# Design, Fabrication and Testing of Lander Ram for Rover Egress

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## Abstract

Rovers must egress from their Landers for the success of planetary surface missions. Deployment of egress systems presents many challenges, complicated by uneven Lunar terrain and unpredictable Lander tilt. This paper details the process of designing and fabricating Lander ramps that enable rover egress. The resulting ramps are a compact, deployable, two-segmented design made from 5052 aluminum alloy. A scalable CAD design is produced, stress analysis is performed on the model, and MATLAB simulations of motion and theoretical joint torques during egress are generated. The ramps are designed, analyzed, fabricated, assembled, and tested for deployment success. Ramps are attached to the Lander in order to test rover egress in worst-case Landing scenarios. Future work will be to fabricate space-ready ramps and make design changes based on test plan results. This project has been successful as a proof of concept for deployment kinematics and design feasibility as well as providing a visual impact on the existing Lander structure.

## 1 Introduction

Lander ramps are required to enable safe and reliable egress of planetary rovers from their Landers. Flawless egress of rovers is critical to mission success. If ramps fail before or during egress, missions fail.

The goal of this project is to further the design of Astrobotic's Lunar Lander by implementing a reliable egress system. The egress system must be low-mass and deploy reliably on uneven terrain. The ramps must also integrate into existing Lander design, be compact, relatively low mass, low cost, and machinable. Ramps will be implemented on the Lander and can be used for deployment and egress testing.

Ramps were designed, prototyped, and tested to ensure that they meet requirements. The current design acts as a demonstration unit for egress concepts, and is used to implement a deployment and egress reliability test plan.

A number of designs were generated, sketched, and compared in a Pugh Chart. The segment design received the highest score. Crucial design considerations are specifications for uneven terrain, stress, and launch dynamics, reliability, compactness, and relative ease of production. Ramps are a good way to egress because they can be optimized for low mass and high strength, require no power for deployment, can be accurately simulated and analyzed, and can be designed such that egress is possible on rough lunar terrain.

The design uses a four bar linkage actuated by two linear springs. A four-bar linkage prototype demonstrating the design feasibility was also created. The design can be scaled for varying material thickness, channel height, and segment length. Therefore the egress design was analyzed for stresses and buckling of ramp platforms, and dimensions were optimized accordingly. Software simulations were also generated to approximate required joint torques which are necessary to spec actuation devices. Manufacturing drawings were produced and the ramps were fabricated using Water Jet technology.

A test plan was developed to study egress and deployment reliability and success in both worst-case and likely conditions. Ramp deployment reliability will be analyzed by noting deployment accuracy, deployment time, geometric constraints, and impact force. Egress reliability will be analyzed by performing egress of small-scale rovers to simulate Lunar and worst-case Earth conditions.

Ramp design will be successful if the ramps are designed, analyzed in MATLAB for theoretical motion and joint torque during, analyzed in CAD software for stresses, fabricated, assembled, and tested for deployment success. The ramps have been successfully designed, analyzed, and fabricated.

Future work includes making all components out of space-rated materials. The egress design may also be updated to resolve any design problems discovered from analyzing test plan results.

## 2 Prior Work

Most unmanned exploratory missions involve a Lander egress system consisting of ramps or a platform lowered from the Lander to ground. Situated on the top of the Lander, the rover proceeds down deployed ramps in a series of sometimes complex maneuvers. Lander egress systems for the Soviet Lunakhod Lander and systems on NASA Mars exploratory missions both offer solutions. Designed by the Soviets, the Luna Ye-8 deployed the first egress ramps on the lunar surface. The Luna Ye-8 had a dual ramp system with two collapsible sections per ramp. The egress system is unsuitable for missions with tight mass constraints because it is heavy and bulky. The NASA Mars Pathfinder mission used a different egress system and carried the rover Sojourner. The Pathfinder lander used two flexible deployable ramps that were located on opposing sides of this lander. These ramps were made out of two stainless steel rails connected by aluminum battens and a lightweight Kevlar mesh. The entire system was unrolled after the Lander's airbags were deflated. In the Mars Exploratory Rovers Mission, the egress phase used small Vectran cloth ramps that folded out over the Lander petals to create a strong, smooth driving surface.

Two proposed Astrobotic solutions are a segmented hinged-ramp and telescoping ramp concept; both would be deployed using a Frangibolt, a non-explosive actuator. The non-explosive actuator works by applying a voltage to a shape-memory alloy cylinder. This heating causes the material to elongate and fractures a bolt, which forces two components to separate.

Figure 1: Soviet Lunakhod, Mars Pathfinder, Mars Exploratory Rover Missions (left to right)

## 3 Methodology

After research into ramp requirements and space constraints was completed, a number of designs were proposed. Proposed designs varied from novel and untested ideas to designs mimicking existing ramp concepts. These designs were compared in a trade study with considerations for important requirements such as weight, reliability and low power of operation. The optimal designs were chosen using these parameters. Design and fabrication was initiated for the segmented ramp design.

The CAD final model includes extensive detail for all hinges, deployment mechanisms, and ramp segments. Manufacturing capabilities were considered in the design of machined components. Accurate images showing feasible geometry and deployment were generated. Additionally, MATLAB simulations showing design geometry and required joint torque were produced. Ramp strength was simulated using Solidworks software and ANSYS. The ramp design was constantly updated based on strength and motion simulation results.

Detailed manufacturing drawings were generated from the final CAD model. A bill of materials, including cost estimation, was proposed. Components that required no fabrication were ordered and parts that required basic fabrication were machined. Sections with complex cut-outs were outsourced to facilities with appropriate machinery. After post-processing and additional manual machining, all components were assembled into the final ramp structure.

After initial deployment testing to ensure functionality and safety, the ramp structure and ramp support structure was integrated into the lander. In addition to visual impact, accurate egress and deployment tests can be run. A rough deployment reliability and egress test plan was proposed.

## 4 Design Considerations and Analysis

### 4.1 Design Selection

A number of design options were proposed based on ramps used on the Mars Exploration Rover Mission, Mars Pathfinder Mission, Soviet Luna Ye-8, previous Astrobotic work, and other novel ideas. The designs were compared in a Pugh Chart where the parameters most important to mission success are weighted more heavily.

### 4.1.1 Requirements

Preliminary research of basic requirements and space constraints, including launch dynamics, vacuum space flight requirements, temperature variation, and material selection was completed.

#### 4.1.1.1 Launch Dynamics

Table 1: Static Loading

| | Min | Max |
|---|---|---|
| Axial | –2G | +6G |
| Lateral | –2G | +2G |

Table 2: Dynamic Loading

| | Min | Max |
|---|---|---|
| Load | 20G at 100Hz | 3000G at 2000Hz |

Table 3: Center of Gravity Lateral Offset

| | Max |
|---|---|
| Spin Stabilized Mission | 0.5in |
| Non-Spin Stabilized Mission | 5in |

Design load factors from the Falcon 9 can be found in Figure 2.

Concerning vibrations, fundamental vibration modes must not couple with the Falcon 9 rocket, or damage to the rocket and spacecraft can occur. Damage from flight and landing loads cannot preclude ramp deployment or rover egress.

#### 4.1.1.2 Vacuum Space Flight Requirements

High voltage charge can accumulate on the spacecraft from voltage potential over non-conducting (composite) surfaces. Uncontrolled discharge of this voltage can damage the surface of the spacecraft. Spacecraft contamination can also come from polymer erosion and out-gassing if ultraviolet radiation damages the spacecraft material. Additionally, surface disturbances can cause cold welding. Cold welding, a materials property by which two surfaces are bonded without heating, can happen when the surface is stripped of an oxidation layer.

#### 4.1.1.2 Temperature Variation

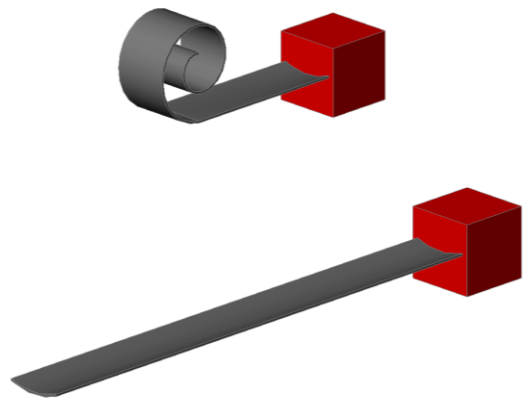
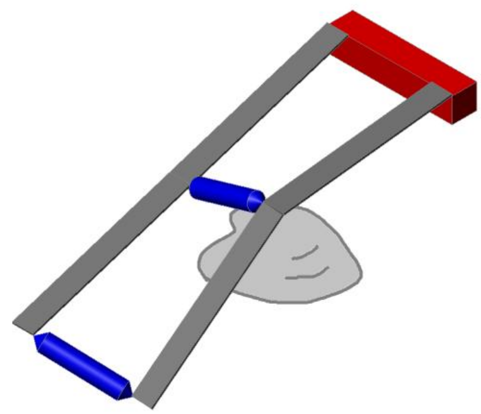
The vacuum of space presents a unique challenge in terms of temperature control. Heat transfer is limited to radiation. As such, spacecraft components are sensitive to material selection, surface finish, and color. It is important for the final ramp design to consider temperature influences. For the first prototype, painted aluminum is sufficient.

