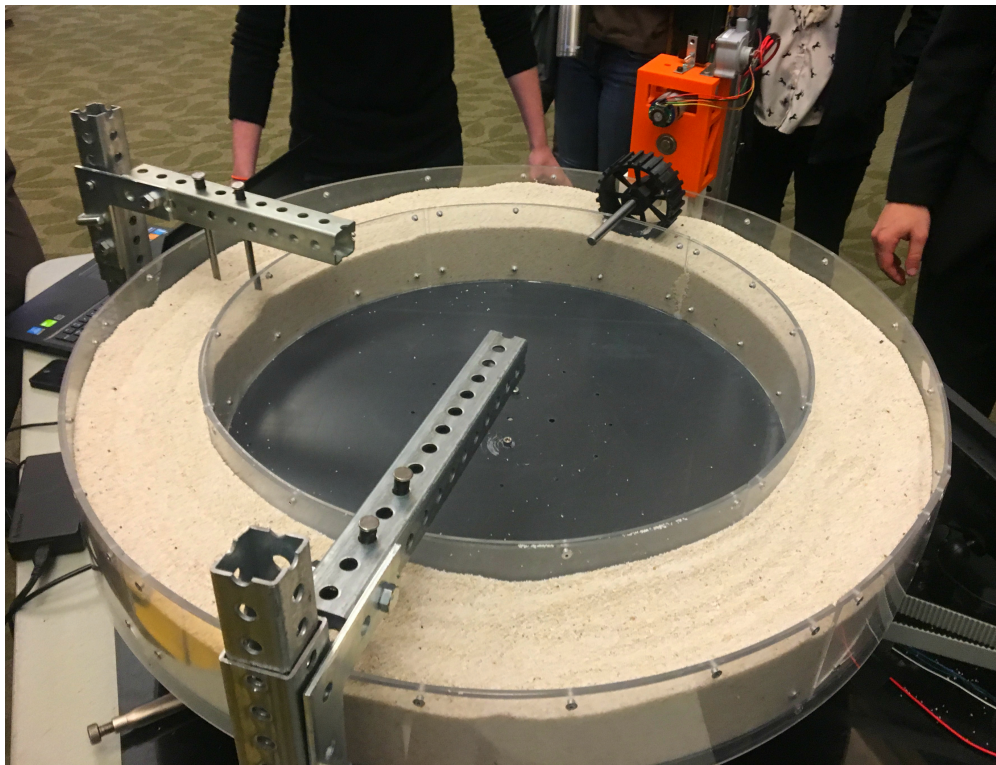


Reduced Gravity Airborne Mobility Testbed

NASA XHAB Final Design Report

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Memorandum

To: Paul Banicevic, Resource Prospector Mission, NASA Ames
From: The UVM xHab Challenge Team
Date: 5/3/2018
Subject: Final Design Report

The following report details the full process of the UVM team's execution of the eXploration Systems and Habitation (XHAB) 2018 Academic Innovation Challenge for the design of a low-gravity single wheel testing rig. The team would like to extend a sincere thank you to Paul Banicevic for offering his constant guidance and support throughout this process. His insights and instruction ensured not only the success of the project, but also provided the team with the opportunity to learn first hand from a respected and successful engineer. We all the strive to achieve the success he has, and hope to one day pass on the knowledge he instilled in us.

Abstract

Working in conjunction with the NASA Ames research center the goal of this senior design project was to develop a mobile test apparatus to enable wheel-soil interaction in a reduced gravity environment. In addition to collecting accurate wheel-soil interfacing data, a method of maintaining the density of the soil being used during the testing was developed to allow for repeatable testing conditions. In order to meet these goals an annular testbed was designed and built, providing an alternative to NASA's linear rover wheel design. The circular design allowed for a smaller footprint and lighter device. The team found it was possible to set the desired slip ratio by rotating both the annular testbed and wheel at different speeds. The Drawbar Pull force on the wheel was then measured with a torque sensor. Future work to be done includes improving the timing belt system, more robust control system, and more secure testbed base.

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1 Introduction

1.1 Problem Statement

NASA’s proposed Resource Prospector mission is an extraterrestrial mining expedition taking place on the poles of the moon. The aim of this mission is to create a rover that will perform ISRU (in-situ resource utilization) to foster more affordable and sustainable human exploration in deep space. Because of the steep and relatively unexplored terrain found at the poles of the moon these mining rovers will be facing some of the most difficult lunar navigation to date, thus creating the need for extensive testing of the rover wheels.

The goal of this project is to create a mobile test apparatus to enable wheel-soil interaction testing in a reduced gravity aircraft. How wheel-soil interactions behave differently in low gravity environments has never been studied before; this project proposes a method to experimentally test a small scale wheel in a low gravity aircraft to record how constantly variable gravities affect wheel performance.

1.2 Prior Art

To better appreciate and understand the work described in this paper a background of past wheel single wheel testers is presented below. Historical work has been invaluable to the design described in this paper, and important conclusions drawn from the prior art are included.

1.2.1 Apollo 15 Mission

The most important sources of prior art in this project were the historical archives at NASA. Extensive wheel tests were done to prepare for Apollo 15, the USA’s first lunar rover vehicle mission in 1971 (the U.S.S.R launched the first lunar rover, the Lunokhod, in 1970 but data from that mission is mostly unavailable). It is worth noting that space rover tires naturally have no air acting as the compliant material. Many different airless tire designs have been used over the years.

Figure 1 shows the original Apollo 15 zinc-coated woven piano wire tire with titanium bumpers and cleats. The wheel is in one of the many single wheel test mechanisms developed by NASA in the 1970’s. Wheels were tested both as a part of the main vehicle assembly and individually, and at least four extensive single wheel test beds were developed by NASA during this period. As a result of this testing, this wheel design was so successful it was used in the subsequent Apollo 16 and Apollo 17 missions. Unfortunately many of these testbeds were disassembled in subsequent decades and their designs lost.⁶



Figure 1: NASA Lunar Rover Vehicle (LRV) Testing Apparatus⁶

Interestingly, NASA has tested wheel soil interaction in low gravity before. In 1971 a test mechanism was placed in a C-135 aircraft and tested at $\frac{1}{6}G$ and 1% atmosphere. This test mechanism is shown in Figures 2.

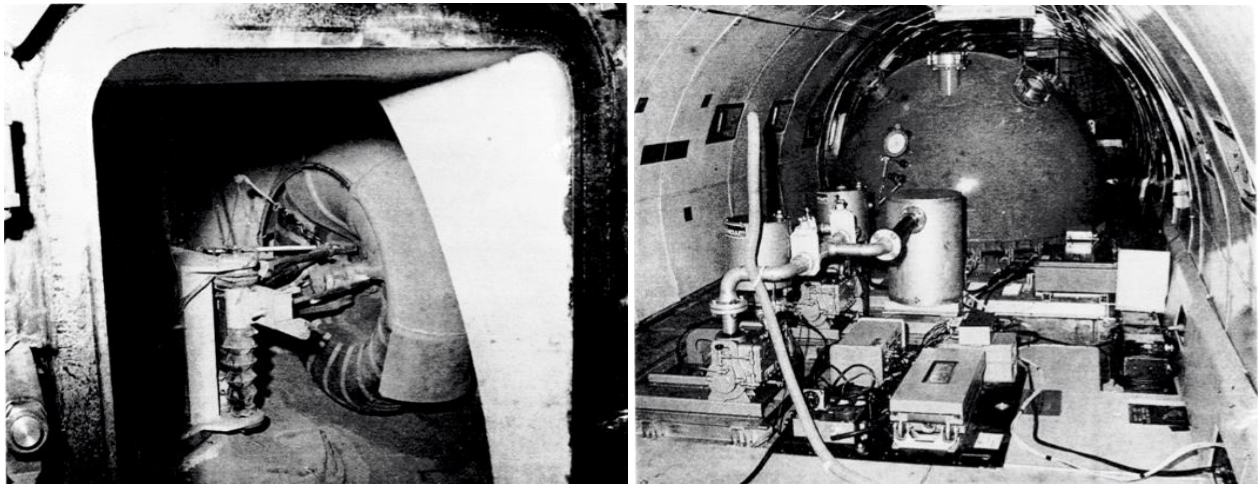


Figure 2: NASA Low Gravity LRV Test Apparatus Interior and Exterior⁶

This mechanism tests full sized wheels, which would be 81.6 cm in diameter and 23 cm wide. This design is testing for stacking and slinging of regolith; it specifically was interested in how wheel soil interaction would change in the vacuum environment of the moon. The design detailed in this paper will instead be testing for sinkage, slippage, and drawbar pull.

A comparable NASA test mechanism is the 1971 dynamometer system shown in Figure 3, which measured load, sinkage, pull, torque, and horizontal and angular velocity. This

system is testing for the same quantities as the XHAB proposed design, but was not placed in a low gravity environment. This design consisted of a truck pulled by the rover wheel along a linear path.

