ENAE788X COURAGE Rover

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1 Project Description and Requirements

1.1 Project Description and Motivation

Project Description: Perform a detailed design of a BioBot rover, emphasizing mobility systems Chassis systems (e.g., wheels, steering, suspension. . .) Support systems (e.g., energy storage) Navigation and guidance system (e.g., sensors, algorithms...) Design for Moon, then assess feasibility of systems for Mars, and conversion to Earth analogue rover

1.2 Requirements: Performance

Maximum operating speed of at least 4 m/sec on level, flat terrain. Accommodate a 0.3 meter obstacle at minimal velocity. Accommodate a 0.1 m obstacle at a velocity of 2.5 m/sec. Accommodate a 20° slope in any direction at a speed of at least 1 m/sec and including the ability to start and stop. A nominal sortie range of 54 km at an average speed of 2.5 m/sec.

1.3 Requirements: Payload

Requirements (Payload) : Capable of carrying one 170 kg EVA crew and 80 kg of assorted payload Payload may be modeled as a 0.25 m box Capable of carrying a second 170 kg EVA crew in a contingency situation. Incorporate roll-over protection for the crew and all required ingress/egress aids and crew restraints.

1.4 Requirements: Operations

Requirements (Operations) : A nominal sortie shall be at least eight hours long. Two rovers must be launched on a single CLPS lander. A single rover shall mass $\leq$250 kg. Capable of operating indefinitely without crew present. Requirements (GN&C) : Capable of being controlled directly, remotely, or automated. Capable of following an astronaut, astronaut's path, or autonomous path planning between waypoints. Capable of operating during any portion of the lunar day/night cycle and at any latitude.

2 Terramechanics

[1] [2] [3]

3 Stability

4 Steering

5 Suspension

6 Motors

7 Sensors, Perception, and Computing

The rover needs to be operable autonomously, so it needs sufficient proprioceptive and exteroceptive sensors and computational power to understand it's environment.

7.1 Lighting

Without an atmosphere to reflect ambient light, the lunar surface is dark and shadowy. Proper illumination will be important for the astronauts to work and for the rover's vision systems to function in a useful way. We've equipped the rover with four 35,000 lumen LED floodlights for illumination. LED floodlights have terrific energy efficiency (especially when compared to incandescent or halogen) and provide excellent brightness for very little weight. By far, most of the weight of the floodlight assembly is the plastic/glass/metal housing, and the LEDs themselves contribute negligibly.

7.2 LiDAR

The rover will be equipped with 4 Velodyne Puck LITEs for complete LiDAR coverage. The Puck LITE was chosen (instead of the Ultra Puck or Alpha Puck) for it's lower weight. The rover is one of just a few vehicles on the moon (as compared to hundreds of vehicles in the immediate vicinity of a car on an Earth highway) and therefore doesn't need the superior response time or resolution of these higher end pucks. The Puck LITE still provides an impressive 100m range, 30° vertical field of view, and 3cm accuracy [4].

7.3 Cameras

A comprehensive vision system will be valuable for autonomous rover operation, as well as more detailed science (especially science/operation conducted remotely from Earth). Camera quality has improved dramatically since the 1960s, and we can now supplement our rover with a number of very high quality cameras with little financial, power, or weight cost. We've selected 7 Earth-analog cameras which (when modified for a space environment) would be excellent for the rover system. We start with two Sony 4K BRC-x400 Pan Tilt Zoom (PTZ) cameras, each weighing 1.8kg and requiring 25W (max). The 3 degrees of freedom in these cameras make them very useful for exploring an environment.
Stereo cameras, in which two cameras side by side can provide binocular depth perception, are useful for both visual perception and depth. These supplement the Velodyne LiDAR pucks' ability to understand the geometry of the nearby environment, adding both additional information and failure-proofing redundancy into the system. Intel makes several stereo vision cameras, including the RealSense D455, which boasts a depth range from 0.4m to 20m.

The cameras listed above can only look in one direction at once. While there may be some overlap in their potential coverage, it will also be helpful to have a camera with an unobscured 360° view of the surroundings. The GoPro Max is incredibly compact, lightweight, and offers 6K video recording capabilities of the entire environment via two opposing wide angle cameras. The addition of this (or a comparable) camera ensures that the rover will have no blind spots and will be able to operate fully autonomously. This camera may also be useful for remote operation or remote troubleshooting.

