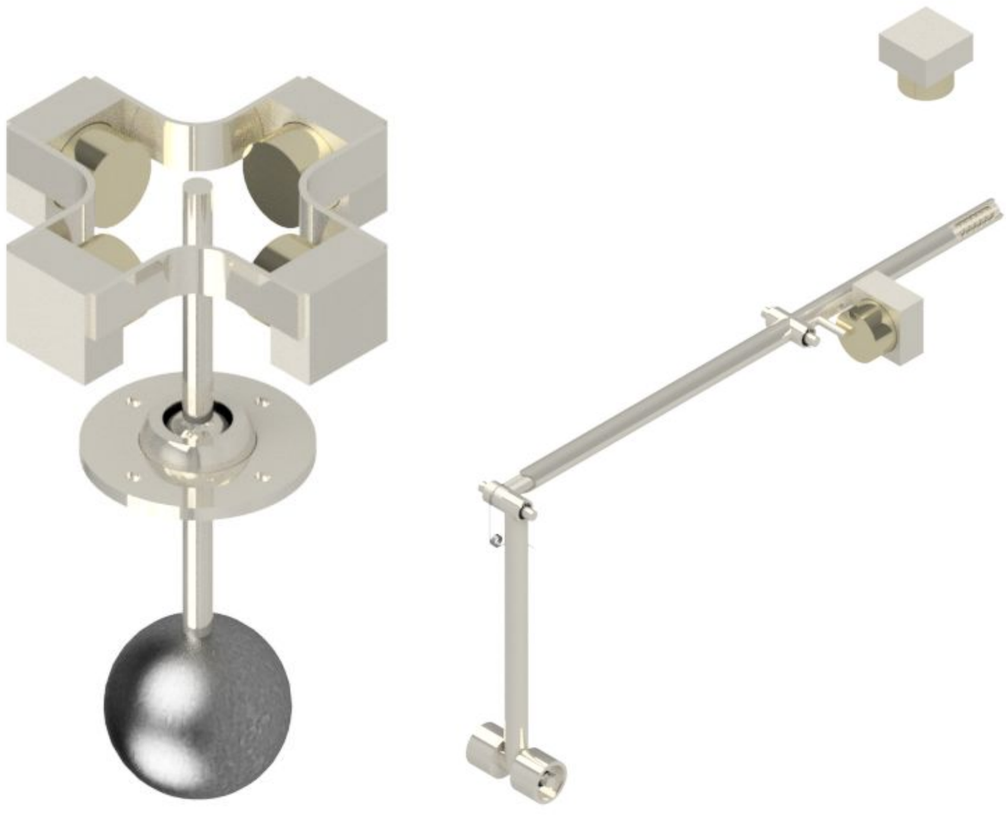
# Venus Rover Obstacle Avoidance with Simple Mechanical Sensors



Team Brotostar

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*Abstract*

To meet the conditions of this challenge, we decided to design two independent sensors that work completely without the use of any electronics or input power. Sensor A will be capable of detecting slopes >= 30° up or down in either pitch or roll directions via a pendulum mechanism. Sensor B will be capable of detecting both valleys >= 0.35m deep as well as obstacles >= 0.35m tall by having an appendage drop into a pit, or be pushed in by an obstacle. A mechanical overview and engineering analysis is offered to ensure the feasibility of both sensors. Based on the preliminary calculations, both sensors A and B will be able to actuate the 6cm diameter pin by 3cm with an appropriate force. Both sensors fit well within the current rover architecture and are environmentally suitable for conditions on Venus.

# 1. Sensor A: The Pendulum

## 1.1. *Mechanical Overview*

The Pendulum is a rather simple design. As expected, it will consist of a bob attached to the bottom of a rod hanging from a fulcrum. The fulcrum itself will be a ball joint attached partway up the rod that will allow the pendulum to swing in any direction necessary. As mentioned earlier, the fulcrum will be only part way up the rod, the remaining rod segment will extend through the ball joint. The pins will reside at the cardinal directions relative to the rover and will be actuated by the end of the upper rod segment when the pendulum tilts too far in any of those given directions. The upper rod will be guided via curved guide rails to ensure the pins will always be reached.

In Figure 1, the Pendulum is shown with different colors so that the different components may be easily discerned. The blue part is the pendulum arm, the red sphere is the bob, and the green part is a sphere joint flange which is fixed to the rover frame. The pins are fixed to the frame of the rover and are shown as magenta cylinders housed in gray boxes. The pins are positioned to trigger if the rover tilts up or down >= 30 degrees in either the pitch or roll directions. Curved pieces of titanium 6-4 are used to direct the pendulum arm towards a button if the rover encounters a slope with compound pitch and roll.

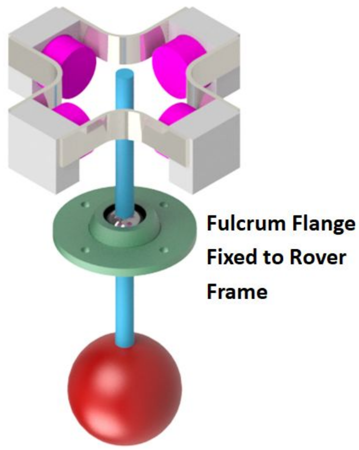


**Figure 1: Full Pendulum Configuration With Pins**

A pin becomes actuated when the rover frame tilts >= 30 degrees in pitch or roll. The weight of the bob keeps the pendulum vertical when the rover frame tilts. Figure 2 below shows the pendulum pin states when a slope is detected:

