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WHEN EARTHMOVER IS A MISNOMER: CONSTRUCTION VEHICLE DESIGN FOR LUNAR AND MARTIAN APPLICATIONS

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ABSTRACT

Mars Direct requires that the Earth Return Vehicle (ERV) carry a truck that can take a reactor several hundred meters away from the ERV. It must also string the power cables between the reactor and the ERV [1]. This paper goes into detail on the requirements for this truck and a design that should meet those requirements. This design is a lightweight semi-autonomous construction vehicle able to do excavation and equipment relocation around a landing site. The vehicle consists of three work sections - a "robonaut" front end, a middle flat bed for carrying heavy equipment, and a backhoe for excavation, road clearing, and lifting and placement of items in the flat bed area. The basic design could be adapted for many uses, with or without a crew present, on Earth, the Moon, or Mars.

REQUIREMENTS

The Mars Direct ERV design requires that a reactor be removed from the craft and placed several hundred meters away in a sheltered area using a robotic truck. The reactor design weight is 3500 kg and the truck design weight is 500 kg, or 1/7 that of the reactor it is designed to carry. The truck must also be able to run the electrical connections between the reactor and the ERV. The truck must reach the reactor site through Martian terrain.

Ground Clearance Criteria

One of the more detailed studies of rock hazards on the surface of Mars cut off the definition of “hazard” at 70 centimeters between the top of a rock and the surrounding ground. Over a 220 square meter area, the odds on such a rock existing are 12 percent on a smoother landing site (such as Meridiani, Gusev and Elysium) and 15 percent on a rougher site (Isidis) [2]. While the number of rocks of a given size increases as the given rock size decreases, the odds remain remote that a vehicle with the maximum 62 cm ground clearance of this design should have any difficulty. The only failure scenario is a landing site completely ringed with rough terrain within a 200-300 meter radius around the ERV. The ERV could simply avoid landing in such locations as determined by satellite imagery during the site selection process, and by hazard avoidance systems on landing.

Reactor Placement Criteria

The reactor will weigh seven times more than the rover, so it should be carried as low as possible in the truck frame to limit its possible negative impact on stability going up and down hills. The reactor should be placed as near the center of the vehicle as possible to equalize the load on each wheel and to reduce tipping when rough terrain induces pitch, yaw, or roll factors.

Terrain Improvement Capacity Criteria

The vehicle should be able to construct a trench or wall big enough to hold the reactor, even in rocky soil, so that it cannot be viewed from ten meters away and two meters in height. Additionally, the ability to mount on a frame, fill, seal, move, and unload sand bags could be created for landings in smooth, sandy terrain. For construction purposes, no more than ten percent of the surface rocks should be considered immobile by the truck because of weight (depth in soil or proximity to other rocks are also factors to consider.)

As an arbitrary figure, let's assume we have a tool that can move a 100 kg load on earth. This means that a cubic rock 30 cm to a side could be moved on earth if the density was 3703 kg per cubic meter, or on mars if the density were 9250 kg per meter. For reference, sandstone is 2323 kg/m^3, iron ore is up to 2900 kg/m^3, and hematite is 5095-5205 kg/m^3 [3]. A cubic rock measuring 30 cm across on earth weighs roughly the same as one measuring 40 cm across on Mars, so the 100 kg tool could move 40 cm rocks on Mars. By contrast, the existing robonaut can lift 11 kg with each arm [4].

Removing hazards from landing and take off sites criteria

First, the ERV is assumed to have landed reasonably well, otherwise the truck would never have been unloaded, or the ERV would have taken other damage which would effectively "decertify" it for launch with a crew. That sets one boundary between what the truck can or cannot achieve in terms of removing risk. On the other side are factors that can be changed using the truck. Perhaps the ERV lands in an area where the soil/rock will support it at landing weight, but not the take-off weight (Up to ten times landing weight). Shoring up landing gear, anchoring the base with guy-wires, or digging out unstable terrain are all possible with this truck design.

While the crew is on site, digging a flame trench under an ERV is also a possibility. Another primary concern will be clearing a landing site for the Hab, and establishing the appropriate beacons for that site. Clearing a landing site takes on additional importance since the hab could land close enough to the ERV base to make debris kicked up by the engines a hazard to the existing base infrastructure. Clearing a small "road" between the two sites is also a possibility.

VEHICLE DESIGN

(See Figure 1.)

Suspension Considerations

The original plan states that the reactor should be placed in a crater. Rocker-bogie construction used on current mars rovers has been shown to loose traction when ascending grades of more than 21 degrees because the front wheels come off the ground. It can continue on the back two wheels up to 32-degree grade [5].

Crawler tracks have great traction but lack ground clearance and can be a maintenance issue. Widening the tires excessively can cause lateral clearance issues. Lowering the vehicle to keep the center of gravity close to slopes will also cause rock clearance issues.