7.4 Motion Sensors

The rover will have encoders on each wheel as well as several multi-axis inertial measurement units (IMUs) on board to fully understand it's pose and how it has traveled. These will serve in feedback loops for the driving controllers to help ensure the rover drives to exactly where it intends to go. The exact details of these sensing systems depend tremendously on the detailed specifications of the entire rover as well as the control schema, the later of which is out of scope for this project.

7.5 Computing

Autonomous path planning and full utilization of LiDAR + cameras requires non-trivial computing power, certainly more than we've sent to the Moon (or Mars) previously. Modern laptops are fairly capable, and it's possible that a very high end laptop would have sufficient computational power (and speed) to be useful in this scenario. In a slightly larger (and much more power hungry) form factor, a gaming desktop computer with a dedicated GPU, more RAM, and 8+ CPUs is certainly a capable solution to this task. The winning trade off between electrical power and computational capability would depend on the available power, weight, and needs of the system. We assumed that a high end laptop (minus the screen) would be viable for this project (1kg, 61W).

7.6 Communication

The idea of a several 8 hour sorties implies that there will be an established habitat ("Hab") on the moon prior to the arrival of the rover or astronauts. We assume the Hab is well equipped with sufficient radio equipment to communicate with Earth at an excellent speed duplex. The rover only needs to be capable of communicating with the Hab, which would then relay any Earth bound communications in that direction. The rover has a specified driving range of 54km. Assuming the astronauts have to be in the Hab at the end of the sortie, the furthest they can drive is 27km (half of 54km out, and the other half back). Modern smart phones communicate wirelessly over a range of cellular data protocols, most of which are fairly long range and high bandwidth. The smart phone requires very little mass or power to engage in these communications. It's not hard to imagine that a Hab equipped with a cell tower could communicate with the rover in a similar way, and that the communication apparatus in the rover are negligibly small in mass and power. We'll roll these communication mechanisms into the on-board computer.

8 Power

The Hab must be equipped with it's own power supply (nuclear or solar, likely). The rover only needs to carry enough power for an 8 hour day of use, and can be recharged overnight by the Hab.