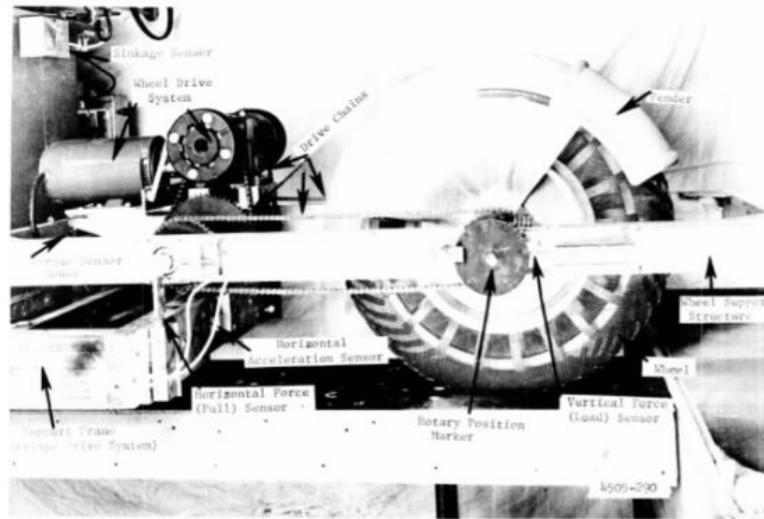


Figure 3: NASA LRV Wheel Mounted in Dynamometer System⁶

One of the features of the XHAB design is the ability to test motion continuously throughout a flight. NASA has also created several continuous motion testbeds before. Two such examples are shown in Figures 4. Both continuous motion designs were testing mostly for fatigue life, however, and have no wheel-soil interaction.

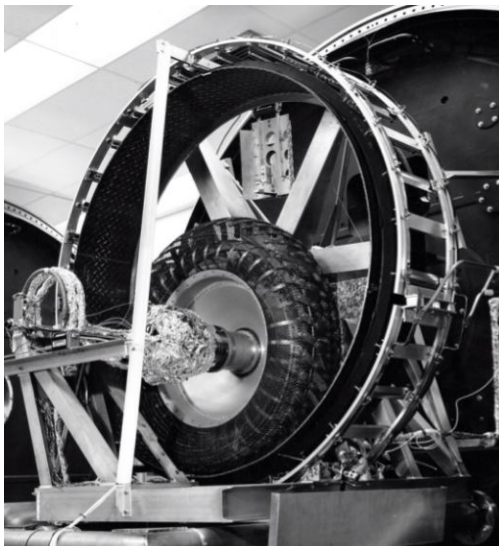
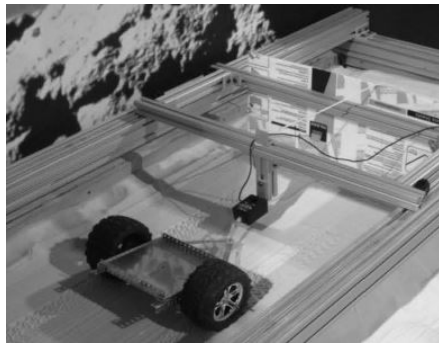


Figure 4: NASA Low Gravity LRV Test Apparatus Interior and Exterior

1.2.2 University Driven Single Wheel Test Apparatuses

In the quarter century since the Apollo missions focus at NASA has shifted off extensive wheel testing. As a result many universities across the US have been contracted to do further research on wheel soil interactions, and several comparable test fixtures have been produced. Three prominent linear motion single wheel test beds are shown in Figures 5 - 6.



(a) University of Maryland Planetary Surfaces Test Rig³



(b) Virginia Tech Rover Wheel Test Apparatus¹¹

Figure 5: Small Scale and Full Scale University Studies

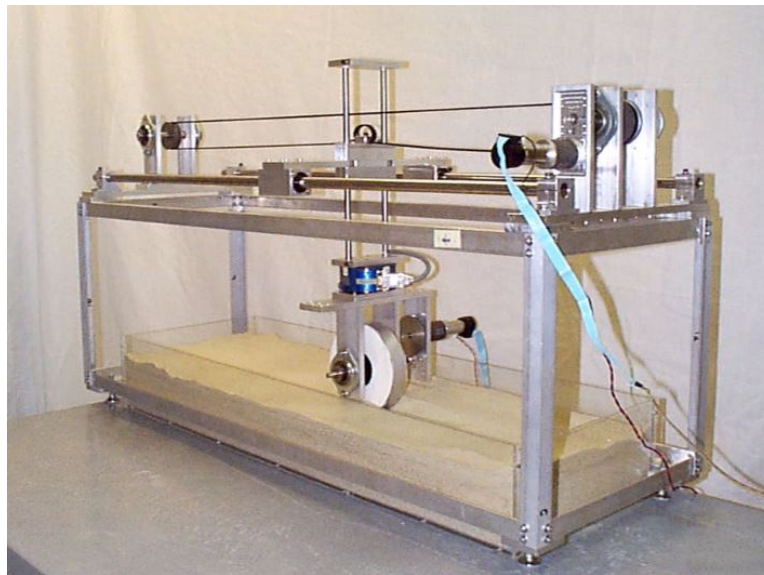


Figure 6: MIT On-Line Terrain Parameter Estimation for Planetary Rovers⁹

These linear test beds are essentially identical, operating under the same ratio of driven wheel to driven test bed methodology. A notable exception is Daniel Flippo's PhD thesis from the University of Oklahoma, shown in Figure 7.

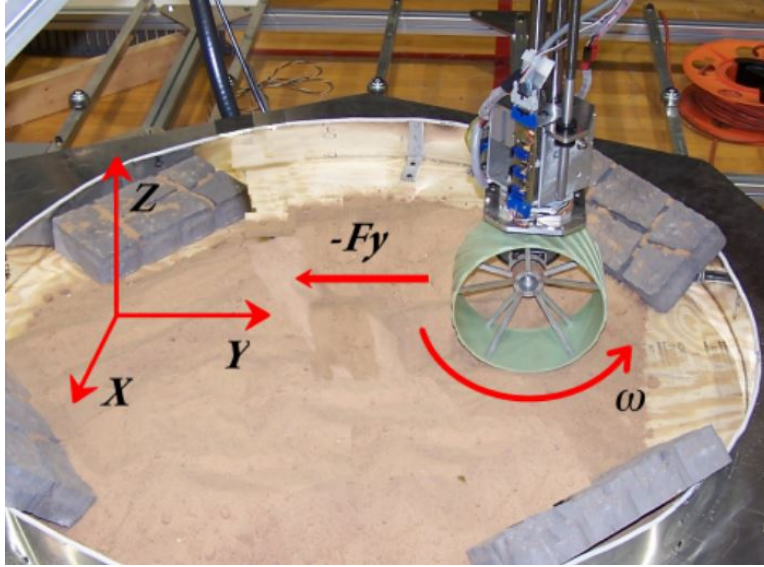


Figure 7: University of Oklahoma Rover Wheel Test Apparatus⁶

This design has a move-able testbed under a stationary, but driven, wheel. A network of motors under the floor of the bed control its movement and allow it to translate anywhere in the X-Y plane. Kinematically this testbed is identical to the linear motion movable wheel testbeds. This design has had a huge influence on the work generated in this report.

1.2.3 Japanese Designs

The majority of modern single wheel test beds are built either in the USA or in Japan. Notable Japanese designs are shown in Figures 8-9.