Because the traditional rocker-bogie solution hangs the entire suspension at a single point on either side of the frame, this probably is not the best solution for stability or strength in a truck designed to carry seven times its own mass. The proposed solution is to construct it on a twelve-wheel platform, then make the suspension height adjustable using worm gears and struts to raise or lower the chassis. To equalize the load on each wheel (and therefore minimize traction demands), the reactor is placed as close to the center of the vehicle as possible. In this design, the rover must unload the reactor off the side of the vehicle to avoid hitting equipment on the ends (backhoe and robonaut). A variable height suspension would be housed in struts, but those struts cannot be so tall or wide that the reactor cannot clear them when unloaded. The proposed solution looks much like the traditional rocker-bogie, with dual axles in back joined to a single point on each side, and a single axle in front on each side. This allows the vehicle to use the same strut for both back wheel sets on each side. To further distribute the load, a wheel is on either side of each axle, rather than on one side with current MER designs. The final proposal has four struts, six axles, and twelve wheels. This allows the reactor or other payload to be unloaded to the side without a middle suspension tower getting in the way.

The traction available to the vehicle is going to be a big issue given the weight loading and rough soft terrain. Tires are wide to help distribute the reactor's weight on soft ground. Putting a wheel on both sides of the each driveshaft doubles the surface area of ground contact with a slight increase the weight and the width of the truck. The suspension towers are moved out accordingly on outriggers or on a wider chassis, and the chassis has wheel wells to allow the vehicle to be lowered over the inner wheels.

Vehicle Size and Ground Clearance

The truck design in this paper assumes the reactor (or largest separate reactor component) is a one-meter cube. A longer reactor power assembly is possible, but in those cases such a reactor design would be pulled on a trailer and so would not impact the design. By making the vehicle around a standard one-meter cube, scaling the vehicle up or down is simplified for larger or smaller payloads. With this design, ground clearances of 62 cm when fully elevated, and can be lowered to 24 cm during climbing and unloading operations.

Reactor Transportation Options

Since the reactor may be placed in a crater or other depression, we have be able to unload it to a lower level than the truck will sit during the operation. We also have to be able to unload something that is much more massive than the vehicle itself, which presents serious weight shift problems. My original design suggested the truck first place a thick hexagonal metal grating at the site where the reactor would be set. This would keep it off the ground to avoid contamination and also give it a pre-leveled platform for operation. Once the path to the site and grating are ready, the truck would move the reactor to the site. It would then lower the ramp from the side so that the base of the ramp hooks into the grating. At that point, it would use the backhoe to nudge the reactor on rollers to the grating. By giving the effective structure a single surface that goes all the way to the ground (truck, ramp, and grating locked together), we avoid the weight shift that could flip the truck. A second option would instead use a simple A-frame gantry crane that could be unfolded and placed over the reactor base plate. After the truck moves the reactor to a location next to the base plate and under the gantry crane, the crane could lift the reactor, move it laterally over the plate, then lower it. The gantry crane could either be removed by the truck for other uses, or left in place for future reactor service. A third option is to simply place locks on the backhoe joints and a wench on the bucket and use it as a truck crane.

Excavator Options: Bulldozer or Backhoe

The bulldozer could be a low mass solution involving a lifting or articulated blade on one end of the truck and clearing rocks from the path. It could also dig a shallow trench for the reactor. However, any action by the blade implies the truck has the mass and power to dislodge and move any rock embedded in the soil over a span as wide as the blade itself, which must also match its wheelbase. Mass would be less of an issue if the reactor were loaded at the time (magnifying the weight dramatically), however, the torque required by the wheels to both move the reactor and push the burden could be substantial, especially if the terrain were uphill at any point.

A backhoe, on the other hand, could remove rocks or simply bury them to level a path using soil or gravel from off the path. If several rocks block the path at once, they could be removed individually at a lower power demand. It could also dig a flame trench beneath the ERV for take-off if necessary or desirable. It could also be of scientific use before, during, and after the crew visit the site. Issues of torque, traction, and grade do not dramatically increase requirements on the entire vehicle the way they do a bulldozer solution. The vehicle must simply be stable and counterbalanced. There are issues of artificial intelligence, cameras, lighting, ground radar to detect hidden rocks, and so on, but that would need to be figured into any design.