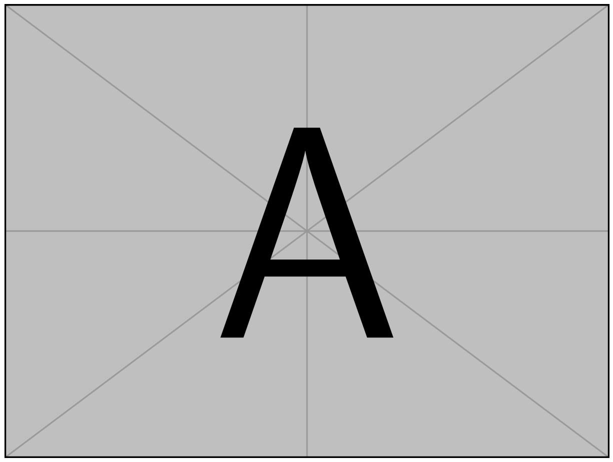

Figure 1: Table showing the total power requirements of the system

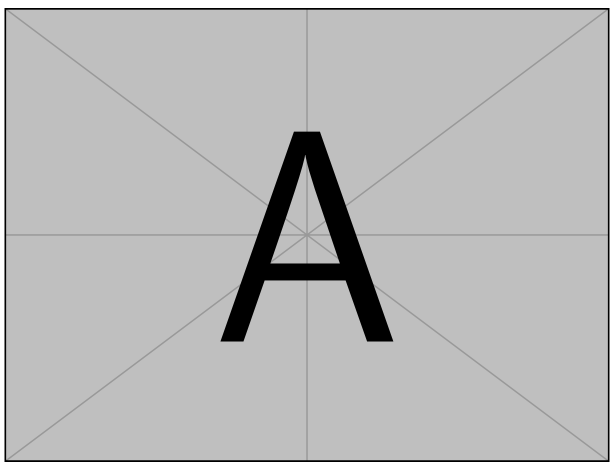

Figure 2: Table showing the total power requirements of the system

9 Mass

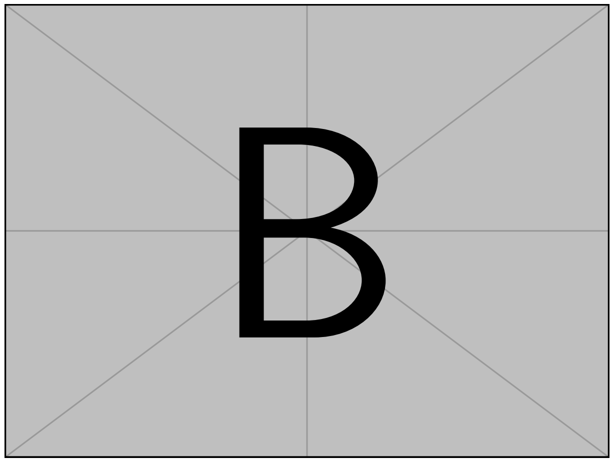

Figure 3: Table showing the mass breakdown of the system

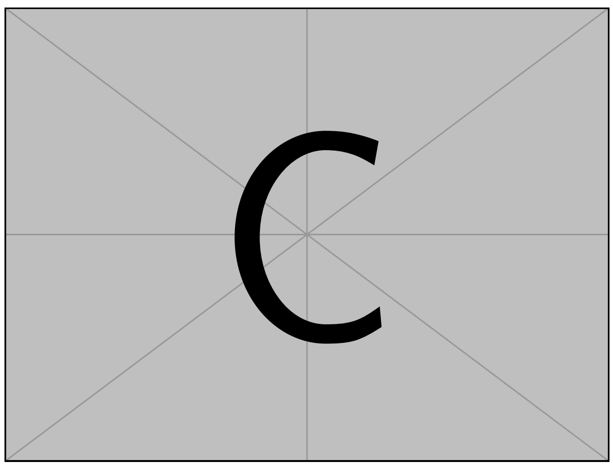

Figure 4: Pie chart showing the total mass breakdown the system

10 Final Design

2nd seat has a traditional 3 point fabric seat restraint to secure the 2nd astronaut. This was done to reduce weight and eliminate the complexity of two rollercoaster style restraint bars.

10.1 Overview

10.2 CAD Renders

10.3 Suspension

10.4 Steering

10.5 Power

10.6 Mass

10.7 Specifications

10.8 Trafficability

10.9 Limitations

10.10 Earth and Mars Efficacy

11 Concepts Explored and Design Evolution

3. "Design is an iterative process. The necessary number of iterations is one more than the number you have currently done. This is true at any point in time.
4. Your best design efforts will inevitably wind up being useless in the final design."
-Akin's Laws of Spacecraft Design

11.1 Inspirational Designs

big wheels, treads, high DoF suspension/leg articulation, treads assemblies instead of wheels

11.2 Mk1 Rover

The Mk1 rover was a preliminary layout prototype. It draws heavily from the Apollo LRV, and features 4 wheels with individual suspension.
incorporates sensor arch, seat restraint

11.2.1 Pros

11.2.2 Cons

11.3 Horsebot

After the midterm presentation, we pivoted away from a traditional car inspired rover and began looking at more novel, bio-inspired concepts. The Horsebot was our next major design concept. It's (as the name implies) a horse inspired design with four 4 DoF legs (there is an additional hip rotation joint that is not shown in Figure 5).

