Autonomous Stabilization and Orientation Control of Hoisted Payloads

Brace White, Kyongchan Song, Iok Wong, Bill Doggett, and Tom Jones

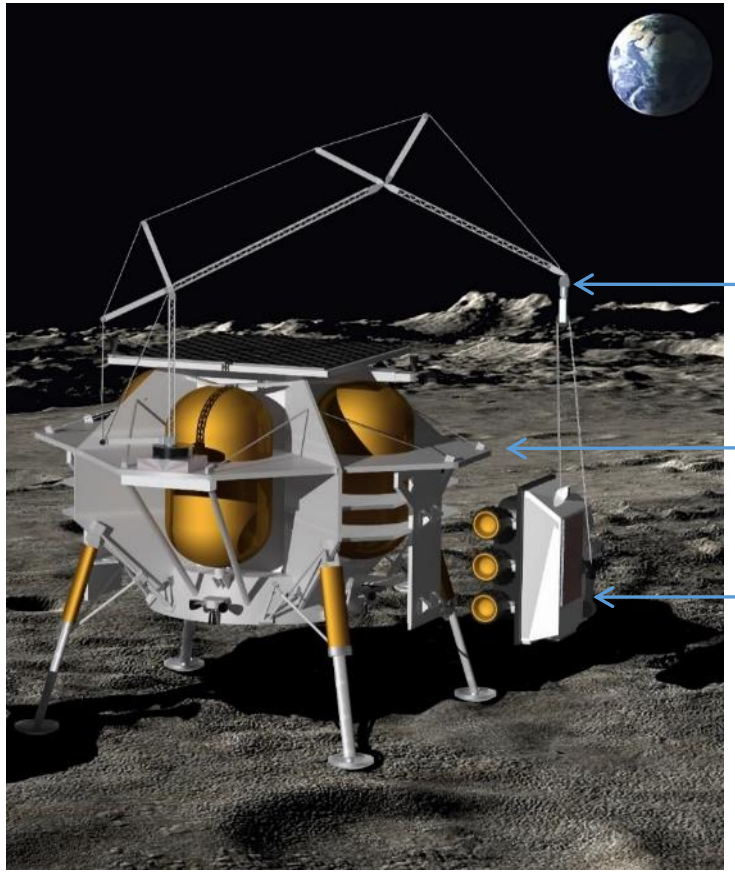
NASA Langley Research Center

D312 Structural Mechanics and Concepts Branch

AIAA SciTech Conference

January 6-10, 2025

Orlando, FL



Lightweight Surface Manipulation System (LSMS) unloading a rover from a lunar lander.

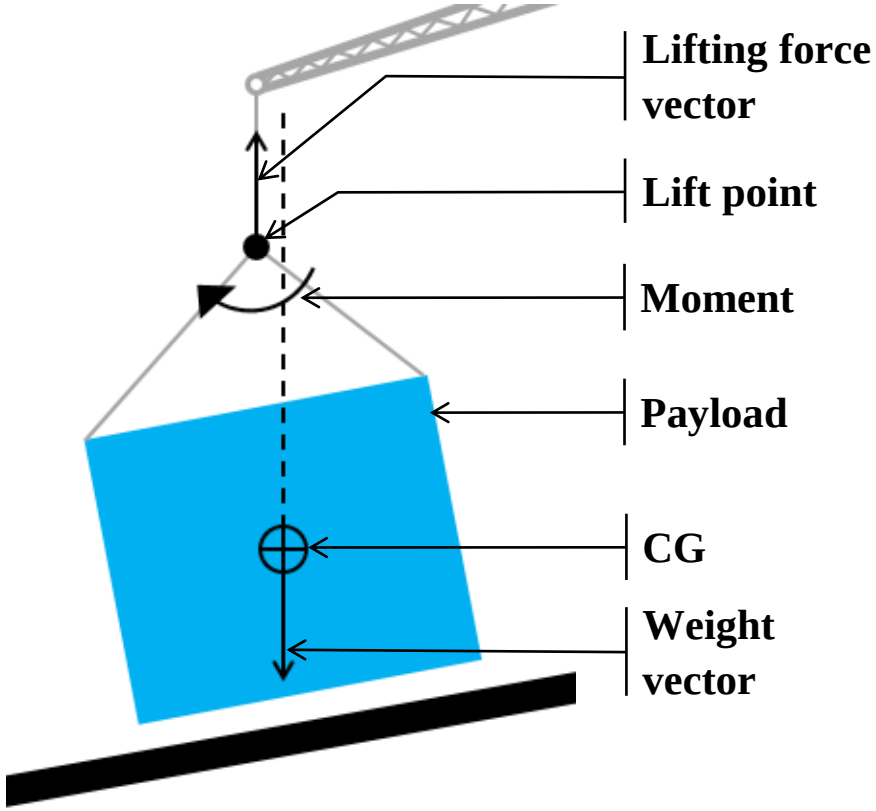
Outline

- Payload lifting scenarios and considerations
- Orientation control system prototype
- Orientation control algorithm development
  - 2D model
  - 3D model
- MATLAB design tool and graphical user interface
- Summary