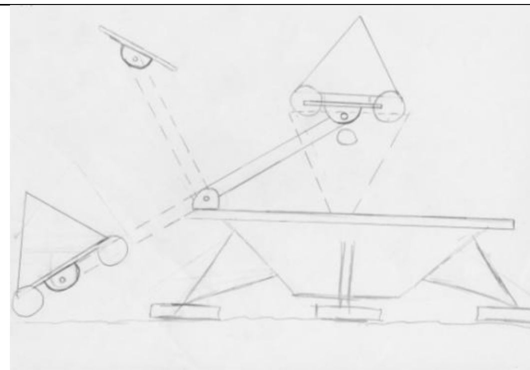
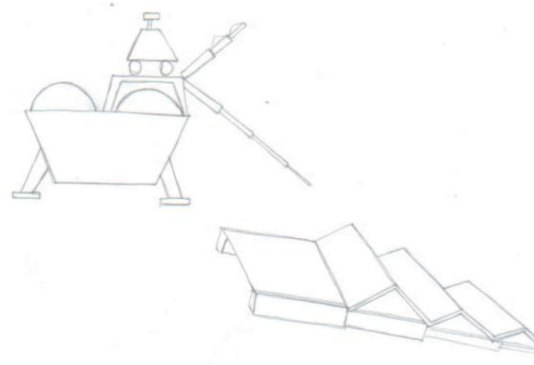
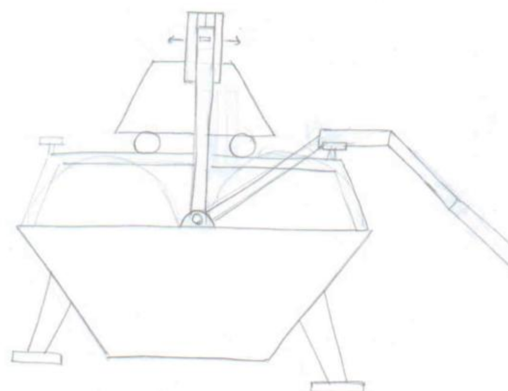
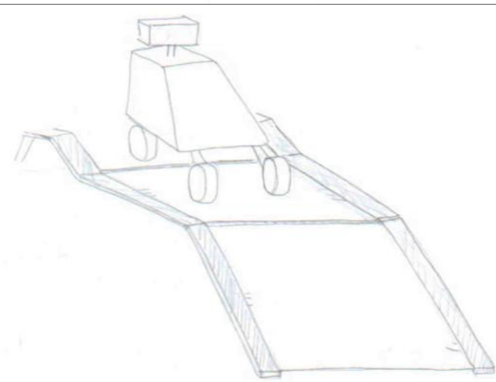
Temperature variation during mission time (pre-launch to lunar day) is found in Figure 3. Thermal regulation is accomplished only through radiation. Figure 4 shows heat transfer dynamics in the system.

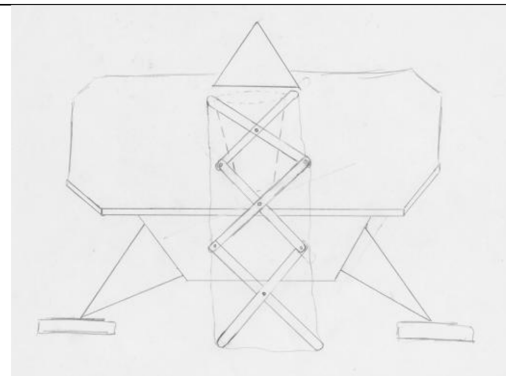
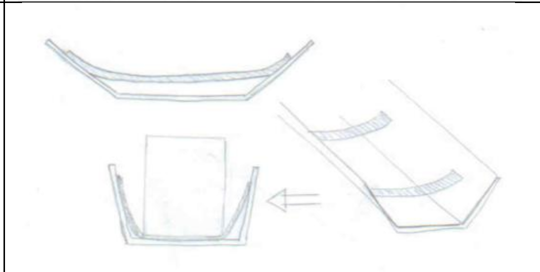
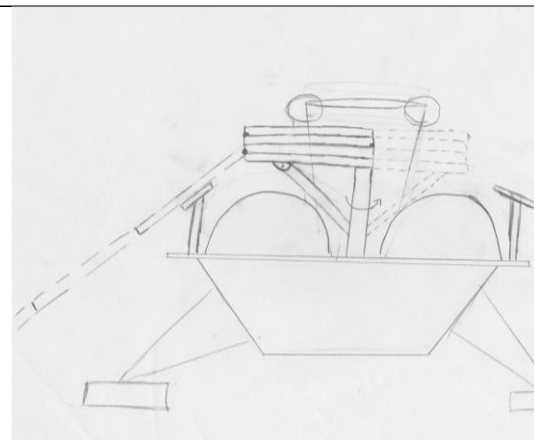
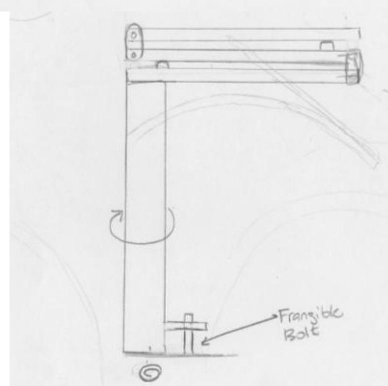
#### 4.1.1.2 Materials Selection

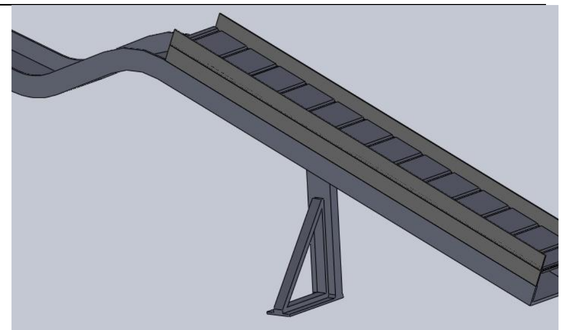
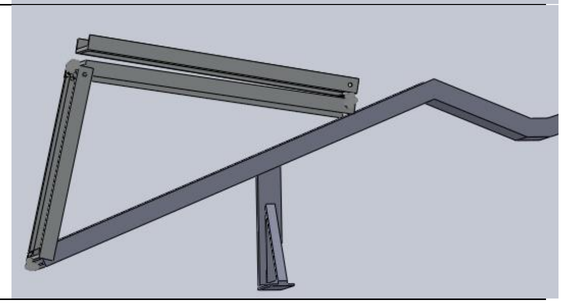
Material properties were used to compare Aluminum, Titanium, and Composites. Results for thermal expansion, thermal conductivity, emissivity and absorptivity are found in Figures 5-7. Aluminum was chosen because of its cost and strength to weight ratio. To reduce weight, composites will likely be selected for the final ramp design.

### 4.1 .2 Preliminary Design Concepts

| Design Concept | Description | Sketch |
|---|---|---|
| Roll Up | The design would "roll up" using a soft material. Final positioning would "lock" the material so the rover could safely egress. |  |
| Rope Ladder | If the segments are connected, ground disturbances like rocks and holes can have a less significant effect. |  |

| | | |
|---|---|---|
| Rotating Arm | The main arm in this concept would be fastened to a pivot at the Lander edge. The arm would rotate, thus allowing the rover to be lifted off of the Lander. The dynamics in this system could be difficult to model accurately. Additionally, this design would likely be very heavy because the weight is located at the arm ends, vastly increasing moments. |  |
| Shower Curtain | The design is similar to the telescoping concept, but creates one large ramp. Although light material could be used, the design will likely be heavier than other concepts and cannot work well with large rocks and holes. |  |
| Rotating Segment | Only one ramp set is built. The ramp deploys based on which side of the Lander has the best egress conditions. Deployment dynamics could become too complicated because joints would need to lock and move in both directions, depending on the chosen side. |  |
| Tension Assembly | The concept uses the segmented ramp design in addition to a mesh or lightweight cloth material between the ramps. Ideally this would assist in rough terrain egress conditions. However, the design would be difficult to fit on the Lander compactly. |  |

| | | |
|---|---|---|
| Scissor Lift | A scissor ramp would function like a typical scissor lift. The design would have high manufacturing complexity because of the large number of moving parts. It would also be very heavy and potentially unstable over large Lunar rocks. |  |
| Ramp Chute | This concept could be implemented in any ramp design with a side. As the rover moves over inner bands, the sides compress ensuring it doesn't fall or drive off of the ramp. |  |
| Dual-Direction | The design would be a segmented ramp that deployed in the direction with best egress conditions, Implementation of the Frangibolt release mechanism is shown in the lower image. A second Frangibolt could be added to release a torsional spring, rotating the ramp to the opposite direction. Rotating the ramp solves the problem of needing complex deployment dynamics as in the “Rotating Segment” design. However, this design also requires a robust system of judging egress conditions (rocks and holes) and is therefore not as reliable as the single-direction design. The main advantage is weight reduction. |    |

| | | |
|---|---|---|
| Telescoping | The telescoping concept from previous Astrobotic work. The design could be complicated to construct because of multiple sliding parts. It might also be difficult to egress over rocks since it cannot bend. |  |
| Segmented | The segmented design is discussed in section 4.2. |  |

### 4.1.3 Selection

The designs listed in 4.1.2 were compared in a trade study Pugh chart.

| | Weight | Segmented Ramp | Telescoping Ramp | Dual Direction Ramp | Roll-up | Rope Ladder | Tension Assembly | Shower Curtain | Ramp Chute | Scissor Arm | Rotating Arm |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Low Cost | 2 | D | -1 | 0 | -2 | -1 | -3 | -2 | 0 | -2 | 0 |
| Ease of Manufacture | 3 | A | -2 | -1 | -3 | 0 | -3 | -2 | 0 | -2 | -2 |
| Low Mass | 4 | T | -1 | 2 | 2 | 0 | 1 | 1 | 1 | -1 | -1 |
| Deployment Reliability | 5 | U | -1 | -2 | -4 | -1 | -4 | -1 | -3 | -3 | 0 |
| Few Friction Points | 3 | M | -2 | 0 | 1 | -1 | -1 | -3 | -3 | -3 | 0 |
| Compact | 2 | D | 1 | 2 | 2 | 0 | 2 | 1 | 1 | 1 | -2 |
| Easy Integration | 2 | A | 1 | -2 | 1 | -1 | -2 | 0 | -1 | -1 | -2 |
| Simplicity | 3 | T | -1 | -1 | -3 | -2 | -3 | -2 | 0 | -2 | 0 |
| Low Power Operation | 1 | U | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | -1 |
| Aesthetics | 1 | M | 1 | 2 | 3 | 0 | 0 | 2 | 1 | 3 | 2 |
| Compliance to Uneven Terrain | 5 | D | 2 | -1 | | | | | | | |
| Total | | 0 | -11 | -10 | -21 | -18 | -42 | -22 | -19 | -40 | -17 |

Figure 8: Design Comparison Chart

The designs that preformed the best in comparison were the segmented ramp and the telescoping ramp. Using first iteration weighting (not shown), the dual-direction ramp also scored highly. Although the segmented dual-direction design reduces weight considerably, it is far less reliable. In a second analysis of design choices (Figure 8), more categories were given to reliability: one for deployment and the other for landing on uneven terrain. It is imperative to the mission that the ramps deploy reliably and the rover can safely egress. Therefore deployment reliability and compliance to uneven terrain are the most important and highest weighted factors.