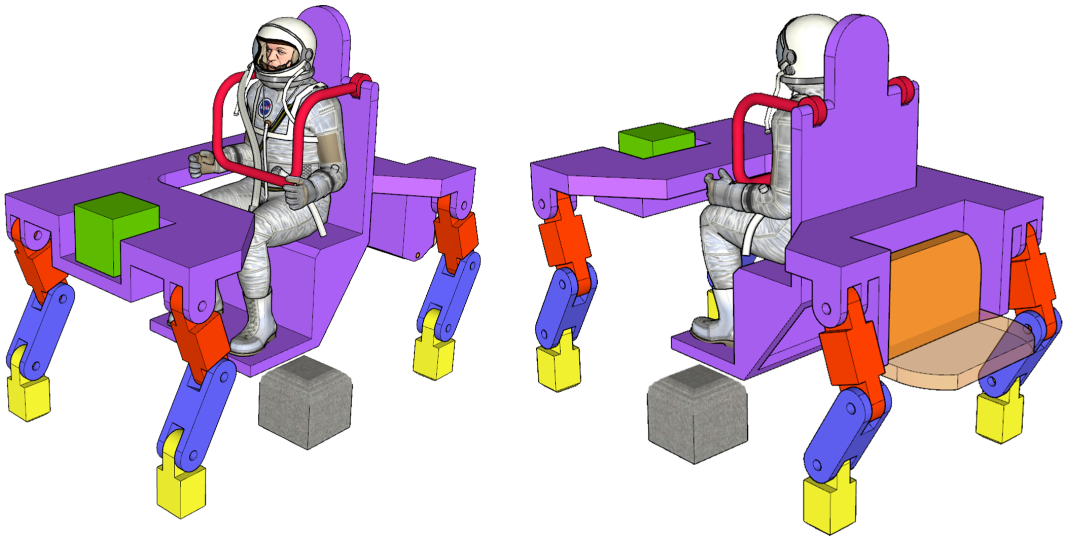

Figure 5: Concept sketch of the Horsebot Design

The green box is our 80kg life support payload (0.25m on a side). There is a fold down seat in the rear for the second astronaut.

11.3.1 Pros

There were a number of benefits to this idea that made it appealing. The tall legged locomotion easily clears any obstacle, and works well on rugged/uneven terrain. The hip joint has an additional 360° hip rotation joint (not shown) which allows Horsebot to walk sideways (or at any arbitrary angle) with its standard ("forward") gait. The incorporation of a second, fold down seat makes it easy to incorporate a second astronaut (this fold down seat is one element of this design that was kept for the final design). The integrated primary seat is strategically positioned to maintain a relatively low center of mass, which is great for stability. (A more directly horse inspired design would have the rider atop the vehicle; much higher up). Ingress and egress in this design are very easy. The right side of the vehicle is open to allow the astronaut to enter with ease, and the entire system can "kneel" (lower itself closer to the ground) to allow the astronaut to simply step onto the foot rest (level with or close to the ground)

11.3.2 Cons

While there are several legged locomotion robots (ex: Cheetah, Spot, ANYmal) in various stages of development, we do not yet have a robotic horse analog on Earth. Robotic legged locomotion with a human passenger is not a well tested concept, and should be proven feasible on Earth first before it is attempted on the Moon.

By their nature, legs are more complex than wheels (ignoring suspension) and therefore offer more avenues for failure. Unlike a wheeled vehicle, which requires 2 motors per wheel (driving and steering), this Horsebot design requires 4+ actuators per leg (for 16+ actuators), which significantly increases the total weight of the system and it's required power. Additional Degrees of Freedom, such as one for hip abduction and another for ankle pronation, might be required for walking on slopes.

The project details require that the rover be capable of a max speed of 4m/s. This speed would require a medium trot or a slow gallop gait, which are only dynamically stable. Trot/Gallop gaits require much faster and higher torque motors, which then drive up the weight and power. An Earth gallop gait is likely not directly reproducible in the 1/6th gravity of the moon.

11.4 Wheeled Horse

The wheeled horse concept is similar to the Horsebot shown in Section 11.3, but includes wheels (mounted on either the ankles or knees) for a reconfigurable driving configuration. Obstacle avoidance would be done at slow speeds with a walking gait, while normal (higher speed) travel on smooth ground would be done with the wheels. This reduces the need for high speed/torque motors for a gallop/trot gait, but requires an additional motor for each wheel. The leg motors act as electromechanical suspension in driving mode. The added complexity and weight of the wheels and their driving motors makes this idea less practical than either a traditional wheeled rover or the original Horsebot.

11.5 Strandbeest

While exploring options for legged locomotion, we briefly evaluated a series of designs inspired by Theo Jansen's Strandbeests and other similar designs. These designs allow for complex leg articulation with very few motors, and can be made to be fairly lightweight. However, the legs have very high mechanical complexity, which offers many different failure modes. Many of these designs are well tested on sand, but few (if any) are well tested on rugged/uneven terrain, and they are largely incompatible with stair climbing due to their leg lengths.