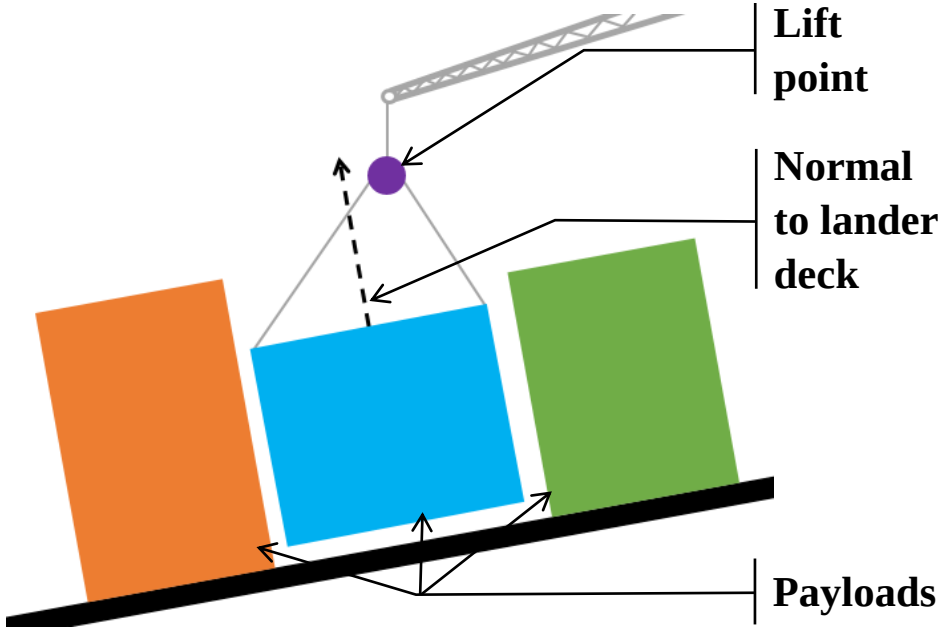
* The use of trademarks or names of manufacturers in this report is for accurate reporting and does not constitute an official endorsement, either expressed or implied, of such products or manufacturers by the National Aeronautics and Space Administration.

Payload lifting scenarios and considerations

- Offload payloads onto lunar surface autonomously
- Lander deck could potentially be inclined as much as 15 degrees
- Goal is to stabilize and control orientation of hoisted payloads to avoid collisions

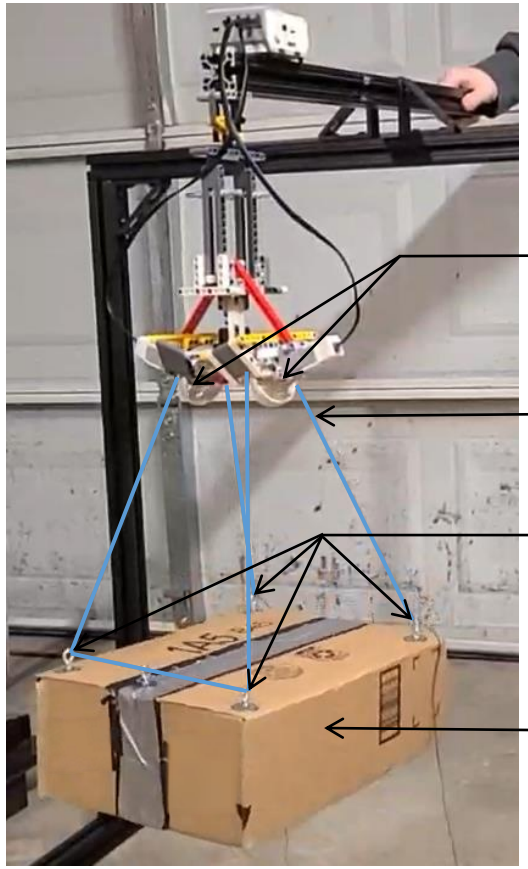


Moment due to misalignment of the lifting force and weight vectors.