## 4.2 Segmented Ramp Design

The segmented ramp design was chosen because it has high deployment and egress reliability, low mass, and has a comparatively high ease of manufacture. The design can best be completed within constraints. Note that the telescoping concept will be investigated in future work.

The design has two segments per ramp, attached to the static mid-section segments. The mid-section (M-shape) of the ramps supports the rover before egress. These segments are supported by tubing. There are two segments connected by a four bar linkage. Because the four bar linkage is fastened to both segments, actuating one segment moves both parts. A compressed linear spring is used as an actuation method. The spring is held in a compressed state before deployment by fastening the segments together with a plate and Frangibolt setup.

### 4.2.1 CAD Model

Extensive CAD modeling was completed to ensure components are accurate and have required strength. Views of the Solidworks model are shown. The CAD model was constructed such that basic dimensions (thickness, length, etc) of the segments can be changed without damaging other parameters. This scalable model will be particularly useful in future iterations of the design if dimensions or materials are changed. The final assembly including a model of the Lander is found in Figure 9. A model of the ramp design is found in Figure 10.

Ideally the static segments (components held by tubing that hold the rover before egress) will be curved. For ease of manufacture they are constructed with flat segments.

The segment cutout pattern in Figure 13 was designed to reduce ramp weight. The segments underwent multiple iterations in order to ensure a sufficient strength while reducing weight. Additionally, the segments are flanged and joints in Figure 11 are designed to increase strength and stability.

### 4.2.2 Strength Analysis

Strength testing was completed in both Solidworks and ANSYS. Earth gravity is used so the ramps will not fail during demonstrations and testing.

Results, using Aluminum 5052, yielded a factor of safety of about 3. Software simulations of ramp strength show that the ramps can theoretically support a 110kg rover during egress. This result will be validated in testing.

### 4.2.3 Egress Simulations

Motion simulations were run in CAD software and MATLAB to find moments on the segments during ramp deployment.

Initially, the spring mechanism proves actuation. The spring force and inertia of the moving ramp segments will drive motion until it reaches just over 70 degrees (Figure 20). At this point, inertia and gravity deploy the ramps to the Lunar surface.

### 4.2.4 Design Feasibility

By building Aluminum ramps, a number of objectives are met, including enabling demonstrations of Rover egress and testing of rough surface terrain. However, the practicality of using the design also depends on strength and expected performance of the ramps using intended (composite) space-rated materials. Strength simulations were run in ANSYS using composite material to show that the ramps will not fail. Also note that testing using earth gravity adds an additional factor of safety for the final ramps.

Results of the composite testing show a factor of safety greater than 2 with a weight of 2.25kg. This result indicates that all four ramps would weigh under 9kg. This number does not include the static support structure or joints. But it should be noted that the ramp was tested without the weight-reducing cut-out pattern. A greater knowledge of composite manufacturing is needed before the analysis in Figure 22 is satisfactory (an arbitrary layup was used which will affect strength).

# 5 Segmented Ramp Fabrication

After materials were ordered, fabrication of the ramps was completed using a complex machining process. Ramp segments were made using a combination of computer and numeric control (CNC), water jet technology, and manual machining. Proper alignment of the ramps was imperative to assembly accuracy, and both assembly of ramps segments and support structure was achieved by drilling and machining while components were fastened in place.

## 5.1 Manufacturing

A bill of materials was generated for joint components and fasteners. Due to cost constraints, the cut-out pattern was only done for the moving segments. Moving segments and most joints were machined using a water jet. (Figure 32) Static segments and remaining joints were cut using a combination of the CNC (Figure 33) and hand machining. Flanges and sheet metal bends were completed by first testing for accuracy of the bend.

### 5.2 Final Components

Final components are found in Figures 26-29. Final components include all joint parts, ramp segments, and brackets for assembly and Lander integration. The segments were assembled by fastening one bracket to a segment and machining attachment points at accurate locations on the second segment. Joints and brackets were also assembled using this method, which provided high alignment accuracy.

### 5. 3 Lander Integration

Integration of the ramps onto the lander has begun. The integration procedure requires many discrete steps including part fabrication, alignment, and final assembly. All parts for the support structure have been produced and are awaiting assembly. A wooden alignment jig has also been produced to ensure proper positioning of the ramps on the lander. Lastly, assembly has commenced and will completed by the end of the semester.

## 6 Testing

Ramp testing is critical to insure ramp performance reliability. Initial testing has been completed. A thorough test plan has also been developed for future testing to more comprehensively test the performance of the ramps.

### 6.1 Initial Testing

Initial testing has been completed on ramp deployment kinematics and reliability. The ramps were released from the retracted position and landed within a one foot diameter landing zone (Figure 37). This procedure was repeated over 50 times with no failures.

These tests determined the optimal number of springs to use to insure successful deployment while not damaging the deployment mechanism. It was determined that six springs are necessary to actuate the ramps which is twice number suggested by theoretical models. This is likely due to un-modeled friction in the joints. Because the extent of frictional effects could not be predicted, the actuation mechanism was designed to be adjustable for higher than expected amounts of friction.

It was determined that the ramps are sufficiently strong to support he mockup rover. The rover was then set on top of the deployed ramps at varying locations (Figure 38). There were no ramp failures or notable deflections in the ramp structure.

The current design does employ purposeful damping. All damping comes from incidental frictional resistance in the joints and spring lever arm (Figures 34, 35). Purposeful localized damping in the joint can be implemented during the part of deployment that is actuated by inertia. A successful frictional damping system would only be employed after the motion-activating springs are compressed. Because frictional effects cannot be noted in modeling software, this result is a direct consequence of developing a prototype.

### 6.2 Test Plan

A more in-depth test plan is also required. The test plan is divided into two categories: deployment reliability, and egress reliability. The test plan is summarized below.

#### 6.2.1 Deployment Reliability

<u>Successful Deployment:</u> Deploy the ramps at varying angles to find the range of successful deployment. Test for all cases with large rocks and holes, shown in Figure 30.

<u>Landing Accuracy:</u> Deploy the ramps at varying tilts on the Lander to understand if and how landing location changes.

<u>Deployment Time:</u> Record deployment and landing times.

<u>Geometric Constraints:</u> Track deployment geometry by deploying with a black and white grid and camera system. CAD simulations can be verified using sketches (Figure 31).

<u>Impact Force, Stress/Deflection:</u> Note bending during deployment and at landing. It is possible find impact force by setting up a pre-calibrated load cell with an outer plate to “catch” the ramp.

#### 6.2.1 Egress Reliability

<u>Successful Egress:</u> Egress using test (small-scale) rovers.

<u>Stress/Deflection:</u> Note deflections in the ramp segments during egress.

<u>Wheel and Ramp Interaction:</u> Note slipping of wheels and or difficulty driving the rover at varying Lander angles.

## 7 Conclusion

The greatest result of ramp design and testing is the development of two functional, deployable segmented ramps. The ramps are mechanically actuated by springs and meet all major design requirements including compactness, manufacturing capability, target weight, strength, and deployment reliability.

A great amount of insight into ramp design was gained by successful completion of the ramps initial testing. Firstly the design phase was longer than expected. This change was largely due to in-depth analysis of theoretical ramp capabilities, and ensuring that every component could be accurately manufactured and assembled.

Additionally, there existed a number of unpredictable manufacturing discoveries. These included difficulty in proper segment alignment, and the existence of friction during all stages of deployment. Frictional effects were expected in the design but the extent is not determinable using CAD modeling. Therefore two types of springs (varying length and constants) were ordered. It was discovered that the stronger springs are required and double the number of springs that were predicted. Frictional damping is also inherent in the system. Later iterations in the design may consider building this damping method into the joints intentionally.

Building the ramps gave insight into manufacturing methods and potential problems using various manufacturing techniques. The most significant was the discovery that using water jet technology caused some of the aluminum brackets to become delaminated. This problem was fixed by adjusting water jet settings, and damaged parts were fixed by filing.

Most importantly, the success of ramp construction was a proof-of-concept of the two-segmented ramp design. The design aimed to test the bounds of feasible design possibilities. The design is novel in including two actuation stages - the first by springs and the second by gravity on the ramps and inertia from the first stage. Although the ramps were modeled based on working designs from successful Lunar missions, the outcome of the current concept was unknown and required assembly and successful testing. The main result and success of the project are working ramps that can be integrated onto the Lander, thus allowing egress and significant visual impact. Implementation of the concept proves both feasibility and success of the two-segment ramp design.

# 8 Future Work

The test plan must be implemented before the large-scale rover can attempt egress. Vibration testing must be done in ANSYS. Additional composite testing is required and the entire ramp structure must be built from composites and space-rated materials. The design should also be optimized to increase stiffness and reduce weight, and updated based on test plan results. Additionally, a damping mechanism must be implemented.