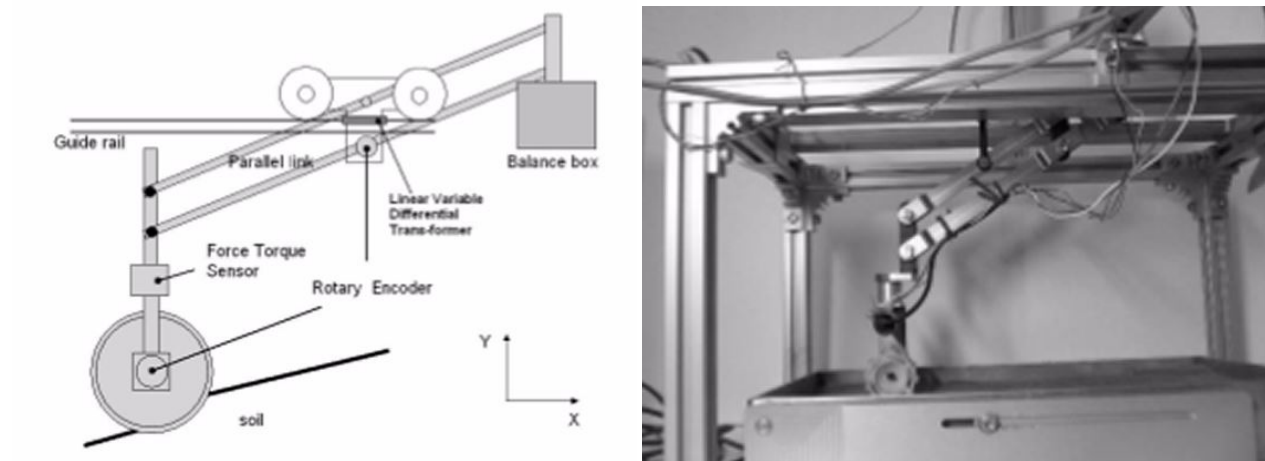


Figure 8: Japanese Consortium Test Apparatus⁶

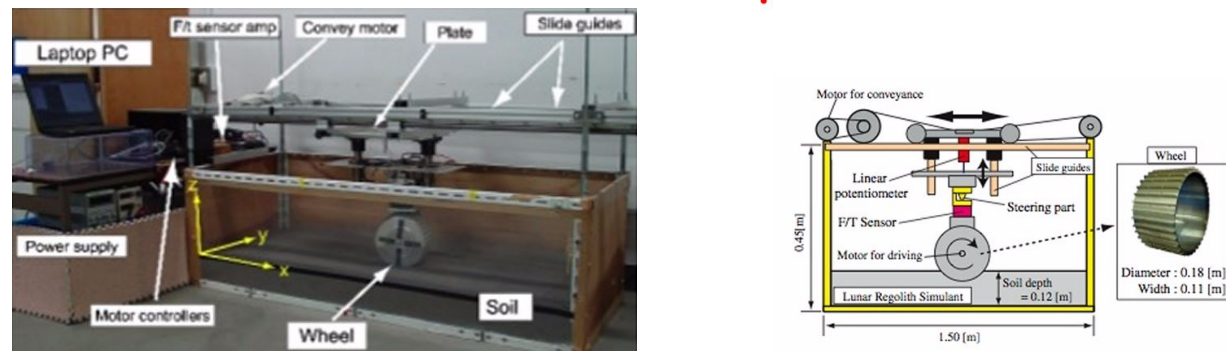


Figure 9: University of Tohoku Test Apparatus⁶

Again, these are both linear motion movable wheel designs, physically identical to the ones depicted above.

1.2.4 Current NASA Operations

NASA has a renewed focus on rover wheel testing after the Mars rover missions and, in the context of this project, in preparation for the upcoming Resource Prospector mission. The heart of this wheel testing is at NASA's Glenn Research Center in Cleveland, Ohio. This research center has NASA's only current single wheel tester, pictured in Figure 10.

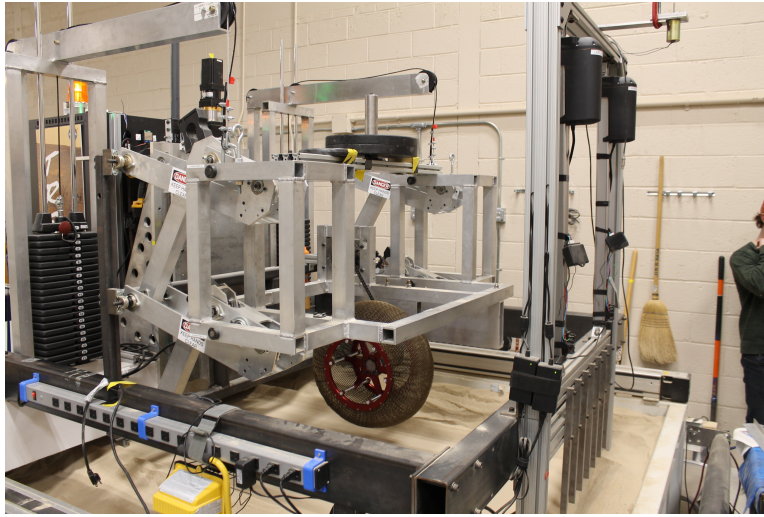


Figure 10: NASA Glenn Research Center Single Wheel Tester

This apparatus, used both for rover wheel testing and for excavation testing, also follows the linear path and movable wheel methodology. It is also one of the first testers to develop a method for resetting the density of the soil to a repeatable value, another important aspect of the XHAB design.

The design proposed in this paper combines aspects of all the previous testbed designs. The XHAB design is interested in sinkage, slippage, and drawbar pull data and specifically in generating a wheel slip % vs drawbar pull curve. Its rotational design allows for continuous motion while still enabling wheel-soil interaction, and the driven testbed gives the ability to passively reset the regolith to a baseline condition.

1.3 Design Objectives

There are four top level objectives for this design:

1. The design shall be safely mounted in a reduced gravity aircraft

This tester is designed to be placed in a reduced gravity aircraft and as such will need to integrate with the plane safely and securely. The portability required to transport and load the design into the fuselage seriously limits the potential footprint and weight.

The design must also consider parabolic flight patterns; on a lunar gravity pass forces in the plane range from $0.16G - 1.8G$. A typical flight does 40-60 parabolic arcs and each arc experiences about 30 seconds of true lunar gravity. The ability to run continuously is such a benefit because there is no need to tailor single tests to this time period as long as there is accurate identification of the periods of lunar gravity.

2. The reduced gravity testbed shall enable wheel-soil interactions in variable gravities

In order to fully test wheel-soil interaction four interaction states must be met: (1) drag, (2) drive, (3) stop, and (4) roll.

3. The design shall allow for direct comparison of data acquired at different gravities

The continuously running testbed must collect data at every gravity between $0.16G - 1.8G$ which allows direct comparison of wheel performance between any points within that range.

4. The design shall be composed of several sub-assemblies that interface with each other in a manner that allows functionality

Throughout this paper four different sub-assemblies will be referred to: (1) the Bed, referring to the annular track and its components, (2) the Wheel, referring to the wheel and its components, (3) the Regolith Resetting system, referring to the components the track passes through, and (4) the electrical system. These sub-assemblies must interface correctly with each other and the plane.

2 Design Options Comparison

Many design options were considered during development. The basic requirement of any chosen design is the ability to generate a Slippage vs. Drawbar Pull curve, an example of which is shown in Figure 11. Wheel slip is the relative motion between the wheel and the surface it is driving on, and is generally represented as the ratio between the two. Slippage of a wheel occurs when the force applied to move a vehicle is larger than the force of friction between the wheel and the ground can resist. Drawbar Pull is a force, and is defined as the difference between tractive effort available and tractive effort required to overcome resistance at a specific speed.

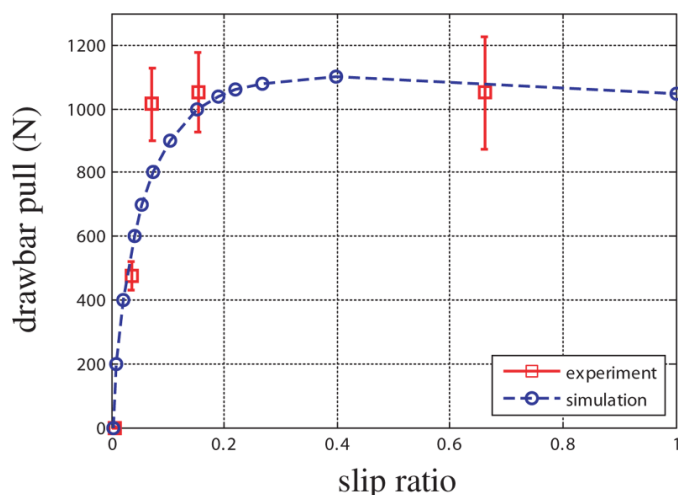


Figure 11: Example of a slippage vs drawbar pull curve¹

Additional useful information includes a Slippage vs. Sinkage curve. Sinkage is the vertical displacement of the wheel that occurs during operation. Any design chosen by the team would be required to generate this data during a flight in a reduced gravity aircraft with limited testing time and user interfacing.

Figure 12 shows the theory behind any single wheel tester. For a wheel tester to use wheel slip it needs to measure two relative velocities an angular velocity from the wheel ($\dot{\theta}$) and a linear velocity (v) which in reality would come from the rover. This linear velocity must be simulated in a single wheel tester either by driving the wheel over the soil or by moving the soil under the wheel in the opposite direction.

Other important values are the normal force of the wheel (F), the drawbar pull force (P), and the torque on the wheel (τ). The compaction of the soil (δ) and the compaction zone generated (l) are important considerations in the design. Any calculated values (in this case sinkage, slippage, and drawbar pull) will be a function of $(F, v, \dot{\theta}, \tau)$.