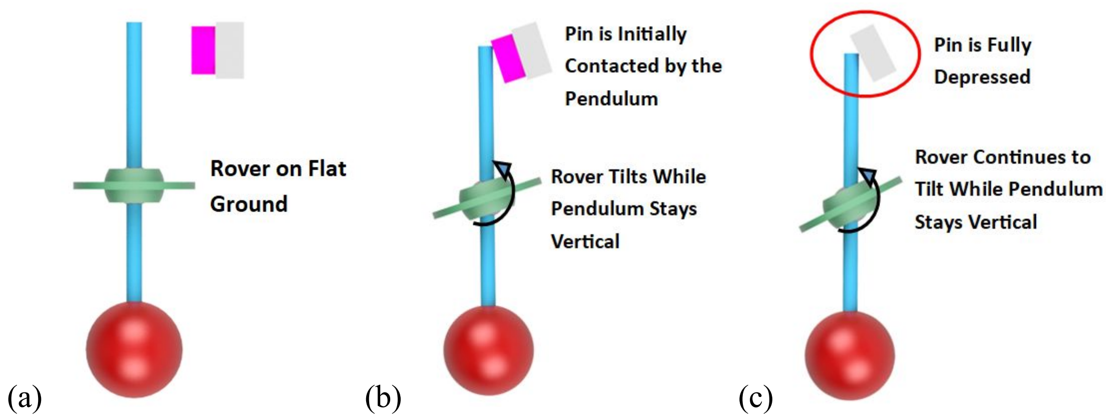


**Figure 2: Pendulum Pin States. (a) No Pin Contact. (b) Initial Pin Contact. (c) Fully Depressed Pin Once Rover Frame Tilts 30 Degrees.**

The bob is made of stainless steel 304 since its density is higher than titanium 6-4 and it is desirable to have a low-volume bob with a desired mass. The pendulum arm and sphere joint flange are made of titanium 6-4 to be as light as possible. Between the sphere joint flange and sphere joint of the pendulum arm is a solid lining of graphite to provide some lubrication to ease any friction occurring at that joint.

## 1.2. *Analysis*

The primary function of the pendulum is to actuate a pin 3cm with appropriate force when the rover encounters a slope >= 30 degrees up or down in either the pitch or roll directions. While the pendulum can detect slopes up or down in either pitch or roll directions via four pins, it is only necessary to analyze the case of one pin since the system is symmetrical in four directions as shown earlier in Figure 1. Figure 3 below is a free-body diagram (FBD) of the pendulum when the rover has tilted an angle of $\theta$ degrees:

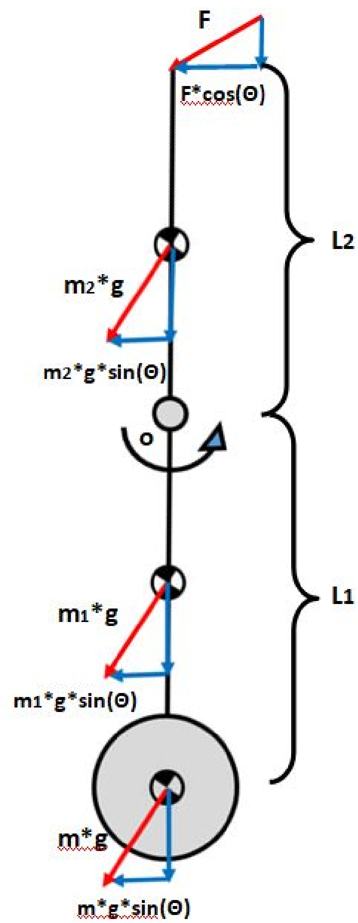


**Figure 3: Pendulum FBD**

Where $F$ is the reaction force of the pin, $m$ is the mass of the bob, $m_1$ is the mass of the lower rod connecting the bob to the fulcrum, $L_1$ is the length of the lower rod, $m_2$ is the mass of the upper rod which extends from the fulcrum to where the pendulum contacts the pin, $L_2$ is the length of the upper rod, $\theta$ is the tilt angle of the rover in either pitch or roll, and

$g = 8.87 \frac{m}{s^2}$ is the gravity on the surface of Venus. The following is a derivation for the force applied on the pin by the pendulum based on Figure 3 above.

$$\Sigma M_o = 0:$$

$$F * cos(\theta) * L_2 + m_2 * g * sin(\theta) * (\frac{L_2}{2}) - m_1 * g * sin(\theta) * (\frac{L_1}{2}) - m * g * sin(\theta) * L_1 = 0$$

$$F = \frac{m_1 * g * sin(\theta) * (\frac{L_1}{2}) + m * g * sin(\theta) * L_1 - m_2 * g * sin(\theta) * (\frac{L_2}{2})}{cos(\theta) * L_2}$$

Using the above equation, a python script was written to determine the force applied to the pin over the change in $\theta$. The following parameters were used:

| **User-Defined Constants** | **Variable** |
|---|---|
| $m$ | $F$ |
| $m_1$ | |
| $m_2$ | |
| $L_1$ | |
| $L_2$ | |
| $g$ | |
| $\Delta x$ | |

The Python script generates a graph of the pin force over the change in $\theta$ required to linearly actuate the pin by 3cm. As defined by the design specifications, the pin actuation force must be at least 25N and no greater than 75N. This design specification was achieved by setting the user-defined constants to the following values:

| User-Defined Constants | Value |
|---|---|
| $m$ | 7.205 kg |
| $m_1$ | 0.157 kg |
| $m_2$ | 0.157 kg |
| $L_1$ | 0.2 m |
| $L_2$ | 0.2 m |
| $g$ | 8.87 $\frac{m}{s^2}$ |
| $\Delta x$ | 0.03 m |

The graph below shows pin force vs. rover tilt angle:

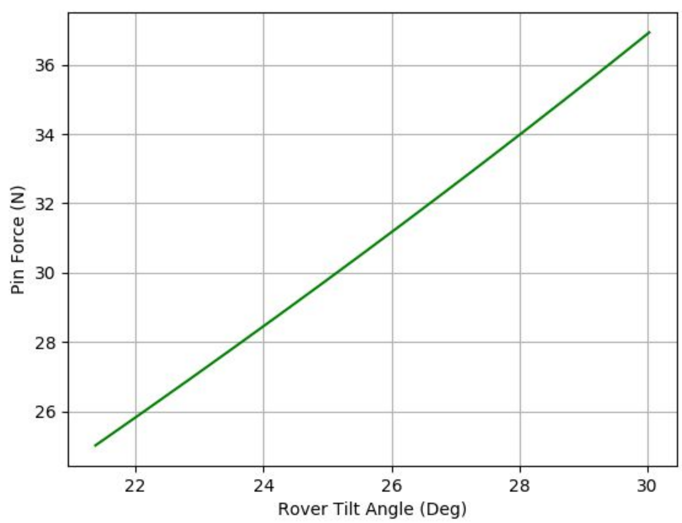


**Figure 4: Pin Force Vs. Rover Tilt Angle**

As shown in Figure 4, the pin is initially contacted at around 21.4 degrees, but it is not fully depressed 3 cm until the rover has tilted a full 30 degrees. This means that angles less than 30 degrees will not be detected by the pendulum. Over the duration of pin contact, the pendulum applies between 25N and 37N to the pin, which is well within the design specifications. It should be noted that the above results are only representative of the chosen user-defined values. There exists optimal solutions with regards to weight and which angle the pin begins to actuate. The python script used for this simulation is in the appendix and may be used as a tool for determining the optimal compromise between desired parameters.

# 2. Sensor B: The Drop-Bumper

## 2.1. *Mechanical Overview*

The Drop-Bumper covers the remaining sensor requirements by means of two functions. The first function is the capability to detect rocks >= 0.35m tall and the second function is the capability to detect valleys >= 0.35m deep. This sensor uses one pin for each function. Our sensor suite is such that there will be two Drop-Bumpers attached to the rover in total; one ahead of each front wheel of the rover.

In Figure 5, the Drop-Bumper is shown with different colors so that the different components may be easily discerned. The orange part is the lever, which has its fulcrum shown close to its midpoint. The fulcrum axis is located 0.35m above the ground and rotates about an axle that is connected to the frame of the rover. The green parts are the roller, which is 0.1m wide and thus ignores all holes thinner than 0.1m. The blue part is the drop-leg, and the red part is the “bolt”. The bolt is named as such because it works in a similar way to a bolt-action rifle, but it is much simpler. The bolt in this design is spring-loaded and can linearly travel through the lever when it is pushed. A peg situated behind the fulcrum keeps the bolt from falling out of the orange lever pipe and keeps it from rotating. The pins are fixed to the frame of the rover and are shown as magenta cylinders housed in gray boxes.

The first pin is placed behind the bolt peg such that the pin is actuated when the bolt is pushed in by a rock >= 0.35m tall. The bolt peg is only able to move a linear distance of 3cm, as it is physically constrained to a track on the lever. After a rock >= 0.35m tall has been detected, an inconel spring returns the bolt to its original extended position. Figure 5 shows the state of the Drop-Bumper before and after a rock >= 0.35m tall has been detected:

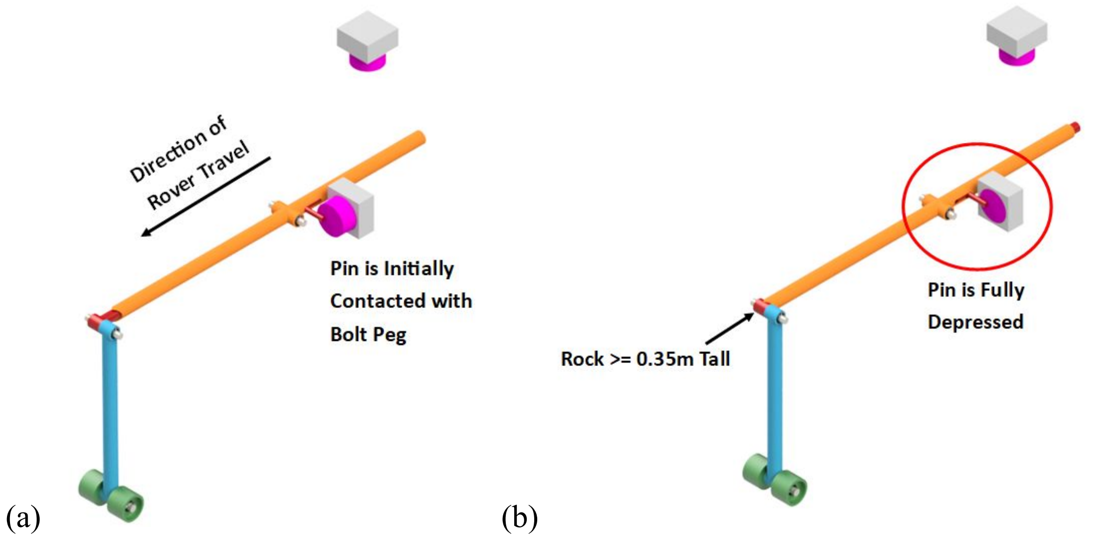


**Figure 5: Drop-Bumper States. (a) Before Encountering Any Obstacle. (b) After Encountering a Rock >= 0.35m Tall.**

Figure 6 shows the placement of the inconel bolt spring. The spring shown is a conceptual placeholder for the actual spring. Calculations for the maximum appropriate spring stiffness are shown in this paper; however, calculations for number of coils and other physical dimensions are not shown. The bolt spring may be placed anywhere along the bolt's linear axis of travel, which is indicated by the double-ended arrow in Figure 6.

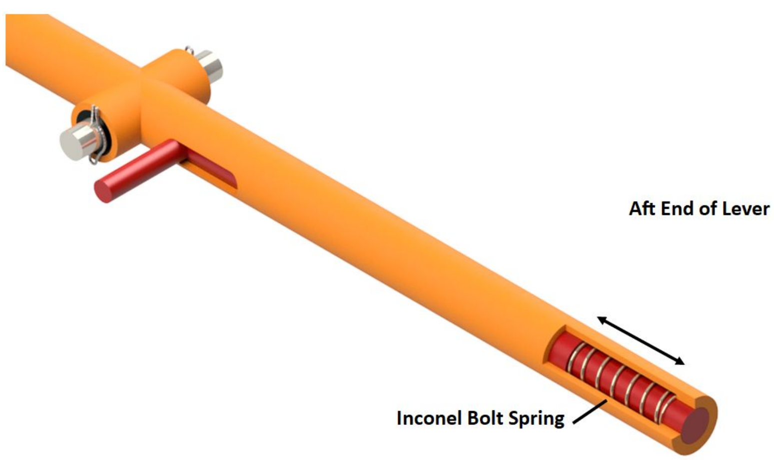


**Figure 6: Bolt Spring Placement**

A notch in the bolt allows the bolt to linearly slide within the lever without clipping through the fulcrum axle as shown in Figure 7 below:

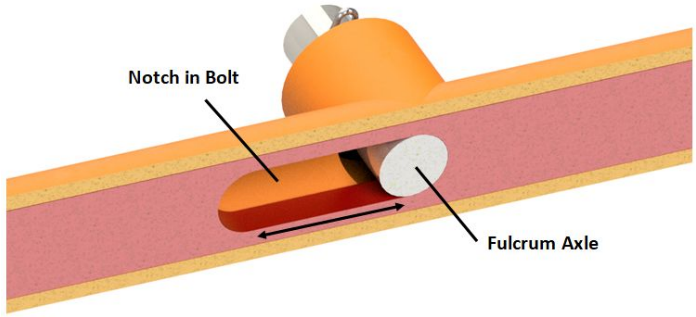


**Figure 7: Cross-Section View of Bolt Notch**

To avoid having the Drop-Bumper tilt forward and easily fold in on itself when being pushed, a torsional spring may be used to provide suspension to the drop-leg. Figure 8 shows the placement of this torsional spring:

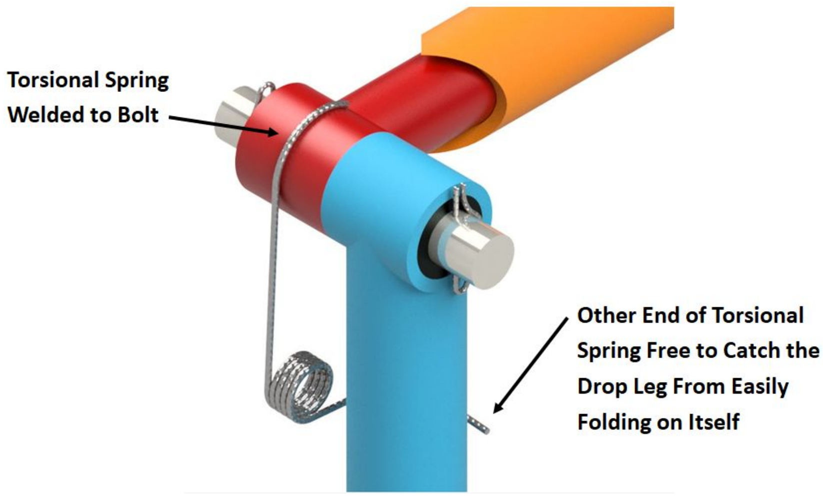


**Figure 8: Torsional Spring Placement**

The torsional spring would be made from inconel and would be welded to the bolt with its other side free to catch the drop-leg from easily folding in on itself. This torsional spring would still allow the drop-leg and roller to fold upwards to roll over small rocks but would offer enough suspension so that the drop-leg's rest position is vertically oriented. The calculations for determining the spring constant for this torsional spring are not shown in this paper; only the concept is being presented for this feature.

The second pin is pointed downwards and is positioned above the aft portion of the lever. When a valley is encountered, the roller and drop-leg are no longer supported by the ground. The weight of the portion of the Drop-Bumper ahead of the fulcrum causes the lever to tilt downwards. This causes the aft end of the lever to raise up and contact the second pin. After pin contact, the lever applies an appropriate force on the pin to fully depress it by 3cm. Figure 9 shows the pin state in the process of detecting a valley >= 0.35m deep:

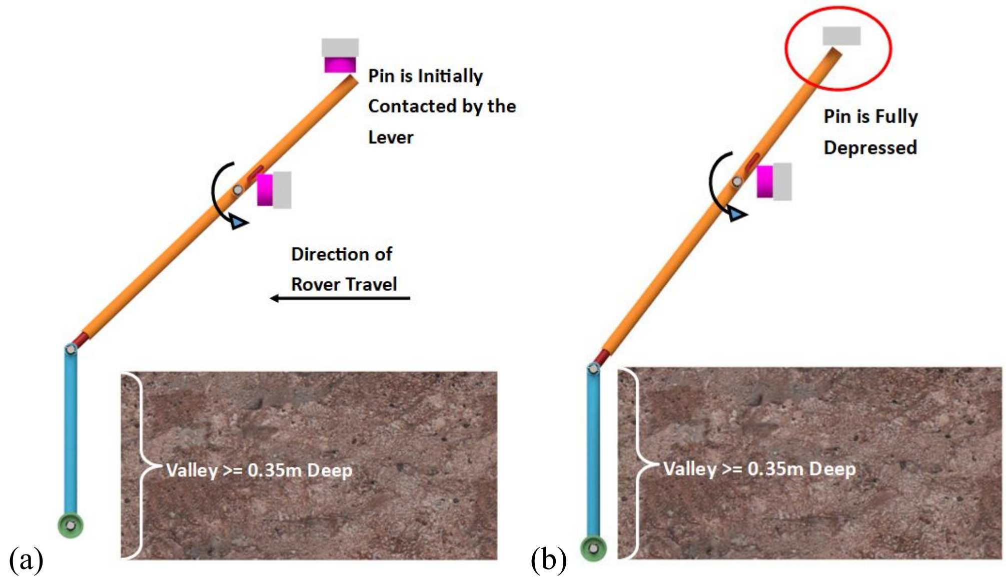


**Figure 9: Drop-Bumper Valley Pin States. (a) Initial pin contact.. (b) Fully Depressed Pin After Detecting a Valley >= 0.35m Deep.**

The lever, bolt, drop-leg, roller, and axles on all revolute joints are titanium 6-4. The bearings on all revolute joints are solid graphite tubes. In the forward portion of the lever, there is an inconel torsional spring which provides suspension to the drop-leg when going over small rocks. In the aft portion of the lever, there is an inconel spring which keeps the bolt extended until a rock >= 0.35m tall is encountered.