## 9 Acknowledgements

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Alex Long (Field Robotics Center)
Eric Meyhofer (National Robotics Engineering Center)
Richard Musgrave (National Robotics Engineering Center)
Ed Wojciechowski, John Fulmer, Jim Dillinger (ME Machine Shop)


## 10 References


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**[6]** Ramp Deployment Simulation
http://astrobotictech.com/


Google
LUNAR
X PRIZE
Carnegie Mellon University

# 11 Appendix

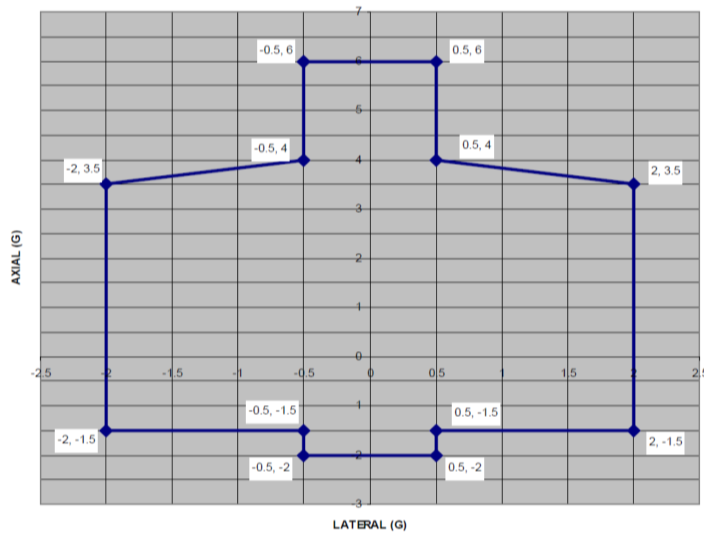


Figure 2: Falcon 9 Design Load Factors

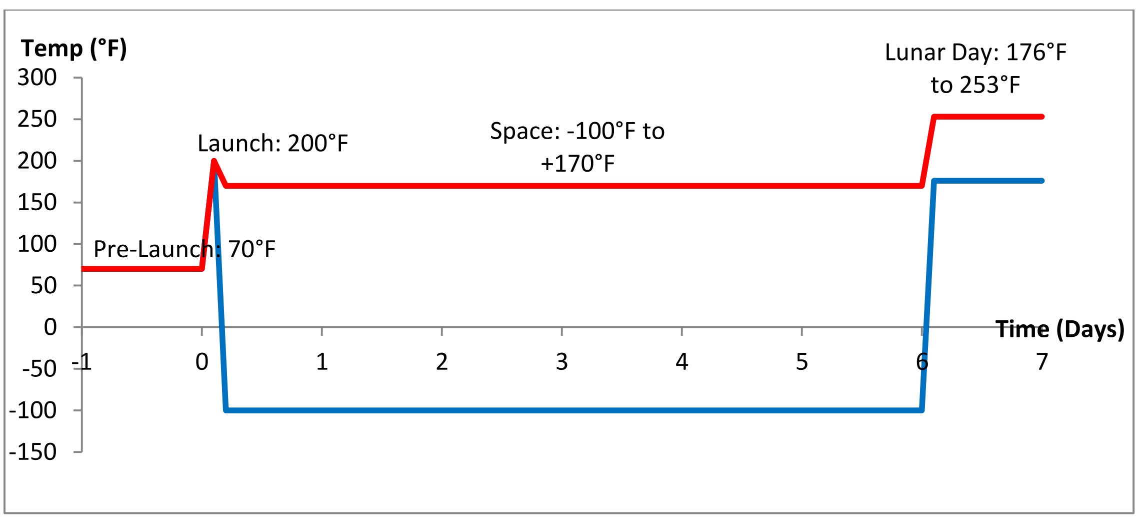


Figure 3: Temperature variation during mission time