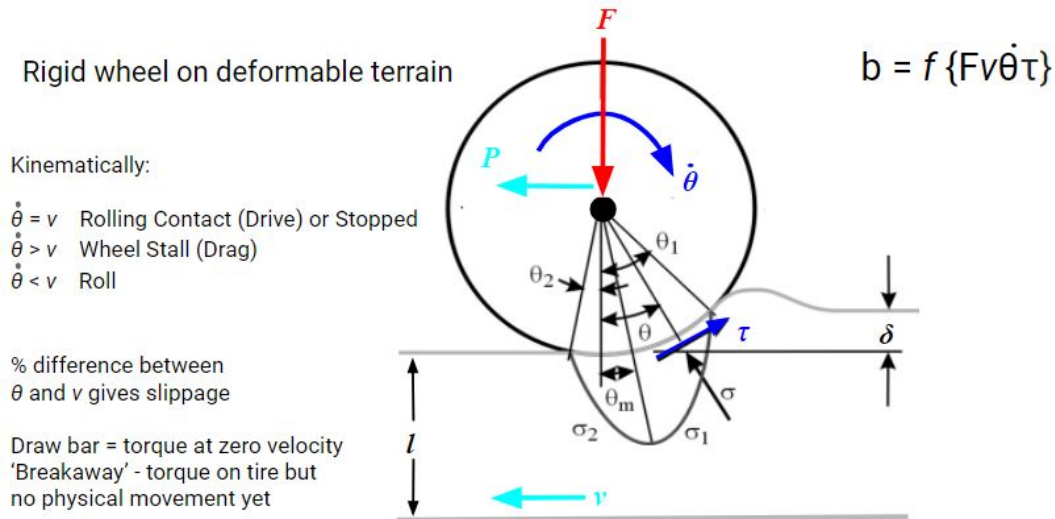


Figure 12: Forces and torques present during forward wheel motion *Adapted from 9*

2.1 Small Scale vs. Large Scale Design

The first major design decision the team had to make was whether the testbed should test a full scale rover wheel (half a meter in diameter) or to scale the wheel size down. If a full scale wheel was feasible it would be preferable to a scaled down version but it was determined that a full scale model would result in dimensions that violate the portability requirement of the project, with the regolith weight alone making it impossible for the design to be mobile.

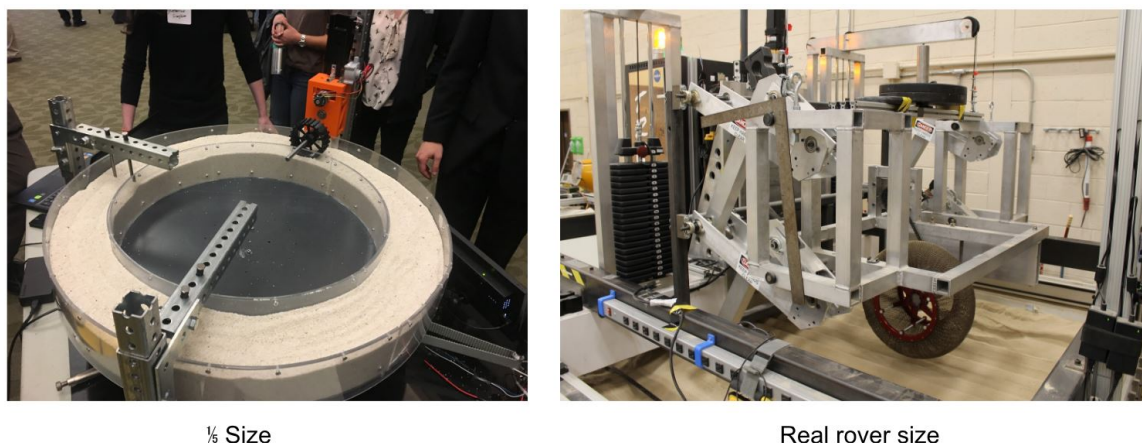


Figure 13: Single wheel tester size comparison (Left: XHAB tester, Right: Glenn tester)

The downside to scaling down the wheel is that mathematically the soil phenomena felt by a smaller wheel cannot be accurately scaled up. Correction factors exist, but it is not a perfect model. Ultimately it was decided that portability and specifically the ability to put

the testbed in an airplane was more important than scalable data so the team moved forward with a small scale design. The output is the comparison of how the tester operates in Earth's gravity with how it operates in variable gravity, with the comparison driving conclusions rather than the data itself. This decision is explained in further detail in Analysis [4.1](#).

2.2 Linear Design

Initially a linear design was considered, shown in Figure [14](#), as most existing wheel testbeds transverse a straight line with fixed endpoints. The wheel is driven at a set angular velocity and the wheel assembly is pulled along the track at a different linear velocity.

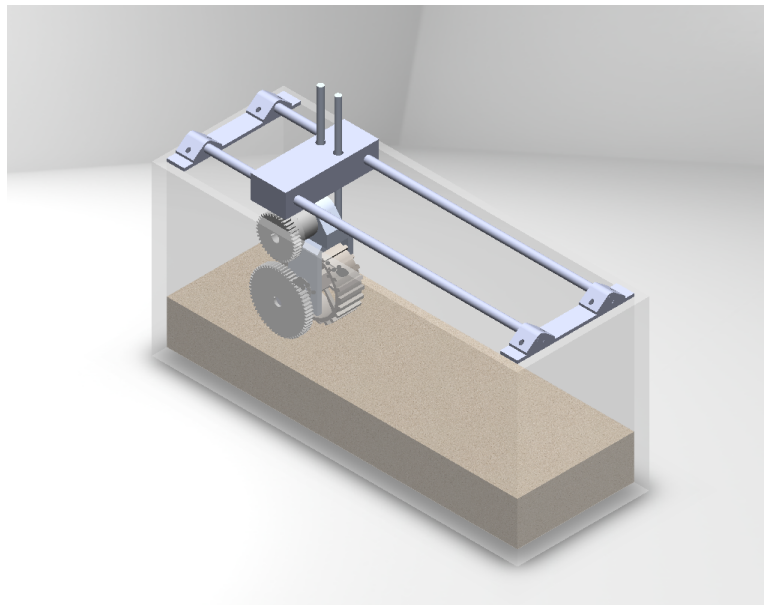


Figure 14: A preliminary linear testbed design

This system is hard to implement in an aircraft because the entire system must be reset after every test, which with the limited time available to run the test in the reduced gravity aircraft was not ideal. The length of track needed to get a full wheel rotation unaffected by starting and stopping conditions also resulted in a design that was acceptably large.

2.3 Annular Design

To address the problems with limited track length the design eventually evolved into a circular track, which allows for a test that can run continuously throughout the entire flight with no starting and stopping conditions.

The drawback of running through an annulus is that there is some amount of forced slippage as the wheel drives around the circle as the curvature of the bed means that it

cannot drive in a completely straight line. The angle of rotation affects slippage data because the inside of the wheel is slipping more than the outside of the wheel, a phenomena that decreases the more the radius of the annulus increases. For more information on the bed radius selection process, see section 4.3.

As the design evolved several different annular designs were created. This iterative design process is shown in Figure 15.

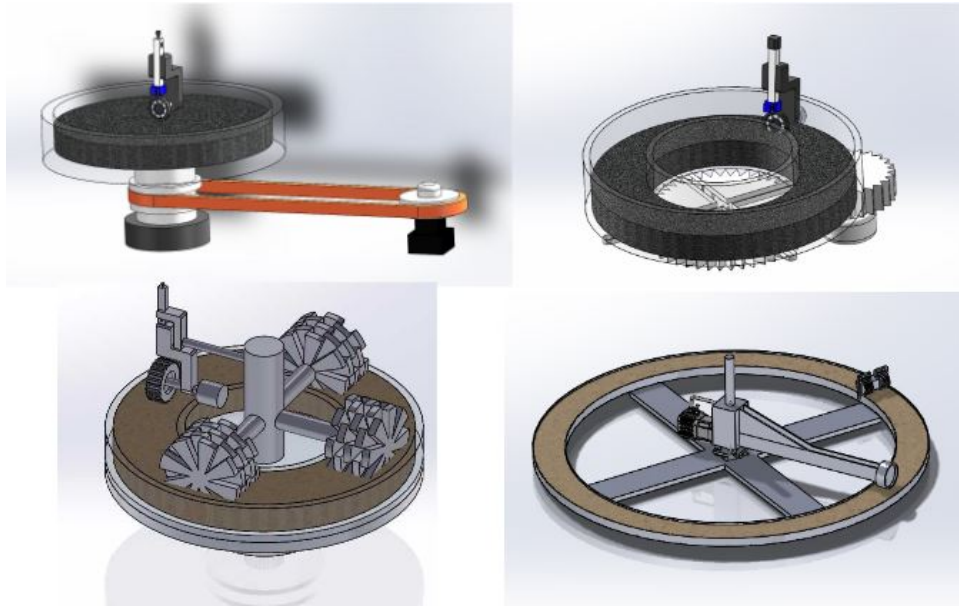


Figure 15: A preliminary annular testbed design

2.4 Movable Wheel vs. Stationary Wheel

After deciding on a rotational test bed the next key decision was where the linear velocity should come from in the design. Physically, moving the testbed under the wheel and moving the wheel over the testbed yield the same results. Two comparable prior art designs are shown in Figure 16. Flippo's design has a stationary wheel with a track moving underneath and the MIT design has a movable wheel that is translated over the track from the top by a driven drawbar.