## 2.2. *Analysis*

The Drop-Bumper will be analyzed for both of its functions separately.

### 2.2.1. Function I: Rock Detection

The first function of the Drop-Bumper is to detect obstacles taller than 0.35m. The Drop-Bumper does this by using the pushing force of the rover to linearly actuate a pin. The bumper ignores all obstacles shorter than 0.30m by folding onto itself. This is feasible since the drop-leg fulcrum is positioned at a height of 0.35m above the ground and the roller is 0.05m in diameter. When fully folded as shown in Figure 10, obstacles shorter than 0.30m can pass underneath the sensor without being detected.

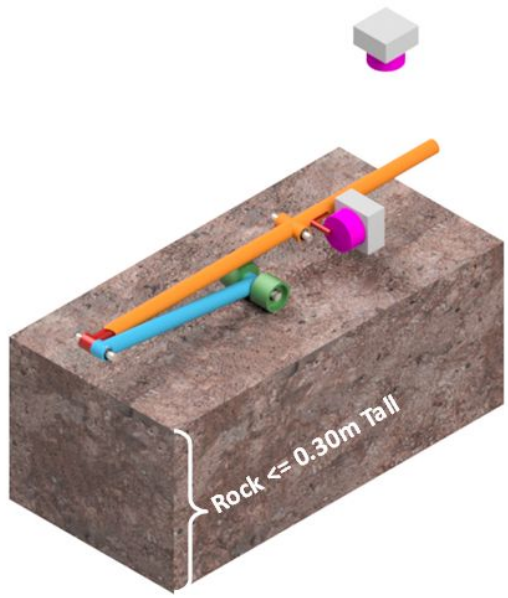


**Figure 10: Rendering of Folded Drop-Bumper**

To design a spring that can return the bolt to its original extended position, there are two cases that must be taken into account. Since our design includes two Drop-Bumpers (one ahead of each front wheel of the rover), one or both may be actuated at any given time depending on the obstacle. If both are actuated, then the system is equivalent to the rover pushing two parallel springs into a wall. If only one is actuated, the system is equivalent to the rover pushing only one spring into a wall. Since the Drop-Bumpers are situated 1.5m apart, it is unlikely that they will both encounter an obstacle >= 0.35m tall at the same time. Nonetheless, this case must be accounted for to ensure that the springs are not too stiff as to restrict pin actuation when in a parallel configuration.

The following FBD can be used to represent an equivalent spring system for when both Drop-Bumper bolts are actuated at the same time:

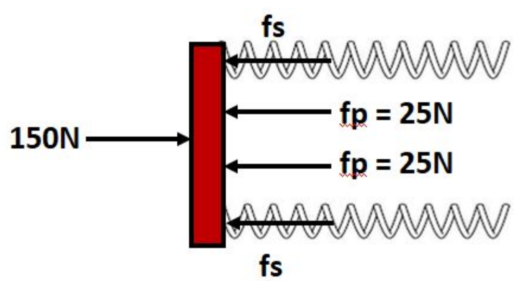


**Figure 11: Equivalent Spring System for Dual Drop-Bumper Actuation**

Where fs is the force of each bolt spring and fp = 25N is the force required to actuate each pin. The following force balance equation is used to find the maximum spring constant that can be used while allowing for pin actuation:

$\Sigma F = 0:$

$$150N - 2fs - 2fp = 0$$

By substituting Hooke's law and fp = 25N, we get:

$$150N - 2(k(0.03m)) - 2(25N) = 0$$

Thus,

$$k = 1,666.67\frac{N}{m}$$

Therefore, the bolt springs used in the Drop-Bumper must not have a spring constant higher than $1,666.67\frac{N}{m}$ so that the pins can still be actuated even when both Drop-Bumpers encounter an obstacle >= 0.35m tall at the same time. In this case, it is guaranteed that the pins are actuated at a constant 25N until fully depressed.

In the more likely case where only one Drop-Bumper encounters an obstacle >= 0.35m tall, the spring constant of the bolt spring found above would allow for the pin to be actuated properly. The FBD below represents an equivalent spring system for only one Drop-Bumper encountering an obstacle >= 0.35m tall:

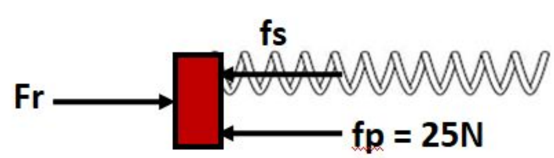


**Figure 12: Equivalent Spring System for Single Drop-Bumper Actuation**

Where Fr is the force that the rover needs to push against the obstacle with in order to actuate the pin with 25N when one spring is involved. The following force balance equation can be used to find the value of Fr:

$\Sigma F = 0:$

$$Fr - fs - fp = 0$$

By substituting Hooke's law and fp = 25N, we get:

$$Fr - (1,666.67\frac{N}{m})(0.03m) - 25N = 0$$

Thus,

$$Fr = 75N$$

Therefore, the force required by the rover to actuate the pin with 25N when one spring is involved is 75N. Since the rover is capable of pushing with a force up to 150N, this design parameter is achieved. It can be concluded that when either one or both Drop-Bumpers encounter an obstacle >= 0.35m tall, the pin(s) can be reliably actuated at a constant force of 25N until fully depressed.