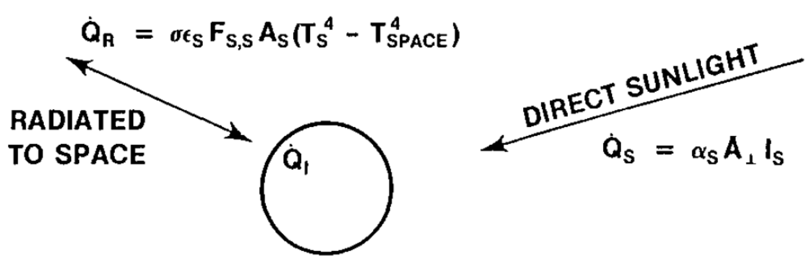


Figure 4: Heat Transfer Diagram

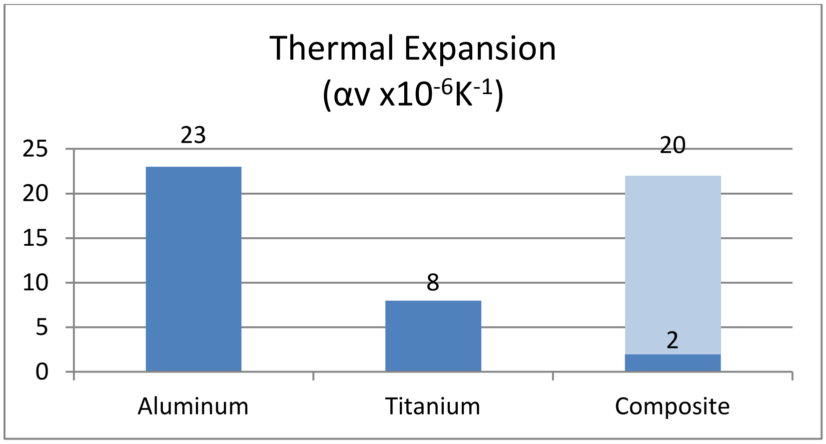



Figure 5: Thermal Expansion

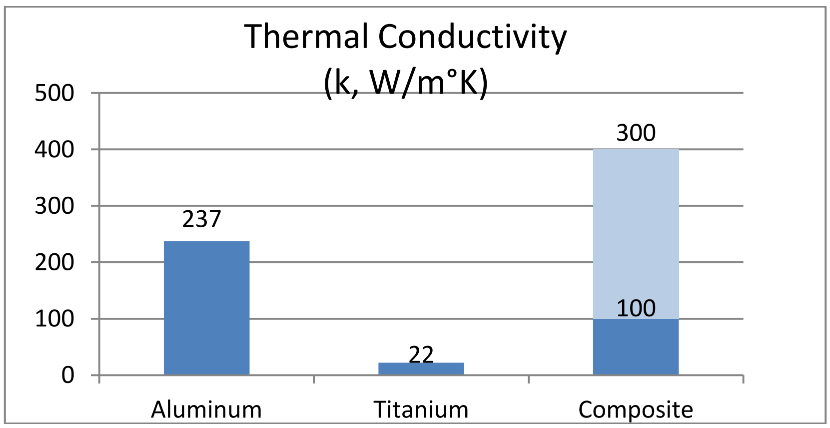



Figure 6: Thermal Conductivity

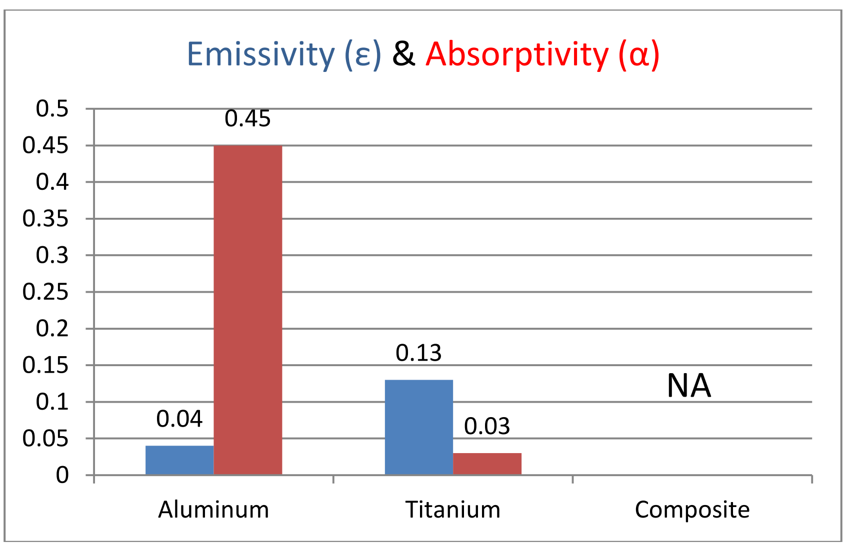



Figure7: Emissivity and Absorptivity

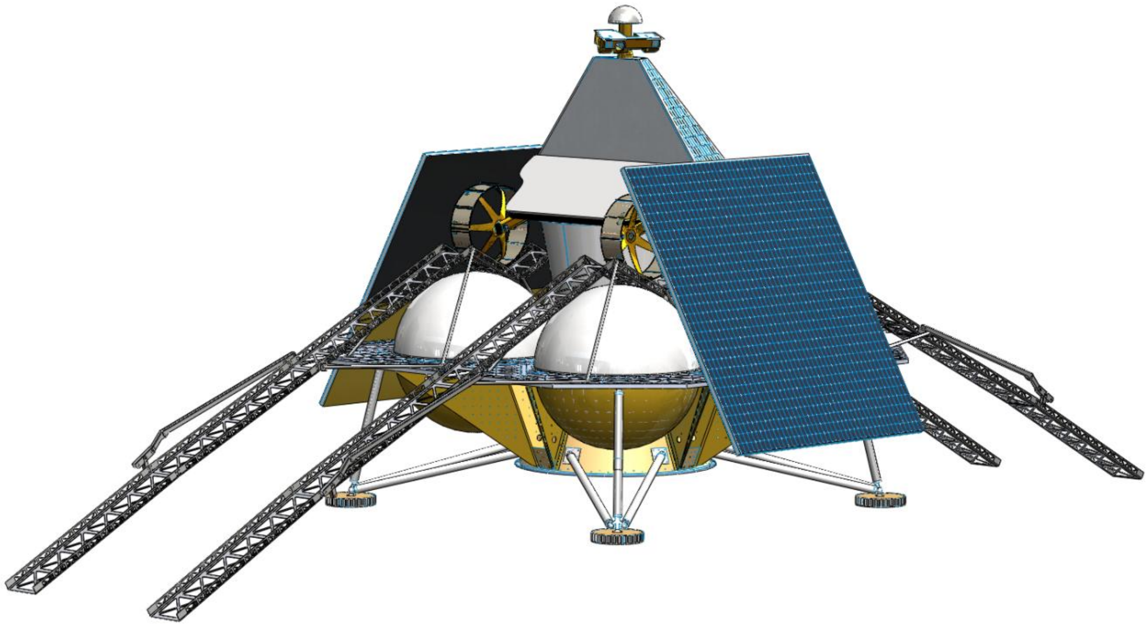


Figure 9: Full Lander and Rover Assembly

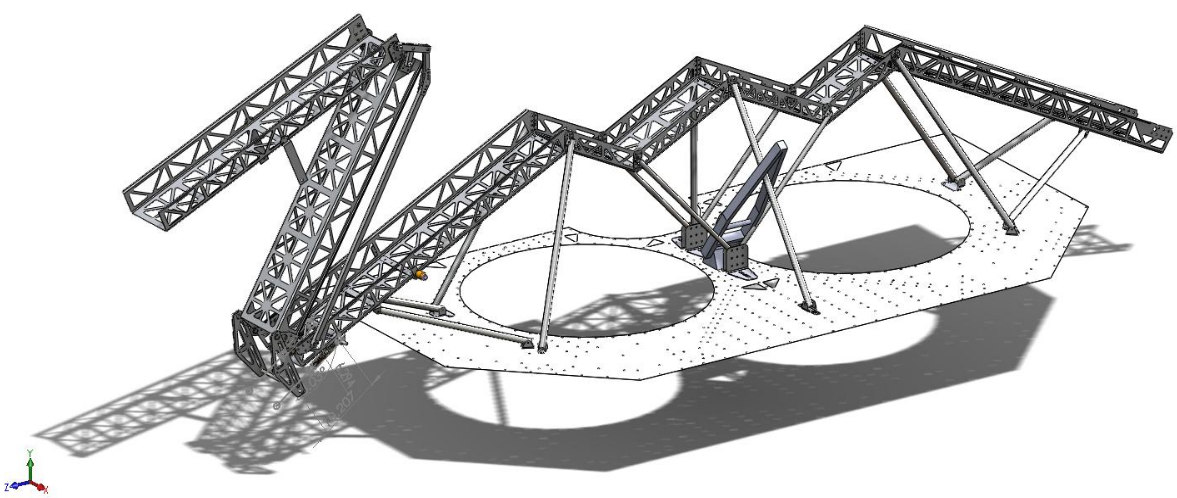


Figure 10: Segmented Design on Lander Platform

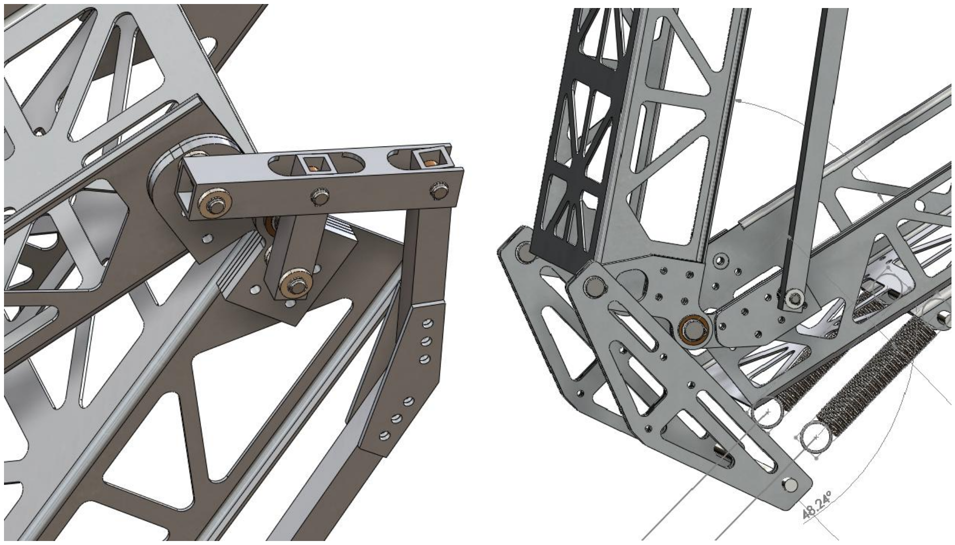


Figure 11: Segment Joints

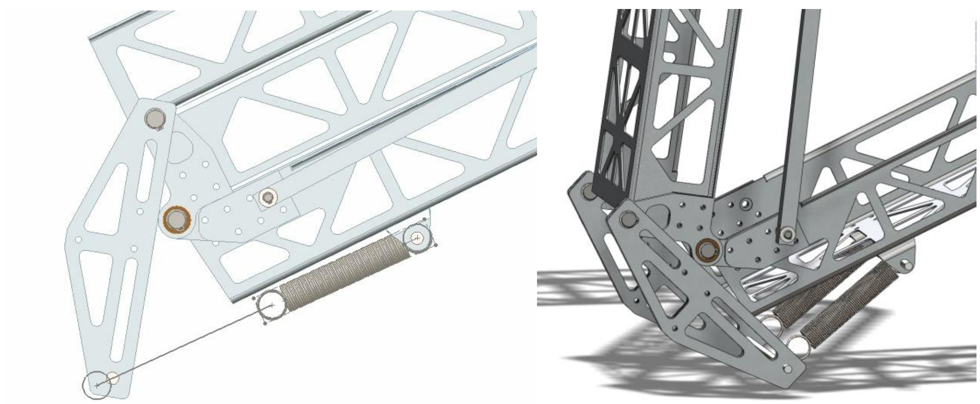


Figure 12: Spring Deployment Mechanism

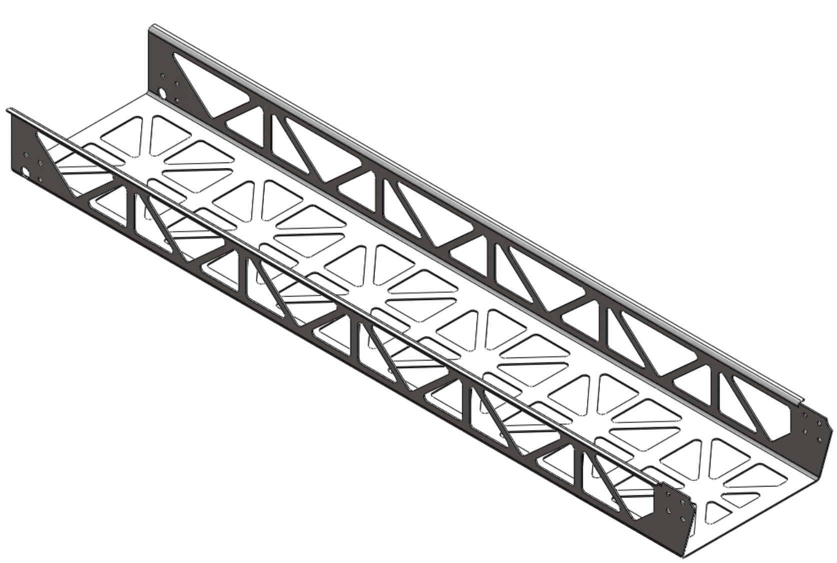