11.6 6 Wheels with Extendable Chassis

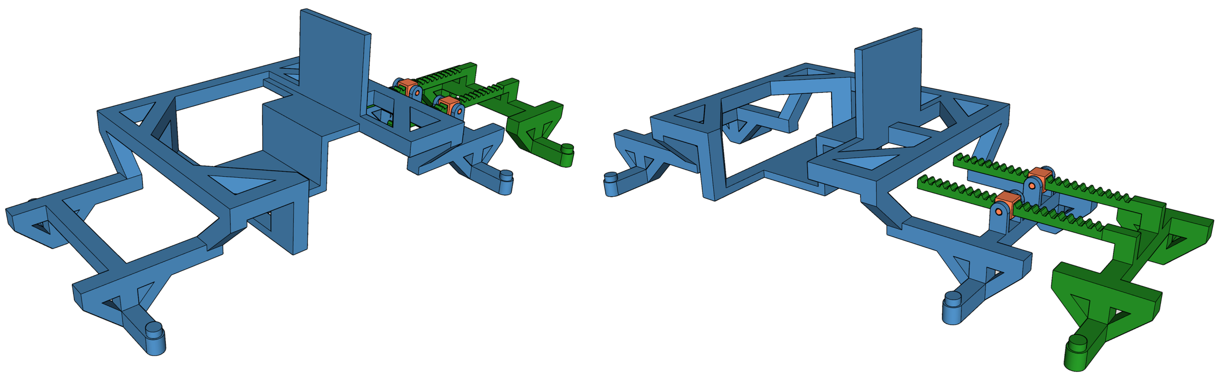

Figure 6: Concept sketch showing the 6 wheeled rover (wheels not shown) with a pivot (orange) rack and pinion (green) extender mechanism

11.6.1 Crank Actuated Extension

11.7 6 Wheels, Chassis Arch

11.8 4 Wheels, Chassis Arch

11.9 4 Wheels, Flat Chassis - Final

Appendices

A Future Work

With additional time and resources, there are a number of additional design improvements that we'd like to explore. While we believe our suspension system (as designed) satisfies the project requirements, having a larger, more robust suspension would empower the rover to handle larger obstacles and more uneven terrain.

The pivot aspect of the rear chassis extender mechanism poses a nontrivial safety risk. The potentially rapidly moving rear extender beams could pinch/crush or otherwise injure an astronaut's fingers/toes or other extremities. To mitigate this issue, we propose a safety covering or sheath around the extender beams. This covering would extend from the floor to the maximum height of the beam, and could be made of plastic or metal, and be either solid or cage-like.

While it is easy to step into the front (primary) seat, the higher geometry of the rear chassis makes entering the 2nd seat much more difficult, especially in a stiff legged EVA suit. The easiest way to enter that seat would be via a fold out set of stairs on the rover side (either left or right) that would give the 2nd astronaut smaller steps to climb up.

We expect that a more rigorous structural analysis of the chassis design would result in improved strength and decreased weight of the structure. It's likely that an exploration of advanced manufacturing techniques (ex: Direct Metal Laser Sintering) combined with computational design methods (FEA, Topology Optimization) could produce chassis geometries with an even greater strength to weight ratio.

A future version of this chassis design should incorporate cargo/stowage space for samples and tools.

B CAD and MATLAB

The entire works related to this project are accessible via our Github page: https://github.com/BrianBock/ENAE788x_Project
You can view our final presentation and associated videos/animations/renders at https://drive.google.com/drive/folders/113_eTfvzxWGKhZmb-tjgHEhFOzATDLpB?usp=sharing

C References

[1] D. Akin, “Lecture 6: Terramechanics,” September 2020. [Online]. Available: https://spacecraft.ssl.umd.edu/academics/788XF20/788XF20L06.terramechanics1x.pdf

[2] ——, “Lecture 7: Terramechanics,” September 2020. [Online]. Available: https://spacecraft.ssl.umd.edu/academics/788XF20/788XF20L07.terramechanics2x.pdf

[3] ——, “Lecture 11: Akin’s Pocket Guide to Terramechanics Analysis,” October 2020. [Online]. Available: https://spacecraft.ssl.umd.edu/academics/788XF20/788XF20L11.stabilityx.pdf

[4] Velodyne, “Velodyne Lidar Puck LITE; Light Weight Real-Time Lidar Sensor,” 2019. [Online]. Available: https://velodynelidar.com/products/puck-lite/