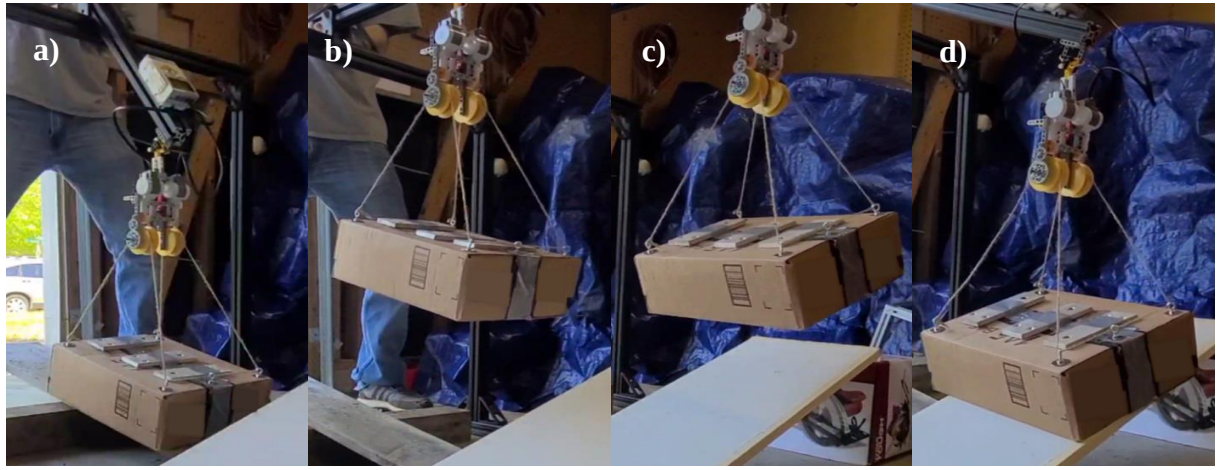


Payload being lifted off a crowded and inclined lander deck. The payload must be in equilibrium when lifted and move along a path normal to the lander deck to avoid colliding with adjacent payloads.

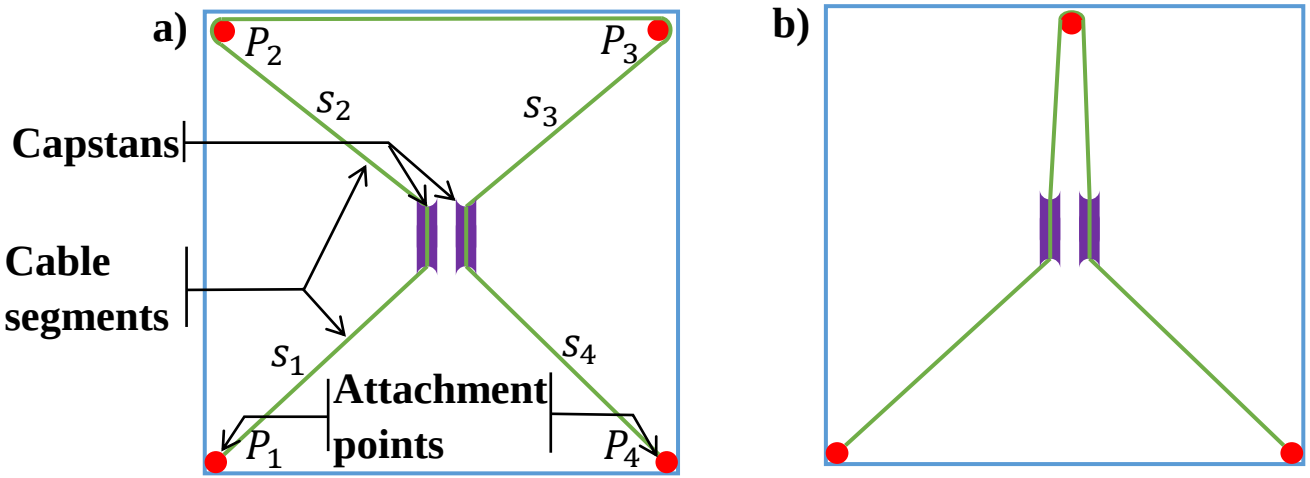
Orientation control system prototype



Auto-Rigging Payload Handling and Off-Loading System (ARPHOLS) LEGO prototype testing.



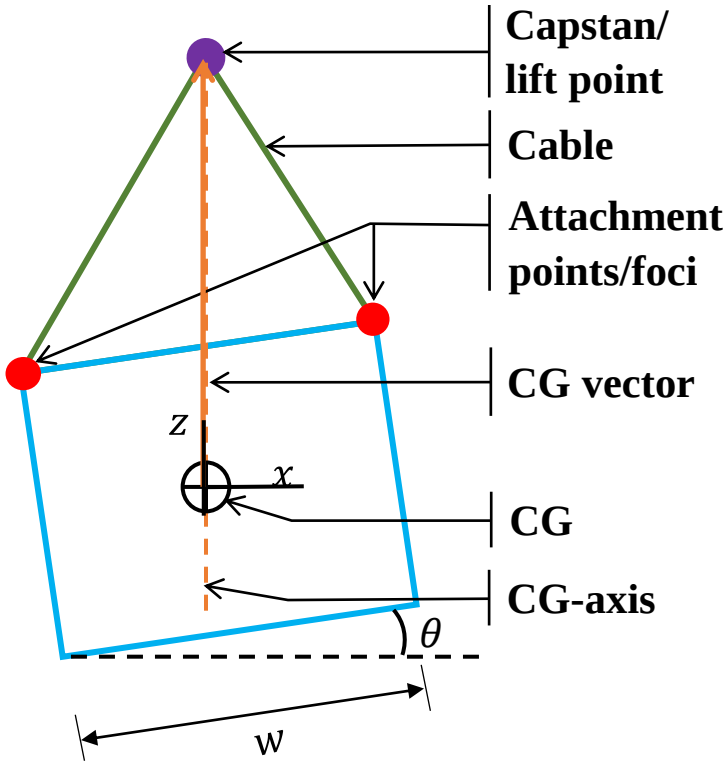
ARPHOLS prototype test sequence, lifting off one incline and offloading onto another incline.