### 2.2.2. Function II: Valley Detection

The second function of the Drop-Bumper is the detection of valleys deeper than 0.35m. To detect valleys, a vertical leg contacting the ground with a roller must drop 0.35m. The leg is attached to a lever which uses the weight of the dropped leg to actuate a pin. Below is a labelled sketch of the Drop-Bumper when on level ground:

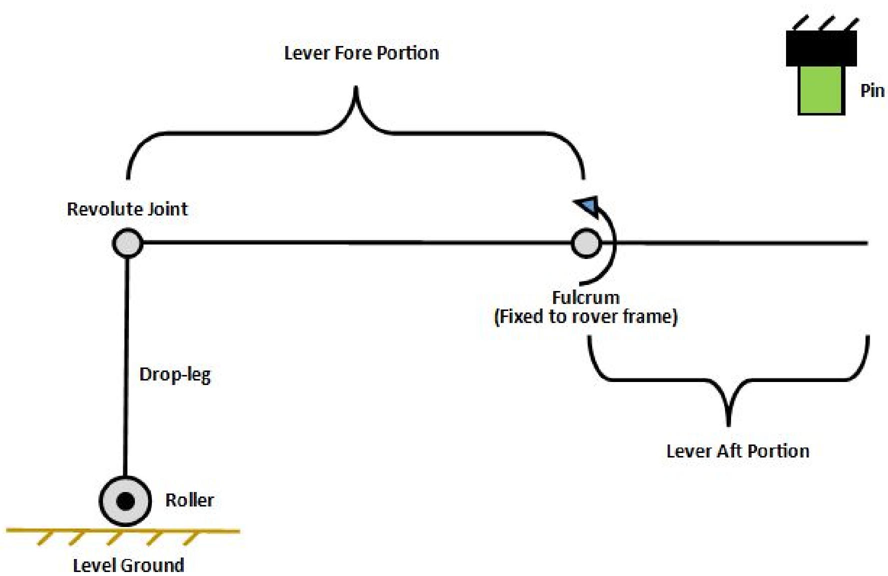


**Figure 13: Drop-Bumper Labelled Sketch on Flat Ground**

Below is a FBD of the Drop-Bumper when a valley has been detected:

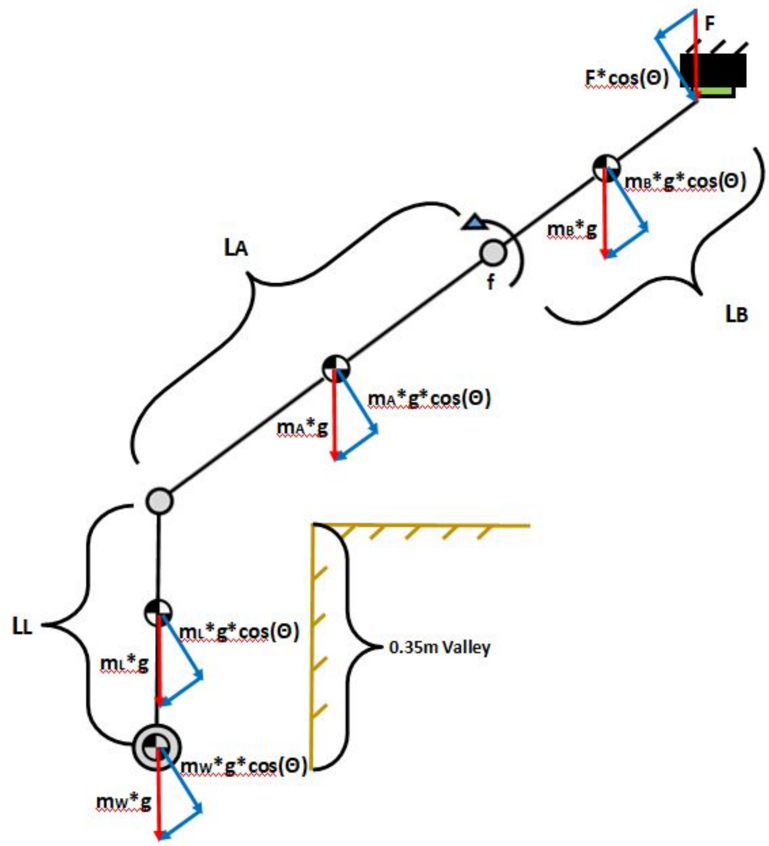


**Figure 14: Drop-Bumper FBD**

The following is a derivation for the force applied on the pin by the Drop-Bumper in Function II based on Figure 14 above.

$$\Sigma M_f = 0:$$

$$-F * cos(\phi) * L_B - m_B * g * cos(\phi) * (\frac{L_B}{2}) + m_A * g * cos(\phi) * (\frac{L_A}{2}) + m_L * g * cos(\phi) * (L_A + (\frac{L_L}{2}) * sin(\phi)) + m_W * g * cos(\phi) * (L_A + L_L * sin(\phi)) = 0$$

$$F = \frac{m_A*g*cos(\phi)*(\frac{L_A}{2}) - m_B*g*cos(\phi)*(\frac{L_B}{2}) + m_L*g*cos(\phi)*(L_A+(\frac{L_L}{2})*sin(\phi))+m_W*g*cos(\phi)*(L_A+L_L*sin(\phi))}{cos(\phi)*L_B}$$

Where $F$ is the reaction force of the pin, $m_A$ is the mass of the forward part of the lever, $L_A$ is the length of the forward part of the lever, $m_B$ is the mass of the rear part of the lever, $L_B$ is the length of the rear part of the lever, $m_L$ is the mass of the drop-leg, $L_L$ is the length of the drop-leg, $m_W$ is the mass of the wheel, $\Phi$ is the tilt angle of the lever, and $g = 8.87\ \frac{m}{s^2}$ is the gravity on the surface of Venus.

A python script was written to determine the force applied to the pin over the change in valley depth. The following parameters were used:

| **User-Defined Constants** | **Variable** |
|---|---|
| $m_A$ | $F$ |
| $m_B$ | |
| $m_L$ | |
| $m_W$ | |
| $L_A$ | |
| $L_B$ | |
| $L_L$ | |
| g | |

To find realistic values for the masses of each component, the following assumptions were made:

- Both the fore and aft lever portions of the sensor will consist of a pipe with a solid rod within. The user must specify the inner and outer radius of the pipe as well as the outer radius of the solid rod within
- The mass of small features like the graphite bearings and axles are not taken into account
- The drop-leg is a hollow pipe with the same inner and outer radius as the fore and aft lever portions
- The roller is a 0.05m diameter cylinder that is 0.1m long
- All components have the density of Titanium 6-4
- The bumper mechanism (Function I) has not been activated or is in its normal reset position