The decision was made to keep the wheel stationary and move the testbed because while the stationary track did allow for wheel soil interaction it would be unable to simulate a drag interaction state (i.e. the wheel being pulled through the soil) and it also made resetting the regolith a complex task. By making the track rotate the regolith can be reset passively, one of the major functions of the proposed design.

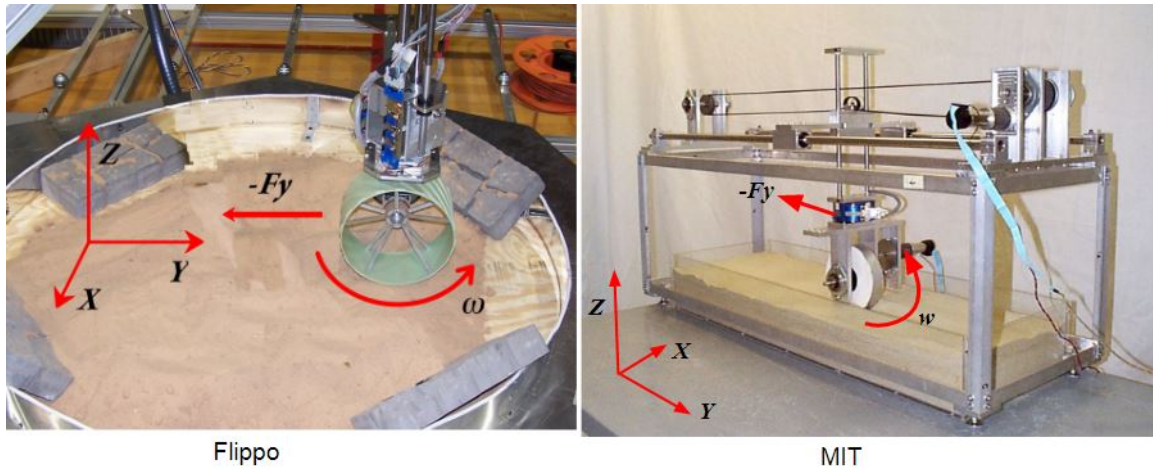


Figure 16: Relevant Physics of Prior Art: Flippo⁶ and MIT⁹

3 Final Design

The final design is pictured in Figures 17-18. It consists of a rotating annular trench, a stationary driven wheel, a passive regolith resetting system, and an electrical control system.

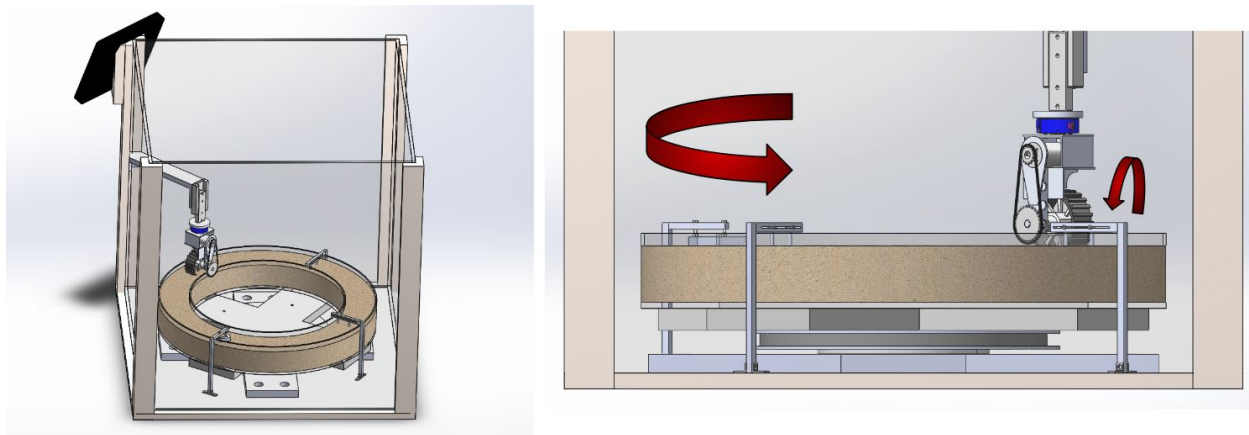


Figure 17: Theoretical CAD Model

Figure 18: Build of Design

3.1 Concept of Operations

The tester is designed to run continuously for the flight duration. The concept of operations is shown in Figure 19. Ideally the testbed will run without needing human interaction for the duration of the flight.

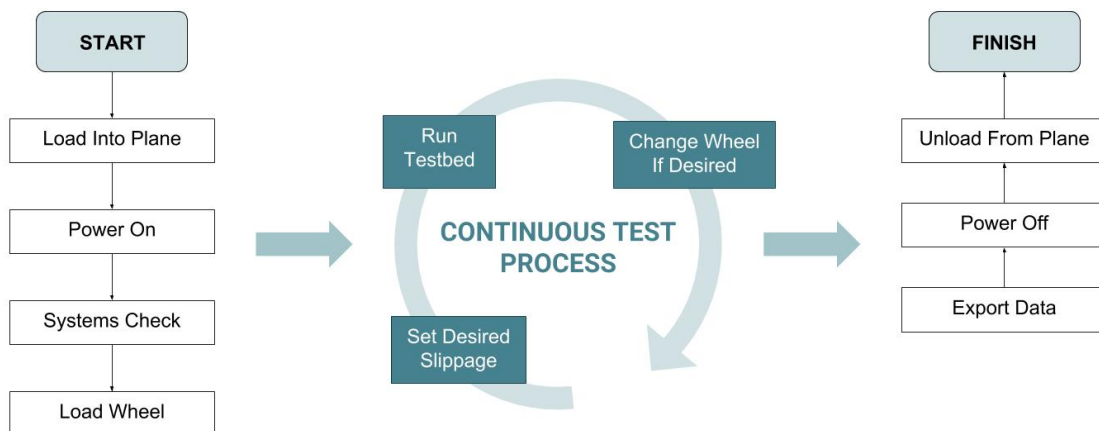


Figure 19: Concept of Operations

There is the option to change the user input at any point during the test. The user can change the PWM input or the effective slip ratio of the wheel at any time during the test. Figure 20 shows the view on the monitor as the test runs. It updates and refreshes continuously.

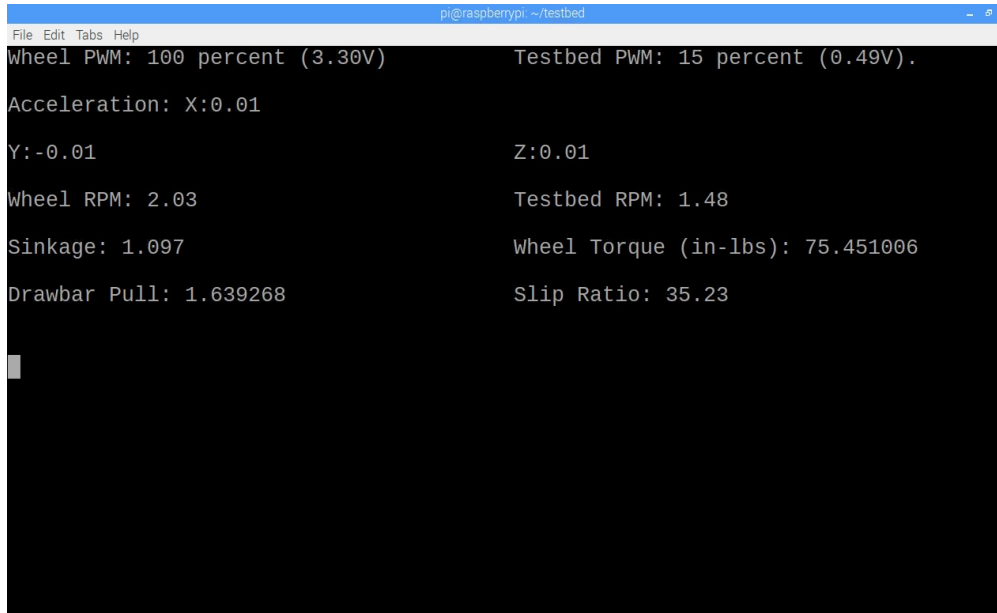


Figure 20: View of monitor user interacts with

The outputs that an operator can monitor throughout the test are the separate PWM inputs and output RPMs for the motors that run the wheel and the circular track and from that the slip ratio between them, the acceleration of the entire system in the XYZ directions (indicating how gravity is changing), the sinkage of the wheel, and the torque on the wheel and subsequent drawbar pull force. Figures 21 - 22 shows an example data file from a past run, saved by time stamp in a (cd /testbed/data/) directory.