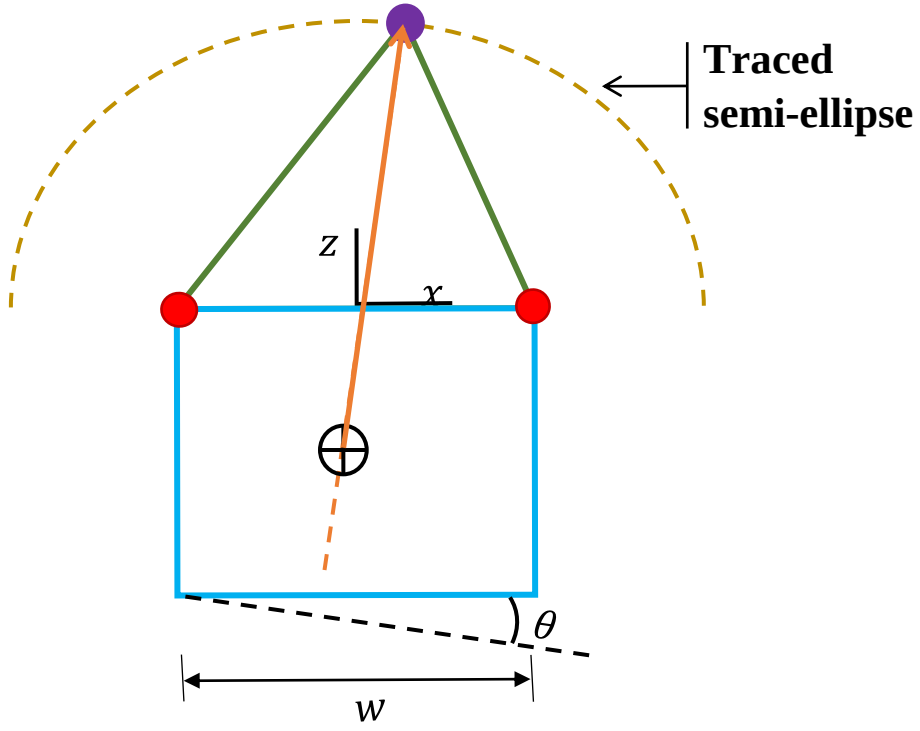
Payload top-down view for a) four attachment point configuration and b) three attachment point configuration.

Orientation control algorithm development – 2D model

- Goal is to calculate lift point location
- Lift point is located at intersection of CG-axis and semi-ellipse traced by capstan path
- CG-axis must be transformed from gravity reference frame to payload reference frame to solve for lift point location



2D model in the gravity reference frame with the origin fixed to the CG. Rotations are applied to the CG vector to transform it into the payload reference frame.



2D model in the payload reference frame with the origin fixed to the middle of the top of the payload. The capstan traces a semi-ellipse relative to the top of the payload as it rotates.

Orientation control algorithm development – 2D equations

System of equations

$$x = x_0 + a_l t$$
$$z = z_0 + b_l t$$

Parametric line equations

$$\frac{x^2}{a_e^2} + \frac{z^2}{b_e^2} = 1$$

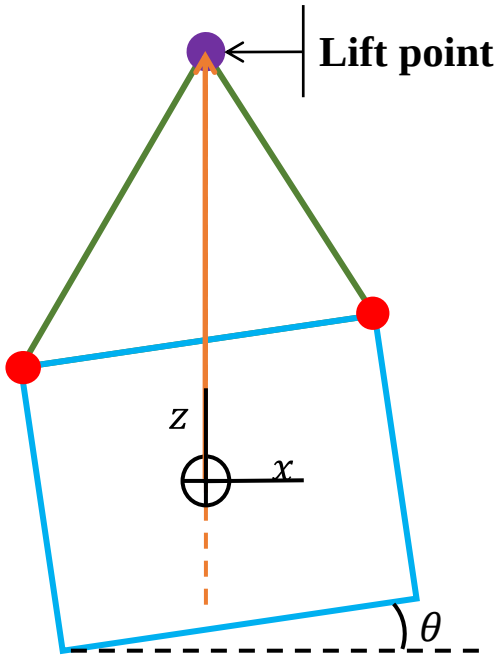
Ellipse equation

Solve simultaneously to find the lift point coordinates (x, z) and CG vector length t required to intercept the traced semi-ellipse

Rotated direction vector

$$a_l = \sin\theta$$
$$b_l = \cos\theta$$

Derived by applying the clockwise rotation matrix to a vertical unit vector located at the CG in the gravity reference frame

