post-retrieval, in cases where diagnosis was not known in advance (the disabled vehicle can be carried during this time, and the defective part can be passed to the automated warehousing and storage unit); 7) swapping in the replacement part module; and 8) lowering the vehicle back to the surface.

6. CONCLUSIONS

Terrestrial mining operations were used for guidance in planning, organization, and estimation of the time and resources necessary for a conceptual planetary surface excavation operation. The functions defined for excavation and material handling of ore are breaking, scooping, hauling, dumping, and crushing. Terrestrial mining vehicle and equipment functions, power usage, and mass were analyzed, as well as precedent prototypes designed for use in space environments.

Autonomous systems will be necessary for each of the functions of breaking, crushing, scooping, hauling, and dumping. All of these functions may be handled by separate vehicles, but may more efficiently be combined into multiples of a single type of vehicle using modular implements and systems.

All systems should be designed for maintenance and repair. We recommend that a minimal set of vehicle types with modular actuators be manufactured and sealed on Earth, and all structures, avionics, sensors, embedded state performance monitoring, and power systems be encapsulated into sealed part modules protected from the dusty planetary environment. All actuators and part modules should be over-designed for strength and reliability. In-situ maintenance or repair should NOT be done by breaking down the actuators or encapsulated part modules. Instead, simple mechanical and power/data connect/disconnect procedures should allow for swap-out of worn or malfunctioning actuators or part modules, replacing the entire sealed assembly each time.

A simple warehousing system should be used for spare actuators and part modules that are prone to wear and tear or malfunction. When new replacements are retrieved from the warehousing system, the old swapped-out parts can be stored in the same slot vacated by the new one. Thus, a warehousing system initially stocked with new parts will gradually be replaced by old malfunctioning parts. It is assumed that this built-up supply of malfunctioning parts can eventually be serviced by either human crews or by additional autonomous systems delivered by future missions designed to open up the sealed part modules.

Autonomous maintenance and repair systems should be thoroughly field tested in various Earth environments (such as dusty, cold, wet, or corrosive environments) to insure reliability of interfaces and maintenance procedures. The maintenance and repair strategy should be multi-pronged, including: 1) integrated system health monitoring within each actuator or encapsulated part module; 2) preventative maintenance, such as replacement before failure; 3) parts management and handling; 4) ability to scavenge parts from other vehicles (use non-functional vehicles as a source of replacement parts to expand the number of spares available in the warehousing system); and 5) use a highly capable repair system, such as a mobile gantry with robotic arms.

Using the excavation vehicles, the first task should be site preparation to reduce wear and improve reliability. Paths or roads should be graded, smoothed, stabilized, and cleared of all obstacles. Beacons and sensors along paths and at operational sites should be installed for ease of operations and for monitoring.

Bringing it all together, our current recommendation is tending toward a single gantry-type vehicle capable of swapping out a variety of modular implements, arms, buckets, and tools as needed. The vehicle should be capable of nesting with identical versions of itself, such that each vehicle can swap in arms or other tools for the purpose of performing maintenance on each other. Implements that can be swapped in would include breaking tools, crushing mechanisms, scooping buckets or blades, and hauling beds that can be swapped out depending on the task at hand. A suite of multiple identical gantry vehicles can thus perform all operations in parallel by each using a different tool, and can also nest with its neighbor in case of malfunction to lift it out of the way or perform maintenance on it.

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