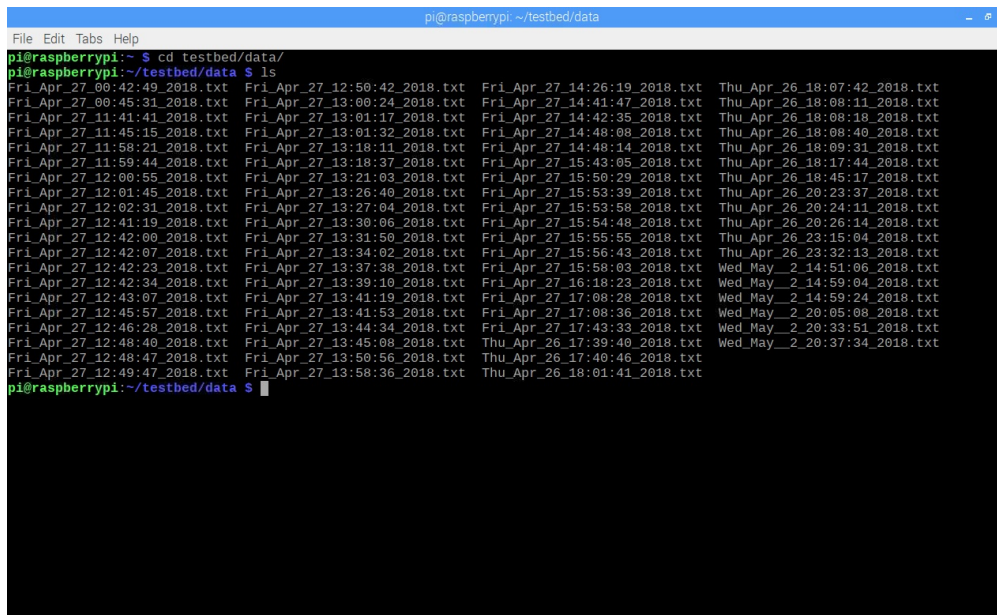


Figure 21: Excerpt of data saved from past tests

```

pi@raspberrypi:~/testbed/data $ cat Thu_May_3_00:54:50_2018.txt
0,0,0,0,0.00251458484586,0.00488589450501,-1187.11394869,1.10250737463,99.4581440623,2.15977516937,0,0,0,0,0,2.41260099411
0,0,0,0,0.00239032477021,0.00429341879132,-1278.16052601,1.10250737463,99.9480856587,2.17041445592,0,0,0,0,0,4.88687109947
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pi@raspberrypi:~/testbed/data $

```

Figure 22: Excerpt of saved data CSV

3.2 Mechanical System Functionality

3.2.1 Rotating Annular Trench

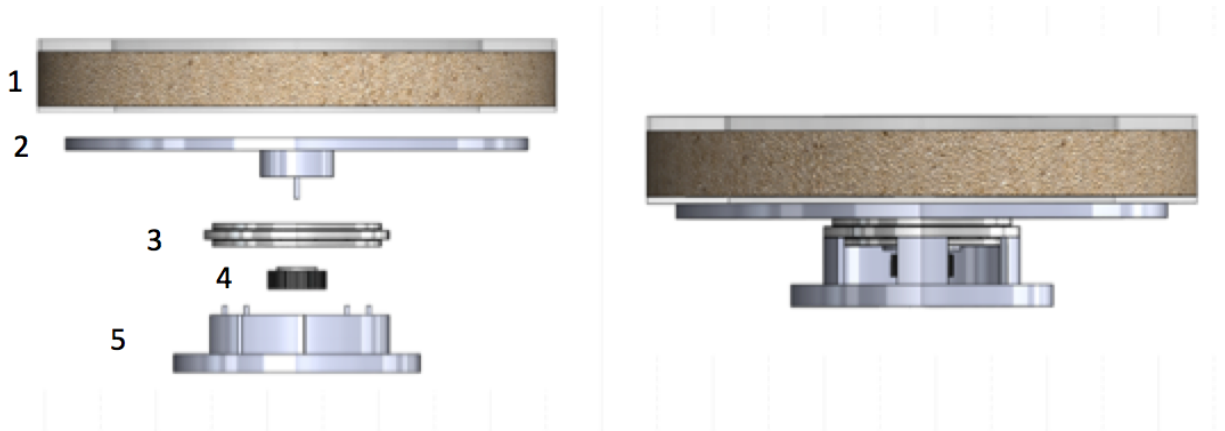


Figure 23: Testbed assembly

The key functions of the testbed are to contain the regolith simulant and to spin at a set speed. Figure 23 shows an exploded view of the rotating testbed system, which consists of a timing belt pulley system. Figure 24 shows a view of the belt system that rotates the bed. The bearing located under the bed (Component 3) is shown on the left, and the motor driving the system is shown on the right.

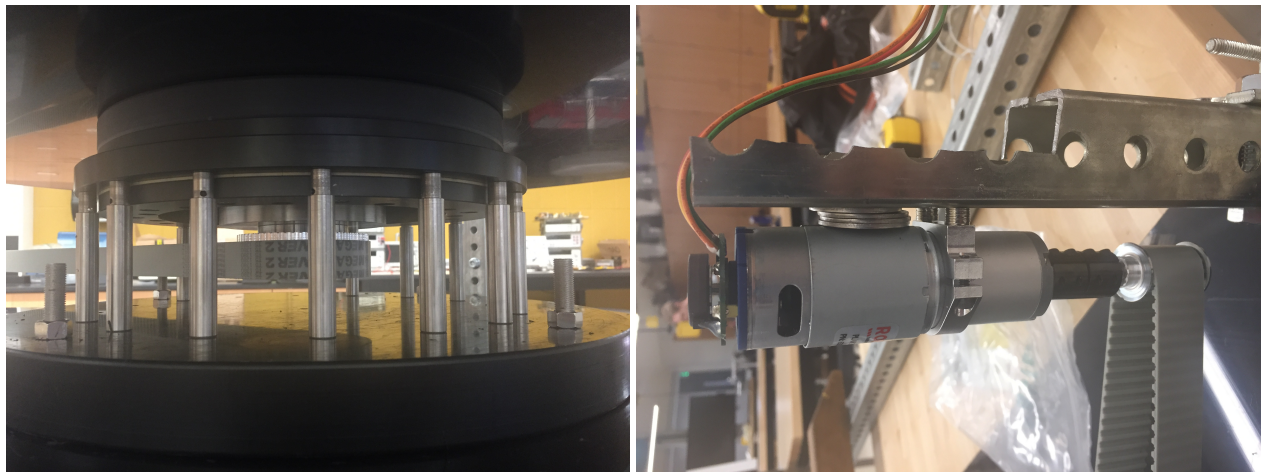


Figure 24: Testbed assembly details

Full technical drawings of this system are included in the attached technical package.

3.2.2 Stationary Driven Wheel

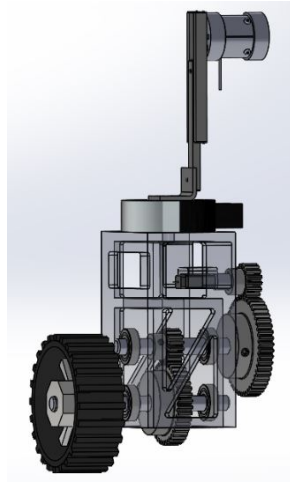


Figure 25: Wheel assembly design

The primary purpose of the wheel assembly, shown in Figures 25-26, is to allow wheel-soil interaction. Key features include a telescoping slide to allow the wheel freedom of movement in only the Z direction, a custom gearbox, a torque sensor to measure drawbar pull and a string potentiometer to measure sinkage. The load on the tire from this system alone is 29N and so no additional weights were needed to hit the correct scaled-down normal load applied from the rover.