The Python script generates a graph of the pin force over the change in valley depth required to linearly actuate the pin by 3cm. As specified by the design specifications, the pin actuation force must be at least 25N and no greater than 75N. This design specification was achieved by setting the user-defined constants to the following values given the assumptions described above:

| **User-Defined Constants** | **Value** |
|---|---|
| $m_A$ | 0.946 kg |
| $m_B$ | 0.663 kg |
| $m_L$ | 0.308 kg |
| $m_W$ | 0.870 kg |
| $L_A$ | 0.428 m |
| $L_B$ | 0.300 m |
| $L_L$ | 0.325 kg |
| g | 8.87 $\frac{m}{s^2}$ |

The graph below shows pin force vs. valley depth when using the above input values:

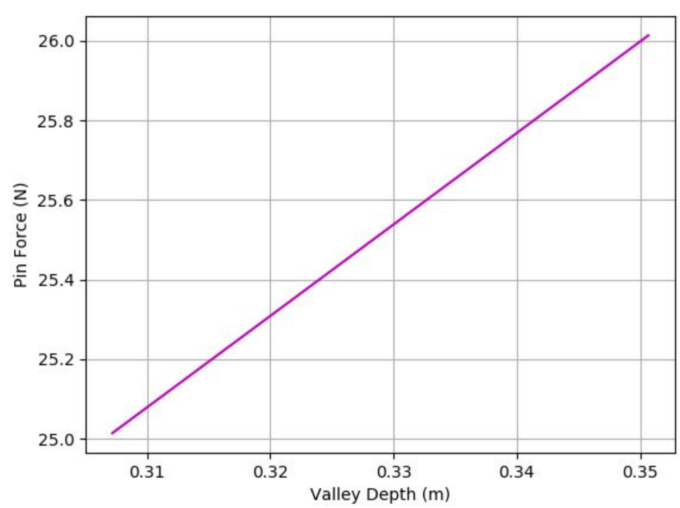


**Figure 15: Pin Force Vs. Valley Depth**

As shown, the pin force is well within the design specifications as the force starts at 25N and reaches the highest force at around 26N. With the chosen user-defined values, the lever starts to push the pin at a valley depth of around 0.31m but does not fully depress the pin until a valley depth of 0.35m has been reached.

# 3. Compatibility with Current Rover Architecture

## 3.1 Requirement A:

Sensor must not extend more than 1m from the body of the rover.

### 3.1.1 Compliance Explanation A:

Neither of the proposed sensors extend outside of the rover more than 1m. Sensor A is proprioceptive and does not need to extend outside of the body of the rover. There will be two sensor B Drop-Bumpers; one ahead of each front rover wheel. The farthest point of each Drop-Bumper will only extend 0.453m from the body of the rover.

## 3.2 Requirement B:

Sensor must not be more than 0.875m off the surface.

### 3.2.1 Compliance Explanation B:

Neither of the proposed sensors will extend more than 0.875m off the surface. The total height of all sensor A components is 0.460m tall. The total height of all sensor B components is 0.631m tall (counting the height of the pin placement).

## 3.3 Requirement C:

Sensor(s) must have a mass at or below 25kg.

### 3.3.1 Compliance Explanation C:

Below is a table that shows the mass of each sensor. The mass of small components are not accounted for in this estimation. Together, the entire sensor suite has a mass of approximately 13.0940kg, which is well below the 25kg limit.

| Sensor | QTY | Mass (kg) |
|---|---|---|
| A: Pendulum | 1 | 7.5190 |
| B: Drop-Bumper | 2 | 2.7875 |
| **TOTAL:** | | **13.0940** |

### 3.4 Requirement D:

Proposed design must be capable of being assembled using environmentally appropriate materials.

#### 3.4.1 Compliance Explanation D:

The four materials used to construct the sensors are stainless steel (SS) 304, titanium 6-4 (Ti 6-4), inconel, and graphite. SS 304 is one of the suggested materials in the HeroX challenge sticky post. It has been shown that SS 304 exhibits high corrosion resistance when exposed to a Venus-like atmosphere compared to other steels [1]. Ti 6-4 is another one of the suggested materials in the HeroX challenge sticky post. It has been shown that Fe–Al–Ti alloys exhibit higher yield stress and creep resistance compared to other iron-aluminide-based alloys at temperatures up to 1100 degrees C [2]. Inconel 718 is a popular choice in high temperature applications such as rocket engines and gas turbines. It also exhibits good corrosion resistance and good weldability [3]. It should be noted; however, that inconel does show some tarnish when exposed to a Venus-like environment for a prolonged period of time [4]. Graphite is the final material used in the design of both sensors. It has been shown that graphite strength almost doubles as temperature increases from room temperature to 2,500 degrees C [5].

# 4. Manufacturing for Venus

The high surface temperature and pressure on Venus does not prohibit the function of either sensor. The function of both sensors is not dependent on pressure differentials and is only dependent on linkage movement to actuate the pins. It should be noted; however, that parts should be selected on Earth that are designed to expand to the desired size once on Venus due to thermal expansion. The provided drawings are represented in their final size once on Venus. To determine how to choose the correct size parts for assembly on Earth, the following equations may be used:

$$\Delta L = \alpha * L_0 * \Delta T$$

and,

$$L_0 = L - \Delta L$$

Where $\Delta L$ is the change in length experienced by the material by thermal expansion, $\alpha$ is the coefficient of thermal expansion for the specific material, $L_0$ is the original length of the part, $\Delta T$ is the change in temperature, and $L$ is the final length of the part. The above equations can be combined to form the following equation:

$$L_0 = \frac{L}{(1 + \alpha * \Delta T)}$$

which can be used for choosing the appropriately sized parts on Earth provided the desired dimensions on Venus.

The geometry of the sensor components consists primarily of cylinders, spheres, and occasional brackets. The geometry should not be infeasible with the use of lathes, CNC machines, drill presses, welders, and other common machine shop tools. One concern that may arise is machining graphite bearings, as they are brittle and could crack in the machining process. If it is too difficult to machine solid graphite, then perhaps a dry spray lubricant of graphite may work just as well.