Figure 13: Ramp Segment

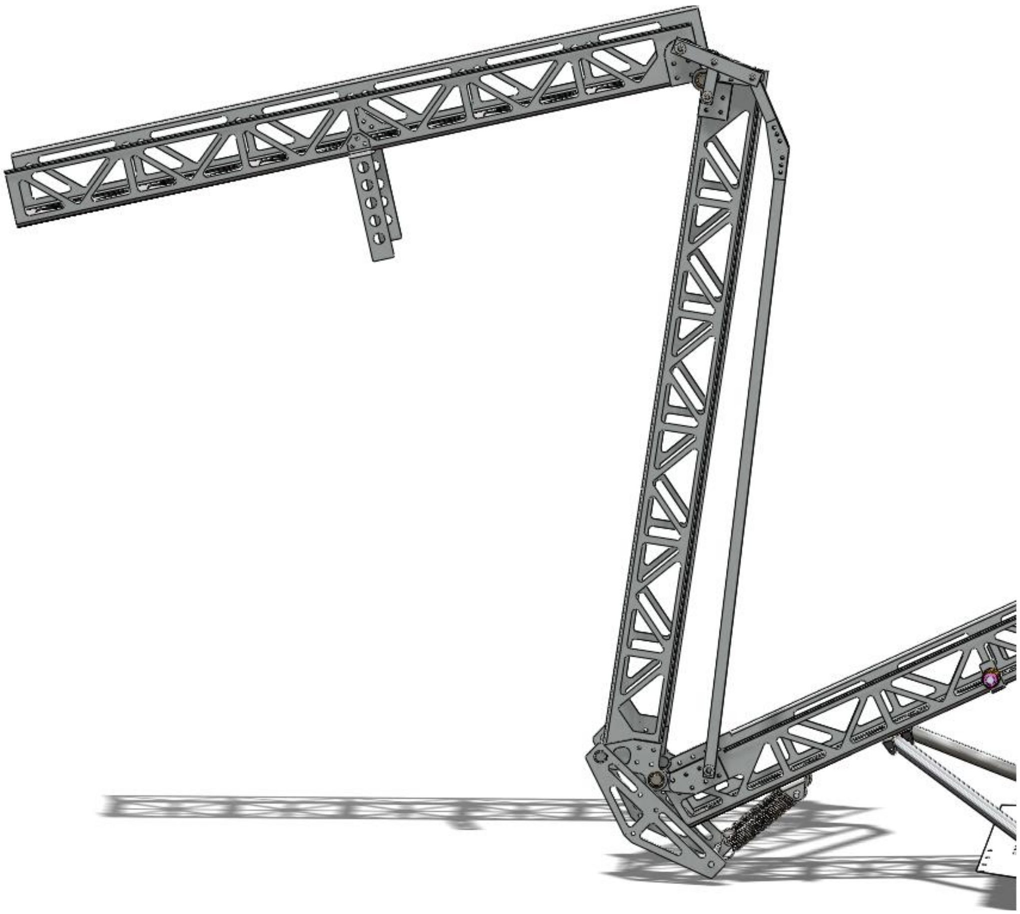


Figure 14: Four-Bar Linkage Mechanism

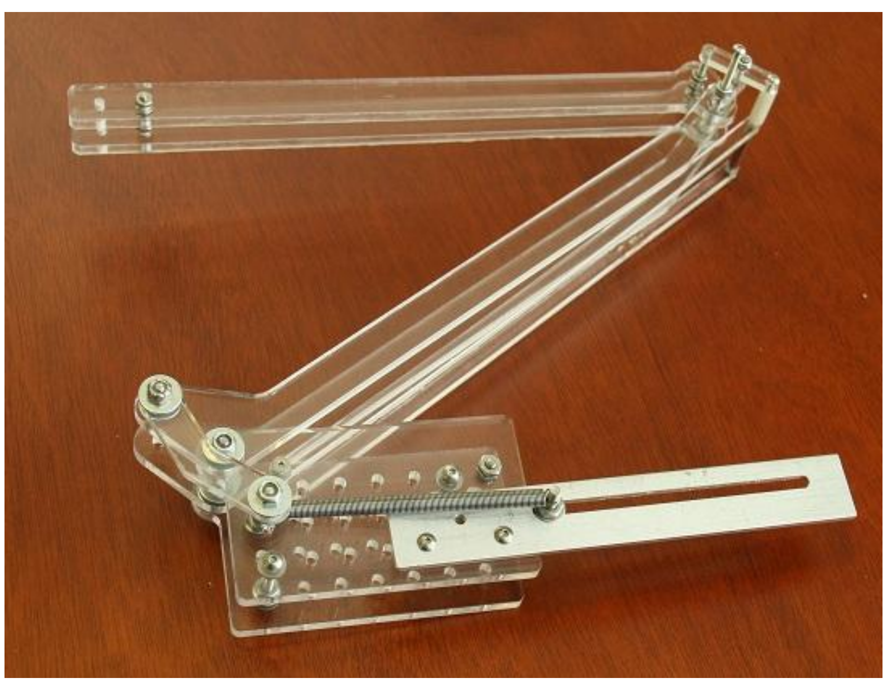


Figure 15: Successful small-scale proof of concept model

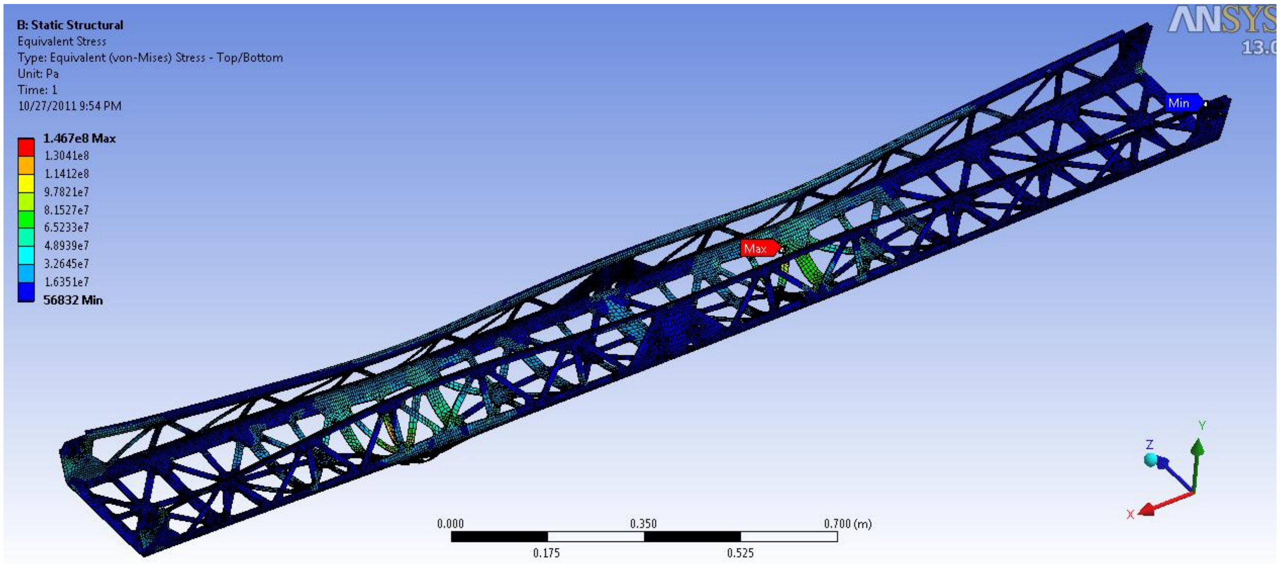


Figure 16: ANSYS Simulations for Strength

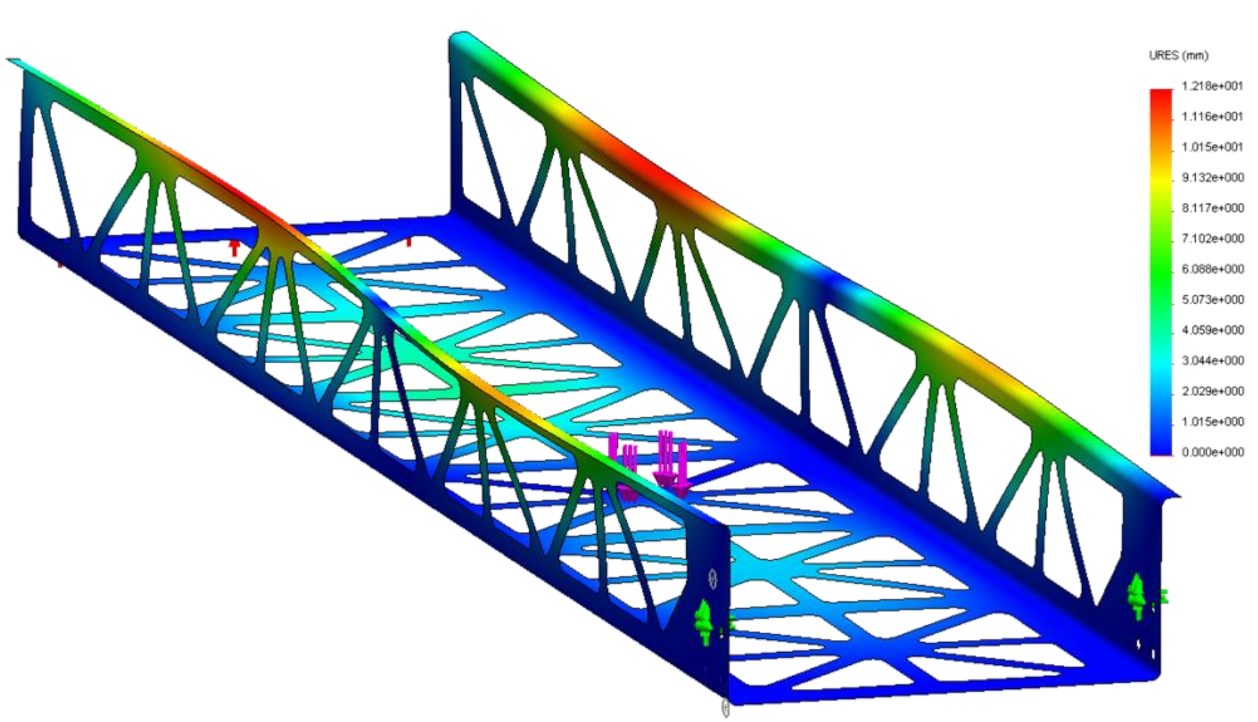


Figure 17: Solidworks Simulations for Buckling

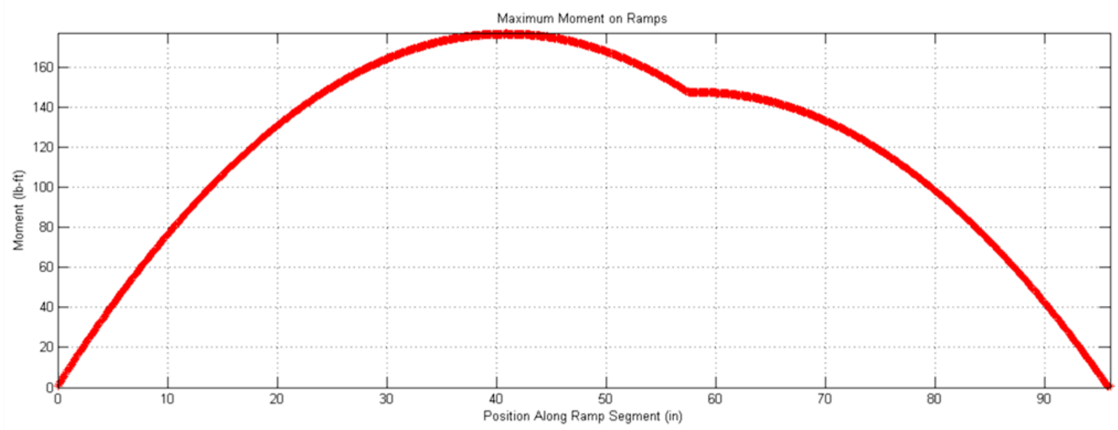


Figure 18: Simulation of maximum moment on the ramps during egress

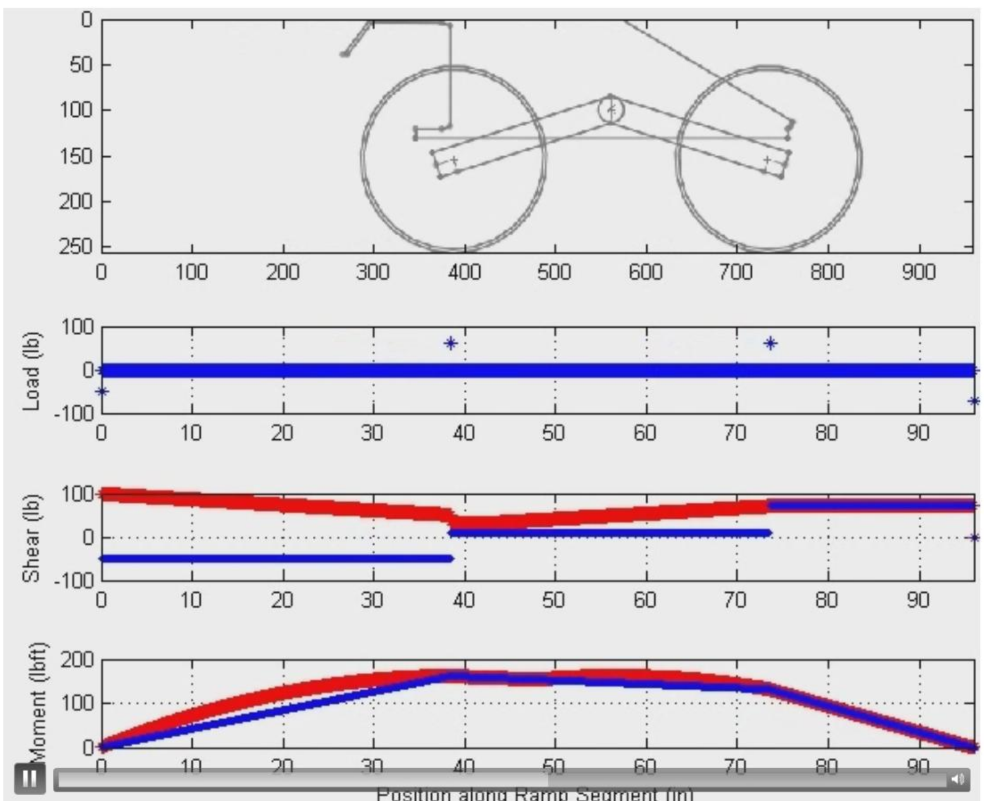


Figure 19: MATLAB Motion Simulation
Calculates shear and moment from the load of the rover during egress