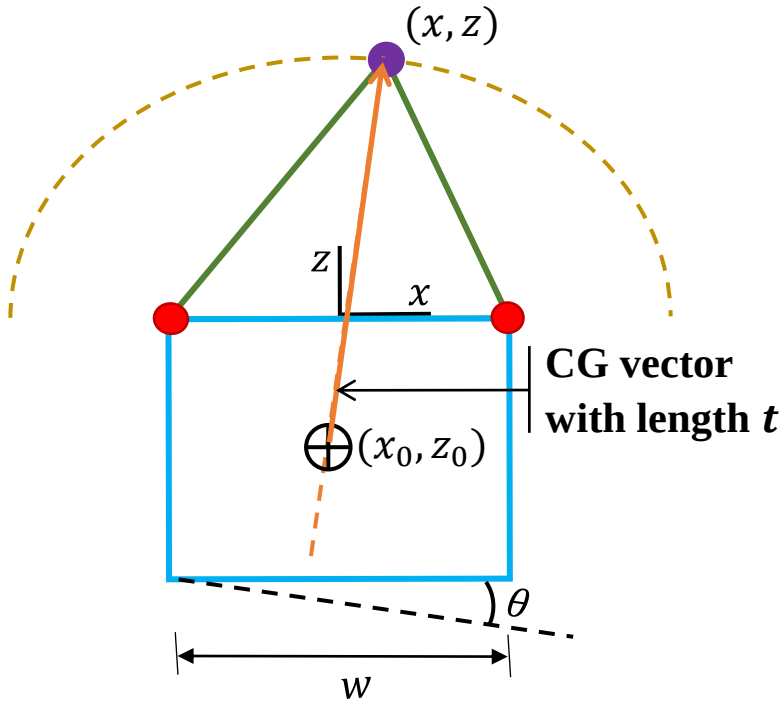


Gravity reference frame.

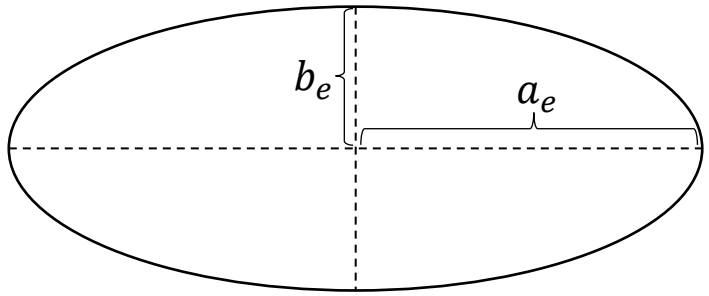
Ellipse semiaxes

$$a_e = \frac{L}{2}$$
$$b_e = \frac{1}{2}\sqrt{L^2 - w^2}$$

Derived by geometric analysis



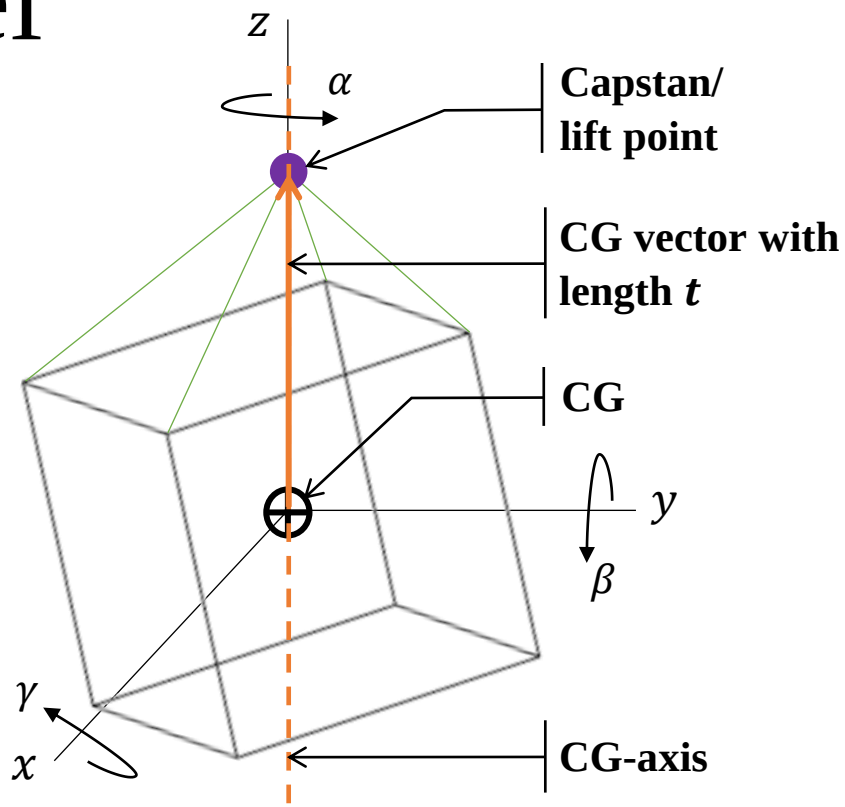
Payload reference frame.