Powering the Backhoe

Standard backhoes use hydraulics that can put incredible force on the arm at any point. Therefore the arm, beam, and bucket can be poorly leveraged (over 7:1 against the hydraulic piston in most cases) and still cut through most soil. In space construction, we may not have the luxury of hydraulics because of maintenance and pressure issues. For this paper, we will consider standard electric motors and shaped memory alloy (muscle) wires for this design. Electric motors improve sufficiently from decade to decade that it is too soon to decide between approaches, but both can easily be designed and used in experiments. An off-the-shelf 375 micron diameter muscle wire can exert two kilograms of force, which with the leverage of the arm would be reduced to 200-400 grams at each axis. The negative is that muscle wires can retract up to five percent of their length, which severely limits the travel allowed in the system [6]. A straight muscle wire to the bucket, for example, could barely move it at all. There are two proposed solutions to this. There is a commercially available wire formed into a helix, which then can expand to 250 percent the original length and then fully retract. A coil (not a solid wire, but the helix itself) with a 2-millimeter diameter can pull with 50 grams of force. While many such coils can be clustered for great strength, the coils would bind together when cycled.

My proposed solution is to feed straight wires back and forth through a series of static pulleys within the framework of the boom and arm. There would actually be two sets of wires, each woven in opposite directions like shoelaces to provide power in both directions on the axis. Each arm, then, becomes a stack of alternating flat elements separated by rows of shafts on the top and bottom edges of each arm, with wires run within each gap in opposite directions to the layers on either side.

One possible solution to the power limits on leverage would be to make the beam/arm joint articulate with a slide or cam. When the system does not carry a load, a simple cam mechanism could flip the joint from one point on the beam (allowing greater reach) to one "choked up" on the beam (for greater leverage and therefore strength). This would be especially useful in freeing difficult rocks. The backhoe I've designed is also articulated at the base to work in the conventional configuration (bucket pointed down) or an inverted position (bucket pointed up) simply by mounting it to a two axis base. The inverted mode will make an excellent "scoop" for digging under objects (such as the ERV for a flame trench). It effectively gives the truck some end loader. It will also greatly simplify the task of leveling ground, such as in clearing the site for the hab.

Adding equipment for driving posts (for guy-wires, core samples, and possible seismic or excavation charges, and beacons, lights, wiring, or other equipment) should be fairly simple. Either a drill or hammer drill could be mounted to the base. A combined solution would also have a driver socket mounted near the robonaut. This socket is basically a closed-end tube that would hold a wire stake, core sampler, or other payload to be driven into the ground by force. The lowering of the suspension could do most of the work in driving the object into the ground, with the driver itself wormgeared to drive the object the rest of the way to the surface if needed. The limit is that the driving force could not exceed the leveraged weight of the vehicle, and that the object being driven must weigh less than the lifting capacity of the robonaut (roughly 30 kg on Mars with both arms).

<u>Powering the Truck</u>

I propose a hybrid-electric system for the truck, where the fuel for the internal combustion engine side is the same as that used for the ERV (Methane, ethane, or butane, depending on the choice for that system, accompanied by liquid oxygen). While hybrids are used normally for greater fuel efficiency, the concern here is adaptability and surge electric capacity for the hardware. This design could function entirely from another power source, such as the solar backup array or the nuclear reactor, when being used for more static excavation tasks.

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FIGURE

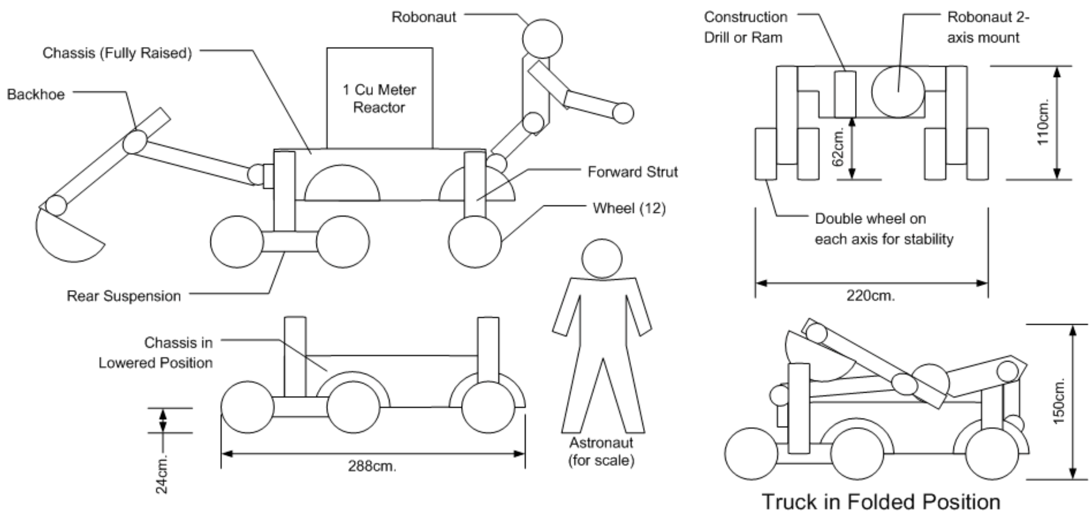

Figure 1 Illustration of Excavator