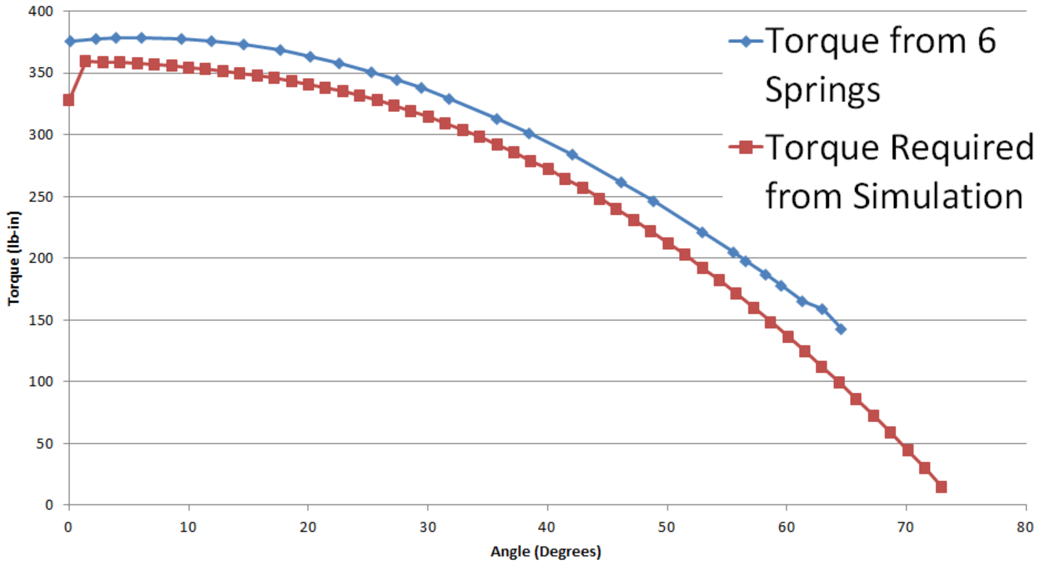



Figure 20: Ramp Deployment Torque

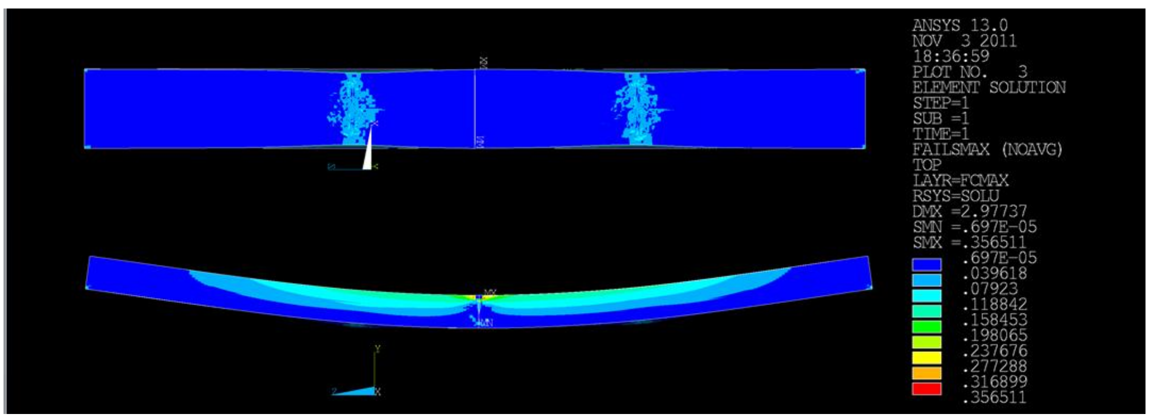



Figure 21: ANSYS composite testing of ramps with no cut outs

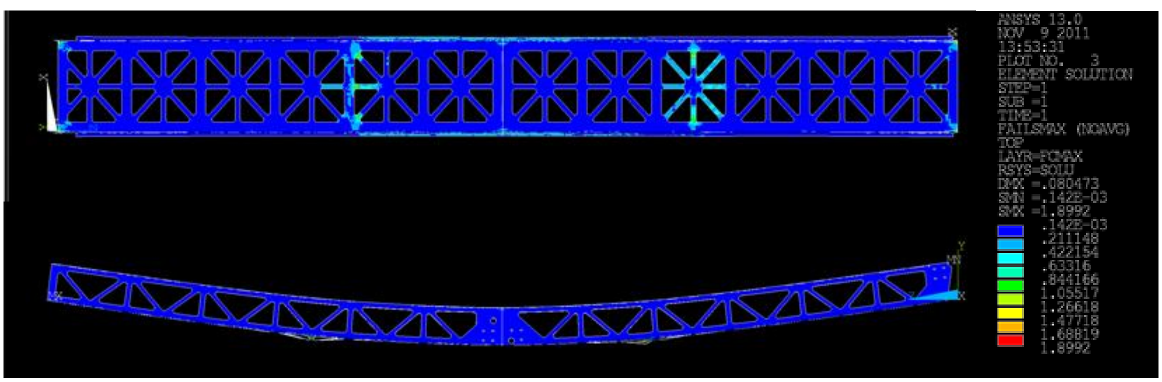
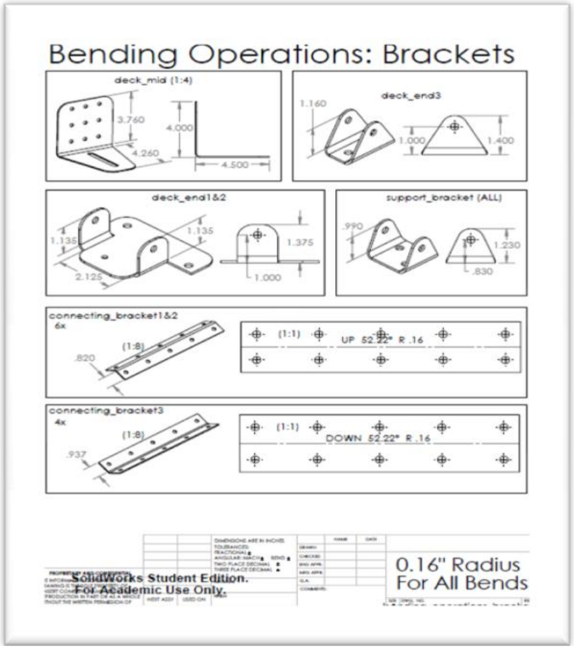



Figure 22: ANSYS composite testing of ramps with cut-outs



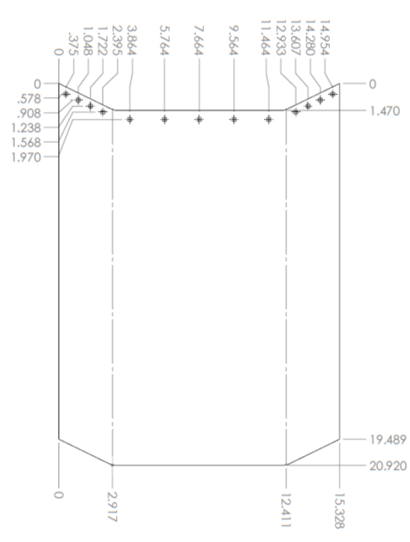


Figure 23: Example Manufacturing Drawings - Bending Instructions (left), CNC (right)

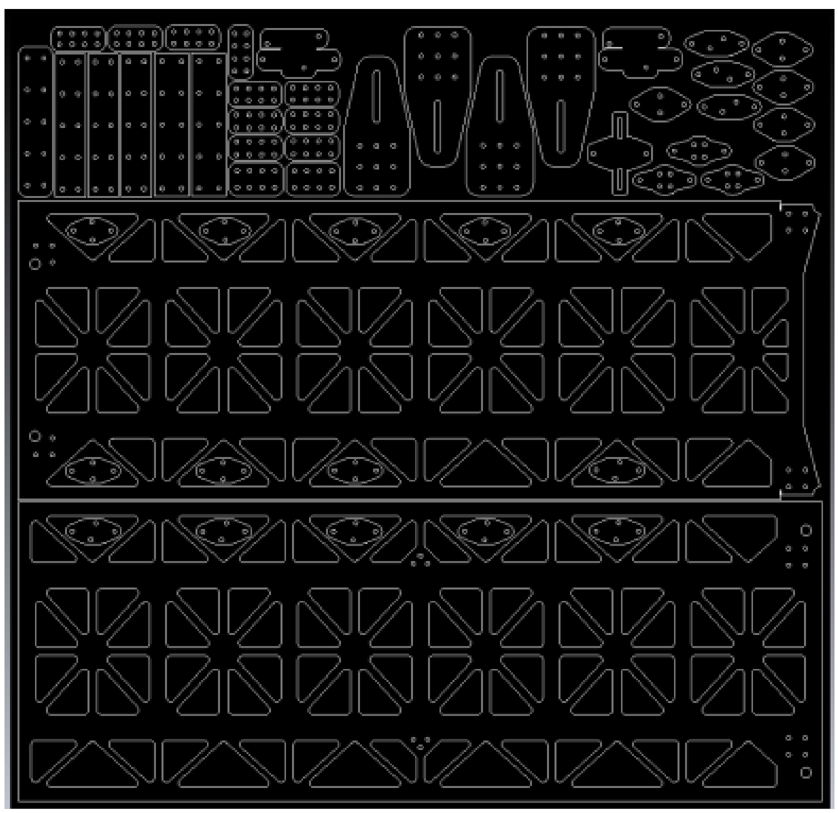
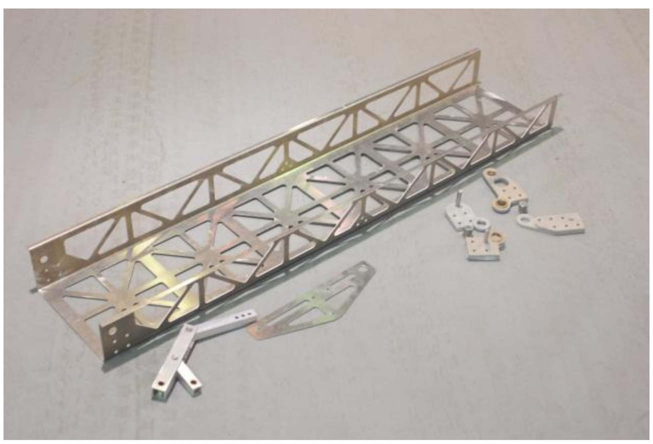