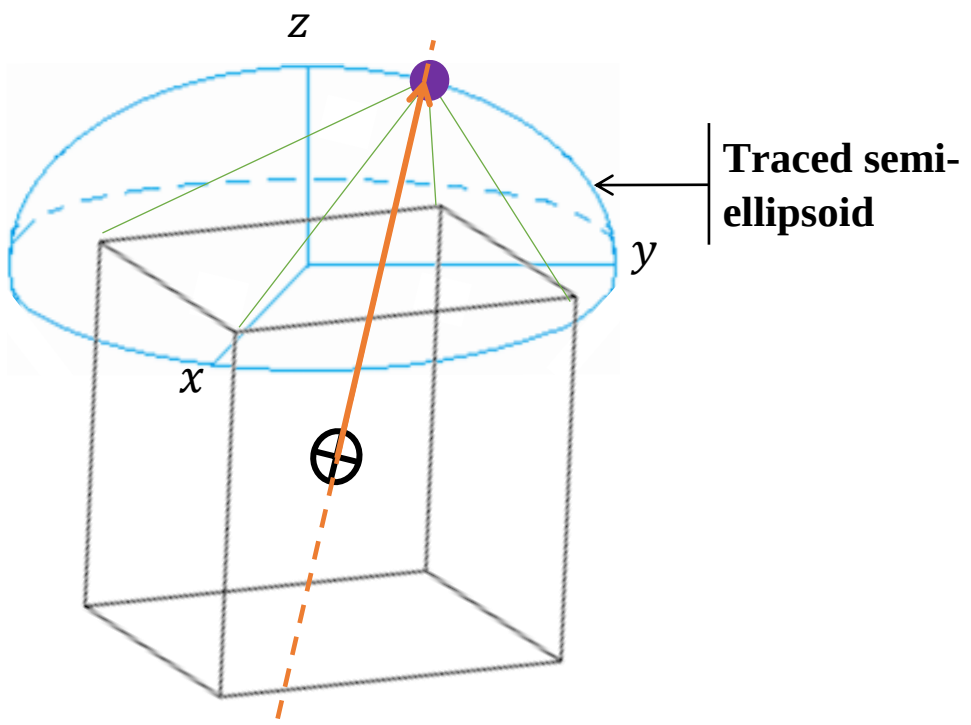
Ellipse with semiaxes labeled.

Orientation control algorithm development – 3D model

- Same process is followed from 2D model but with added dimension
- In payload reference frame, the capstan traces a semi-ellipsoid as it rotates



3D model in the gravity reference frame with the origin fixed to the CG. Rotations are applied to the CG vector to transform it into the payload reference frame.



3D model in the payload reference frame with the origin fixed to the middle of the top surface of the payload. The capstan traces a semi-ellipsoid relative to the top of the payload as it rotates.

Orientation control algorithm development – 3D equations

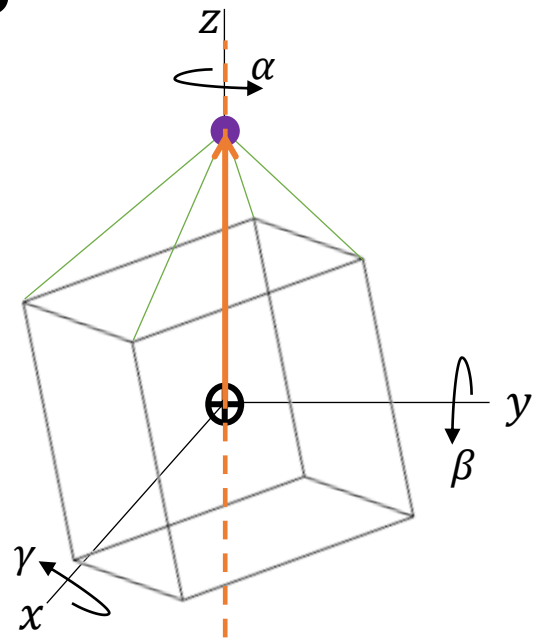
System of equations

$$x = x_0 + a_l t$$
$$y = y_0 + b_l t$$
$$z = z_0 + c_l t$$

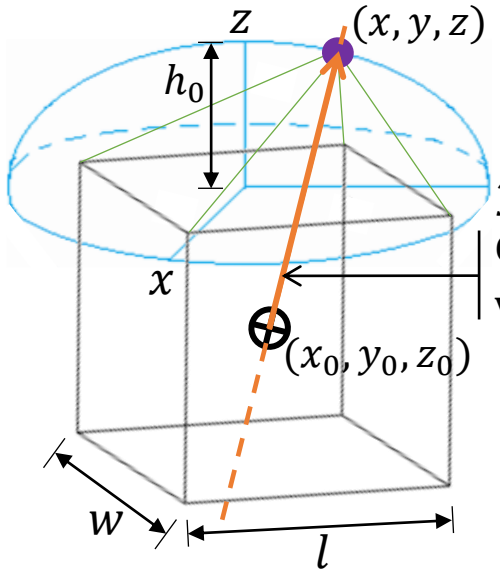
Parametric line equations

$$\frac{x^2}{a_e^2} + \frac{y^2}{b_e^2} + \frac{z^2}{c_e^2} = 1$$

Ellipsoid equation



Gravity reference frame.