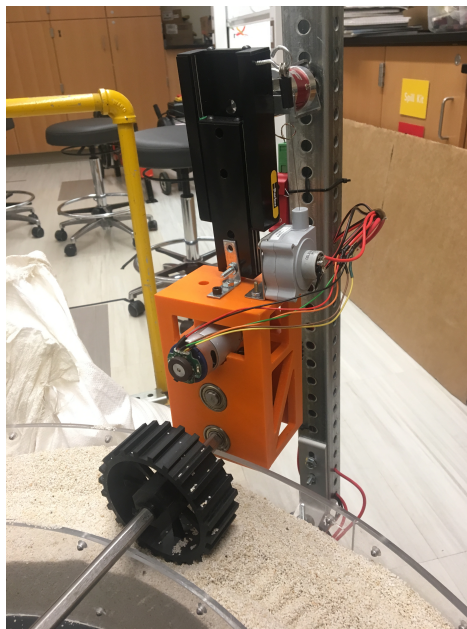


Figure 26: Final wheel build

3.2.3 Passive Regolith Resetting System

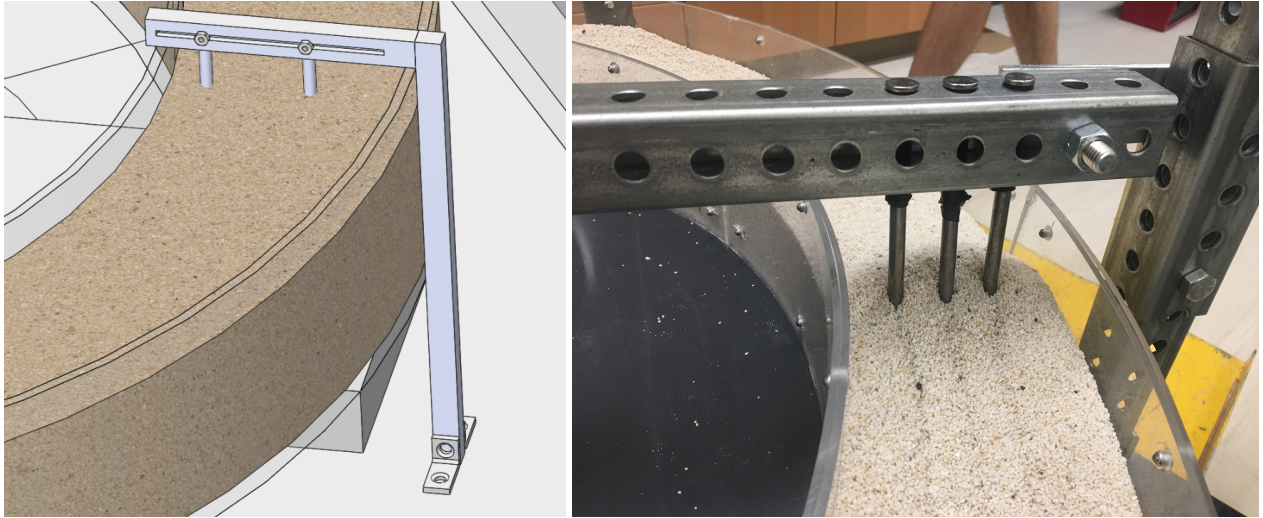


Figure 27: XHAB design regolith resetting system

The regolith management is handled by a system of stationary tines, shown in Figure 27. There are two stations of tines the bed rotates under. During rotation the regolith is dragged through the tines and returned to a uniform condition. The system was modelled after NASA Glenn's method to loosen and level soil, shown in Figure 28, although that system moves linearly along the testbed and the system in the XHAB design is stationary as the bed moves under it.

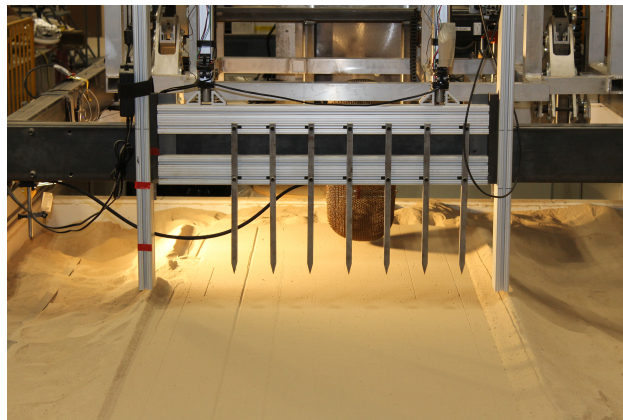


Figure 28: SLOPE Lab regolith management system

The ability to use a passive system to break up the compaction zone is one of the key advantages of this design and greatly simplified the system.

3.3 Electrical System Functionality

Figure 29 shows a high level overview of all the components used in the electrical system.

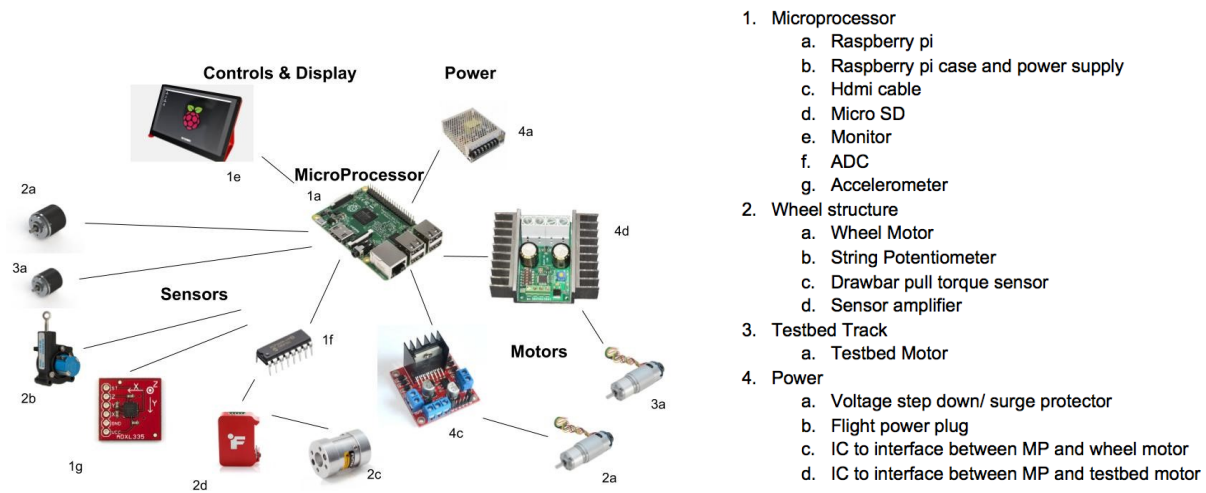


Figure 29: Electrical system overview

The main functions of the electrical system are to drive and provide control to the mechanical systems and control all the sensors. The design is run by a Raspberry pi and the final build is shown in Figure 30.

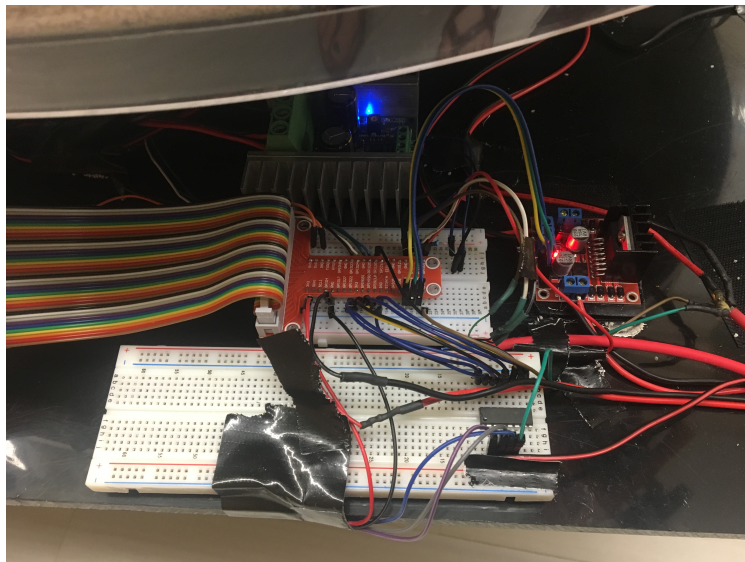


Figure 30: Detail of electrical system

3.3.1 Control System Logic Flow

A broad overview of the flow of software logic is shown in Figure 31.

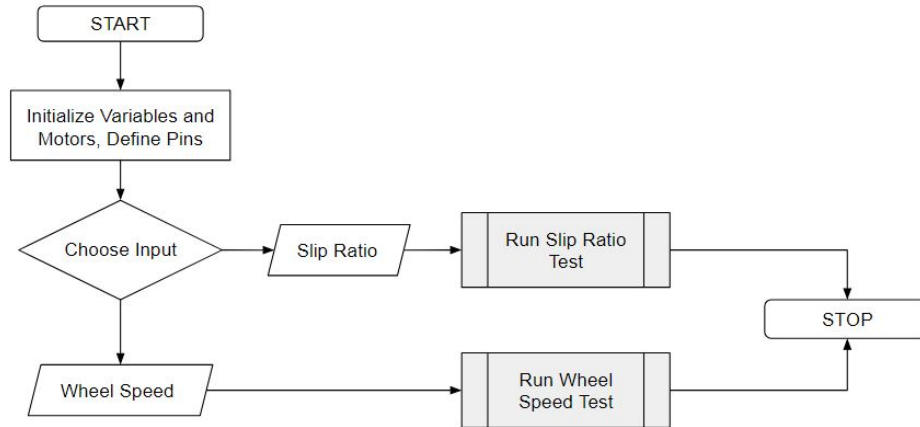


Figure 31: Baseline logic flow

There are two general types of control, one of which is chosen per test run in the main loop depending on if the user wants to set the individual speeds of the wheel and track or the slip ratio between them. These two scenarios are shown in Figures 32 - 33.