Figure 24: Example Water Jet Manufacturing Plan

Figure 25: Purchased parts and sheet metal



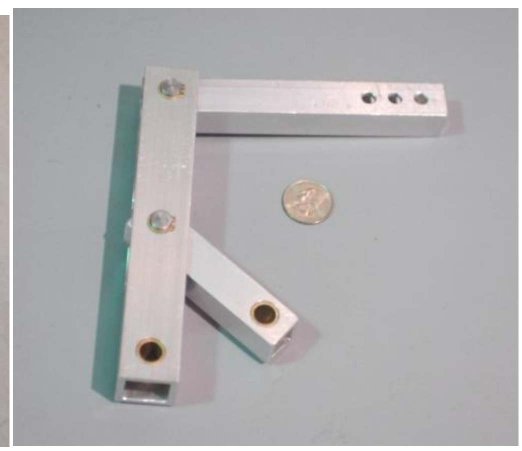


Figure 26: Completed Parts

Figure 27: Assembled Linkage Component

Figure 28: Joints, Hinges, and an Axle

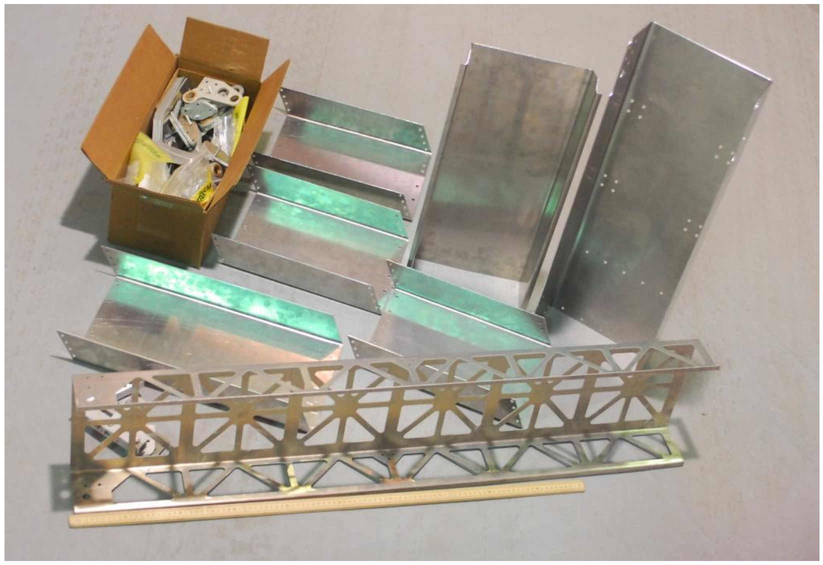


Figure 29: Completed Segments with Flanges, Joints, Components for Assembly

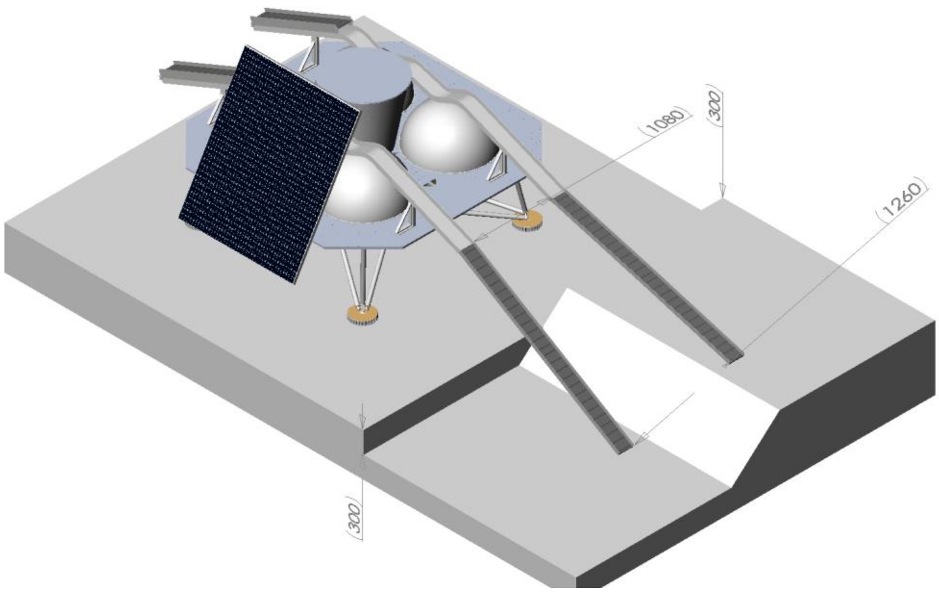



Figure 30: Worst Case Landing Condition – 30cm Rock and 30 cm Hole

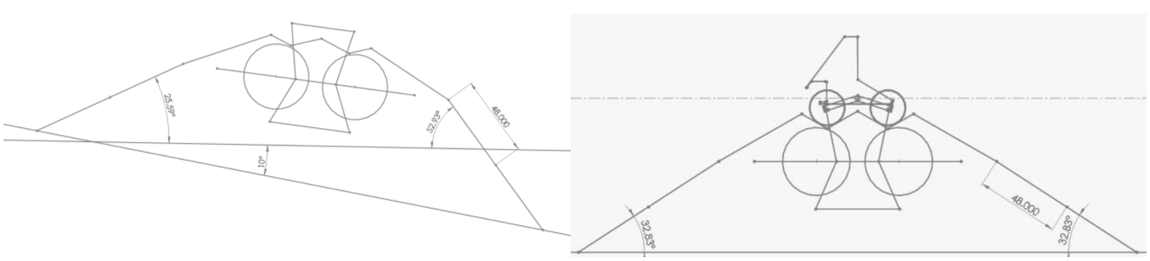



Figure 31: Software “sketches” used to find landing geometry.

Figure 32: Ramp Segment Manufactured by a Water Jet

Figure 33: CNC

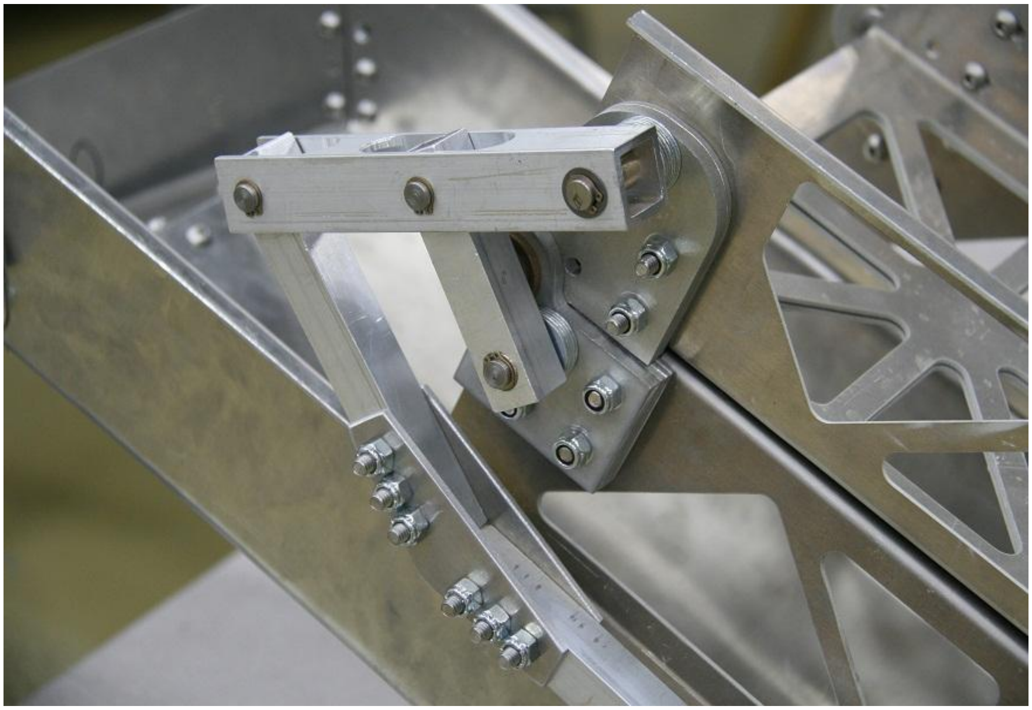


Figure 34: Hinge from the Four Bar Linkage

Figure 35: Spring Lever Arm, 6 Actuating Springs

Figure 36: Ramp Setup with Prototype 2 Rover


Figure 37: Ramp Deployment Test

Figure 38: Egress Test

Figure39: Completed Ramp Design before Lander Integration

Figure 40: Rare images highlighting the Soviet Lunakhod Lander Ramps