CG vector with length *t*

Payload reference frame.

Rotated direction vector

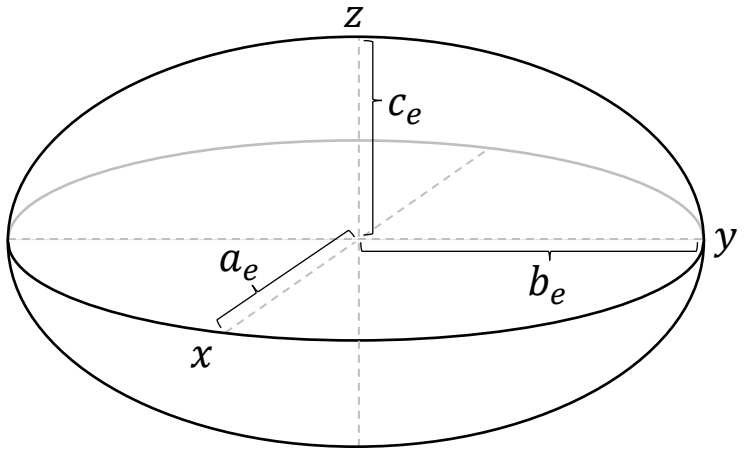
$$a_l = \cos\alpha \cos\gamma \sin\beta + \sin\alpha \sin\gamma$$
$$b_l = \cos\gamma \sin\alpha \sin\beta - \cos\alpha \sin\gamma$$
$$c_l = \cos\beta \cos\gamma$$

Ellipsoid semiaxes

$$a_e = \frac{\sqrt{h_0^2(4h_0^2 + l^2)(4h_0^2 + l^2 + w^2)}}{4h_0^2 + l^2}$$

$$b_e = \frac{\sqrt{h_0^2(4h_0^2 + w^2)(4h_0^2 + l^2 + w^2)}}{4h_0^2 + w^2}$$

$$c_e = h_0$$



Ellipsoid with semiaxes labeled.

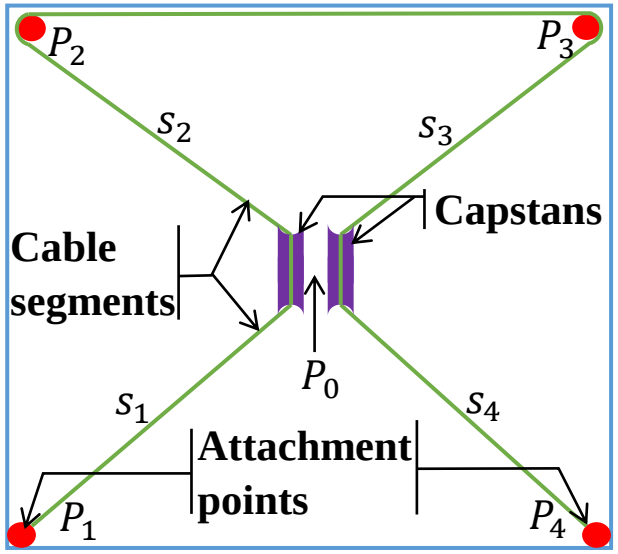
Orientation control algorithm development – cable segment lengths and capstan rotations

- Cable segment lengths

$$s_n = \sqrt{\left(P_{0,x} - P_{n,x}\right)^2 + \left(P_{0,y} - P_{n,y}\right)^2 + \left(P_{0,z} - P_{n,z}\right)^2}$$

$$P_1 = \left(-\frac{l}{2}, -\frac{w}{2}, 0\right) \quad P_2 = \left(-\frac{l}{2}, \frac{w}{2}, 0\right)$$

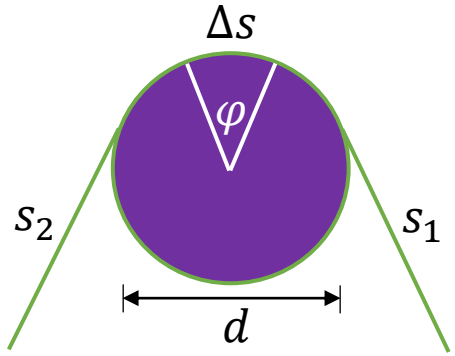
$$P_3 = \left(\frac{l}{2}, \frac{w}{2}, 0\right) \quad P_4 = \left(\frac{l}{2}, -\frac{w}{2}, 0\right)$$



Top-down view of the payload showing the cable segments.