# 5. About the Authors

Our team, Brotostar, is the sibling duo Dan and Mitchell Brogan. We together share a deep appreciation for the cosmos in which we live. Dan being an aspiring space engineer pursuing robotics engineering and rocket science, and Mitchell being an avid reader and writer of science fiction. We often spend our time conversing about what possibilities we should be expecting in our near future in terms of off world prospects amongst many other subjects. Together we worked to design sensors for the unique Venus automaton rover.

# References

[1] Lukco, D., Spry, D. J., Harvey, R. P., Costa, G. C. C., Okojie, R. S., Avishai, A., ... & Hunter, G. W. (2018). Chemical analysis of materials exposed to Venus temperature and surface atmosphere. *Earth and Space Science*, *5*(7), 270-284.

[2] Palm, M., & Sauthoff, G. (2004). Deformation behaviour and oxidation resistance of single-phase and two-phase L21-ordered Fe–Al–Ti alloys. *Intermetallics*, *12*(12), 1345-1359.

[3] Thomas, A., El-Wahabi, M., Cabrera, J. M., & Prado, J. M. (2006). High temperature deformation of Inconel 718. *Journal of materials processing technology*, *177*(1-3), 469-472.

[4] Costa, G. C., Jacobson, N. S., Lukco, D., Hunter, G. W., Nakley, L., Radoman-Shaw, B. G., & Harvey, R. P. (2017). Chemical and microstructural changes in metallic and ceramic materials exposed to Venusian surface conditions.

[5] Malmstrom, C., Keen, R., & Green Jr, L. (1951). Some mechanical properties of graphite at elevated temperatures. Journal of Applied Physics, 22(5), 593-600.

# APPENDIX

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#######################################################################################
# PENDULUM SIMULATOR 2020
# PYTHON CODE DEVELOPED BY DAN BROGAN
import math as m
import matplotlib.pyplot as plt
import numpy as np
from mpl_toolkits.mplot3d import Axes3D

# ALL VALUES IN SI UNITS

# CONSTANTS:
M  = 7.205 # Stability stone
M1 = 0.15657 # Lower rod mass
M2 = 0.15657 # Upper rod mass
L1 = .2 # Lower rod
L2 = 0.4-L1 # Upper rod
DX = 0.03 # Pin Displacement
DT = m.asin(DX/L2) # Delta Theta
g = 8.87 # Venus Gravity
pi = m.pi # Abbreviation for pi

th = [] # Rover tilt angle array
F = [] # Force array

inc = 0
tilt = 30*(pi/180)
```

```
for inc in range(0, 1000):
    theta = tilt - DT + inc/1000
    th.append(theta)

F.append((M1*g*m.sin(theta)*(L1/2)+M*g*m.sin(theta)*L1-M2*g*m.sin(theta)*(L2/2))/(m.cos
(theta)*L2))
    if theta >= (tilt):
        break

angle = np.array(th)
degangle = angle*(180/pi)

# Prints discrete version of the contents shown in the graph:
print(degangle)
print(F)

print('Needs to rotate through '+ str(DT*(180/pi)) + ' degrees to actuate the pin by 3cm.')

# Plot Pin Force Vs. Rover Tilt Angle:
plt.plot(degangle, F, color = 'g')
plt.xlabel('Rover Tilt Angle (Deg)')
plt.ylabel('Pin Force (N)')
plt.grid(True)
plt.show()

#######################################################################################
                                   --NEW SCRIPT--
#######################################################################################
# DROP-LEG SIMULATOR 2020
# PYTHON CODE DEVELOPED BY DAN BROGAN
import math as m
import matplotlib.pyplot as plt
import numpy as np

# ALL VALUES IN SI UNITS

# CONSTANTS:
LL = 0.325 # Length of vertical leg
LA = 0.428 # Length of fore lever portion
```

```
LB = 0.3 # Length of aft lever portion
g = 8.87 # Venus Surface Gravity
pi = m.pi # Abbreviation for Pi
R = 0.0127 # pipe outer radius
r = 0.009652 # pipe inner radius
rr = 0.009525# inner rod outer radius
rw = 0.025 # Wheel radius

# VOLUMES:
VL = (pi*(R**2)-pi*(r**2))*LL
VA = (pi*(R**2)-pi*(r**2))*LA+(pi*(rr**2))*LA
VB = (pi*(R**2)-pi*(r**2))*LB+(pi*(rr**2))*LB
Vw = pi*(rw**2)*(0.1)

# DENSITY
rhoTi64 = 4430 # kg/m3

# MASSES
ML = rhoTi64*VL
MA = rhoTi64*VA
MB = rhoTi64*VB
Mw = rhoTi64*Vw

print('ML', ML)
print('MA', MA)
print('MB', MB)
print('Mw', Mw)
print('Total Mass', ML + MA + MB + Mw)


y = (0.35)*(LB/LA) # Using similar triangles, find vertical displacement of the aft tip of the aft lever portion once the drop-leg drops 0.35m
h = ((y-0.03)*LA)/LB # Find the vertical displacement of the fore tip of the fore lever portion when the pin starts to be pressed
theta = m.asin(h/LA) # Find the first angle at which the pin starts to be pressed

inc = 0
H = [] # Valley Depth
th = [] # Lever Angle Array
```

```
F = [] # Force Array

for inc in range(0, 10000):
    theta = theta + inc/10000
    H.append(LA*m.sin(theta))
    th.append(theta)

F.append((MA*g*m.cos(theta)*(LA/2)-MB*g*m.cos(theta)*(LB/2)+ML*g*m.cos(theta)*(LA+(
LL/2)*m.sin(theta))+Mw*g*m.cos(theta)*(LA+LL*m.sin(theta)))/(m.cos(theta)*LB))
    if theta >= m.asin(0.35/LA): # Stop code once the leg has dropped 0.35m
        break

# Prints discrete version of the contents shown in the graph:
print(H)
print(F)

# Plot Pin Force Vs. Valley Depth:
plt.plot(H, F, color = 'm')
plt.xlabel('Valley Depth (m)')
plt.ylabel('Pin Force (N)')
plt.grid(True)
plt.show()
#################################################################################
```