- Capstan rotation angle (derived from arc length equation)

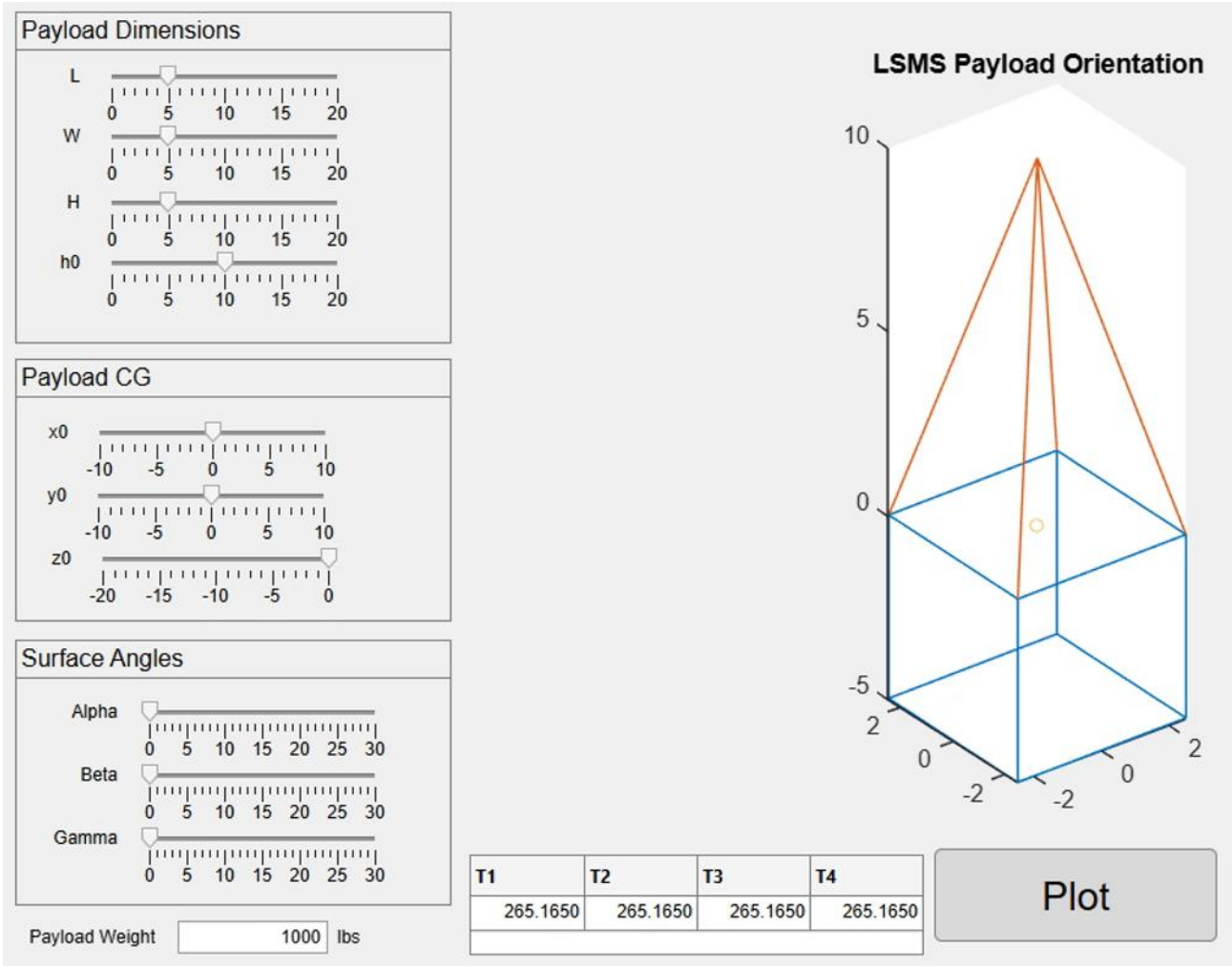
$$\varphi = 360\frac{\Delta s_n}{\pi d}$$



A counter-clockwise rotation of φ degrees of the capstan makes the cable travel through an arc length of Δs, shortening s_1 and lengthening s_2 by Δs. However, since s_2 and s_3 are coupled in the left diagram, $s_2 + s_3$ lengthens by Δs.

MATLAB design tool and graphical user interface

- Allows user to experiment with different payload parameters and surface angles
- Background code and algorithm solves for lift point, cable segment lengths, and tensions
- 3D payload is plotted to show resulting orientation
- Future version will read in measured surface angles from sensors and include capstan rotations



MATLAB app GUI that allows the user to adjust different payload parameters and incline angles. The resulting payload orientation is plotted, and the tensions (T1, T2, T3, and T4) in each cable segment are displayed.

Summary

- Automated orientation control system is necessary to safely offload payloads onto lunar surface
- Prototype was successfully developed and tested
- Primary control algorithms were developed for prototype
  - Lift point location
  - Cable segment lengths
  - Capstan rotations
  - Cable tensions
- MATLAB design tool and GUI was developed to perform calculations and display resulting orientation
- These prototypes and algorithms provide the initial components necessary to develop an autonomous payload offloading system