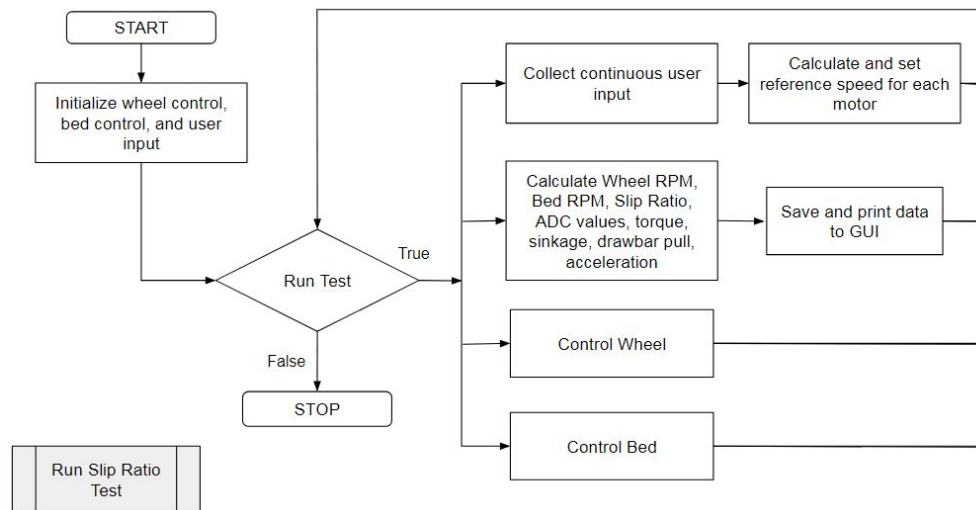


Figure 32: Logic for running a test with input slip ratios

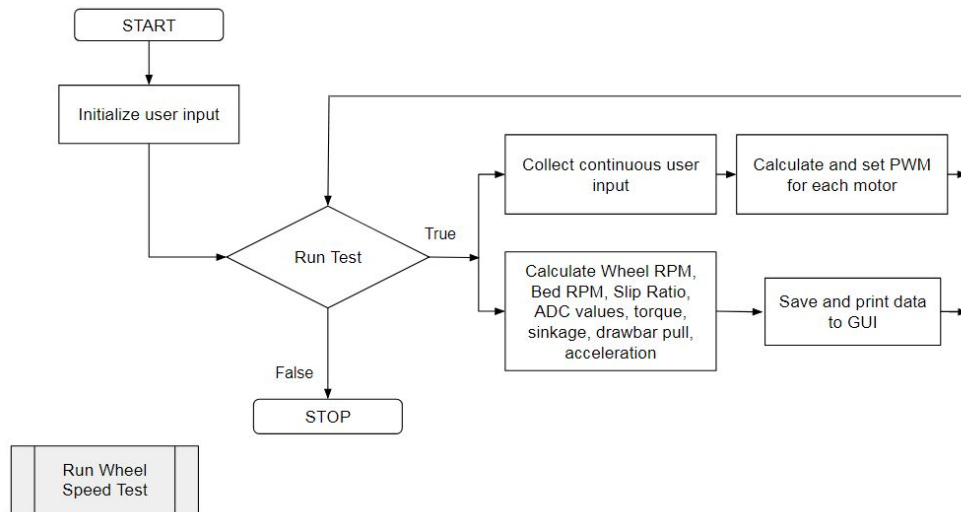


Figure 33: Logic for running a test with input wheel speed

Figures 34 and 35 show the circuit schematics for the motors and sensors respectively. Refer to the technical documentation for more information on how the chips in these schematics operate.



4 Critical Analyses

4.1 Scalability

The first major decision that must be made in regard to testbed design is whether to use a full scale or scaled down model of the rover wheel. The full scale rover wheel has a diameter of 50cm , and one requirement of the testbed is that it must be portable enough to be transferred to and fit inside the reduced gravity aircraft.

Research shows that terramechanical models do not behave the same way in small scale as they do in large scale. Firstly, small scale wheels under-predict sinkage measurements during testing. Bekker-Wong theory is known to yield modeling errors for wheel diameters under 50cm and forces under 45N . A correction called the Meirion-Spenko correction factor yields a more accurate estimation, however it does not account for phenomena present at the small scale that are otherwise negligible at large scale (i.e. ripples in the soil). Figure 36 shows the discrepancy between Bekker theory and the experimental results from small-scale wheel tests, as well as how the Meirion-Spenko correction factor shifts the Bekker model to a more accurate approximation. This approximation does not take into account how different phenomena occur as continuum mechanics breaks down at the micro-scale.

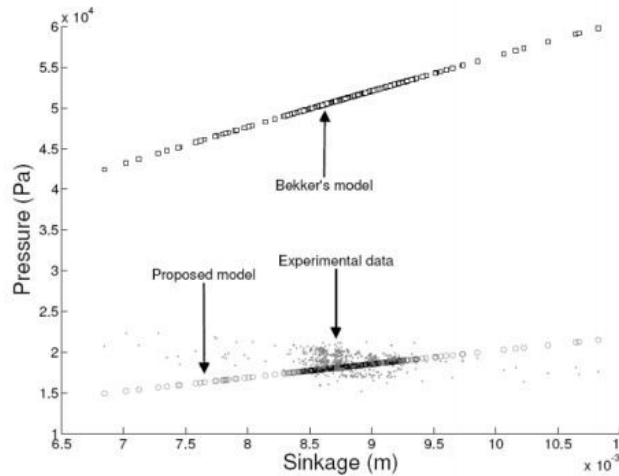


Figure 36: Experimental and Predicted Sinkage Differences⁷

A full scale single wheel tester has its own constraints, however. The minimum dimensions of the testbed, shown in Table 1, give the volume of soil needed for the design. For the lowest acceptable soil density of 1300 kg/m^3 the weight of the soil alone in a full scale build would be 838kg , which cannot be put in an airplane.

The most important goals of the design are to experimentally evaluate the effect of gravity on wheel traction and to develop a method for preparing soil on the low-G flight where you

Parameter	Value
Regolith bin dimensions	length: 1 wheel circumference width: 3x wheel width depth: 1 wheel diameter

Table 1: Track Parameters

have very short periods of time between tests and the gravity is constantly changing, and so even though the data collected in a small scale design may not be able to be accurately scaled up the comparison of data between tests run in different gravities is valuable. The XHAB design uses a wheel that is $\frac{1}{5}$ the size of the real RP wheels.

4.2 Compaction Zone

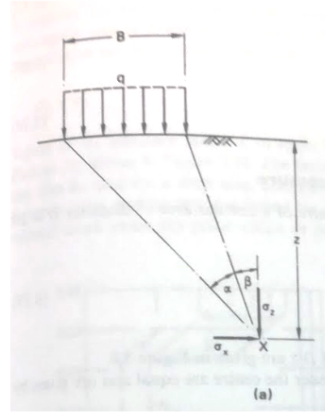
The final dimensions of the track are driven by the propagation of a compaction zone of the soil as the wheel drives over the surface and applies a load. The boundaries of the developing compaction zone must not reach the walls of the track for fully accurate data.

Strip area carrying uniform pressure

The stresses at point X due to a uniform pressure q on a strip area of width B are given in terms of the angles alpha and beta

$$\sigma_x = \frac{q}{\pi} \{ \alpha - \sin \alpha \cos(\alpha + 2\beta) \}$$

$$\tau_{xz} = \frac{q}{\pi} \{ \sin \alpha \sin(\alpha + 2\beta) \}$$



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$\sigma_x = 4.454\%$ of wheel pressure load

$\tau_{xy} = 8.529\%$ of wheel pressure load

At a depth of 9cm and a width of 12cm the impact of the walls is negligible

Figure 37: Track cross section analysis⁵

4.3 Bed Radius Selection

Because of the circular design of the bed the test wheel will be in a constant state of turning. While this approach offers a compact footprint, it also introduces additional wheel slip as the inner most point on the wheel must translate slower than the outer most. It is important to minimize this phenomena and approximate linear motion as closely as possible,

but there is a competing need to keep the bed radius as small as possible to minimize the weight. An equation to determine the relationship between wheel slip as a function of bed radius is derived below.

4.3.1 Input Variables

br = radius of bed

r = radius of wheel

gl = grouser length

ng = number of grousers

4.3.2 Calculated Variables

bc = bed circumference

nc = number of times a grouser must contact the soil to make it a full circle

dpc = degrees traveled per grouser contact

c = circumference of wheel

gs = space between grousers

4.3.3 Output Variables

$Slip$ = Slip on the outer most points of the grouser each time they contact the soil.

4.3.4 Derivation

$$c = 2 * \pi * r$$

$$gs = c/ng$$

$$bc = 2 * \pi * br$$

$$nc = bc/gs$$

$$dpc = 360/nc$$

$$Slip = \sin(dpc) * (gl/2)$$

4.3.5 Conclusions

The input variable for the equation described above are all known, with the exception of bed radius, which is to be determined. By inputting the known values into the equation, the following plot was generated for slip as a function of bed radius.

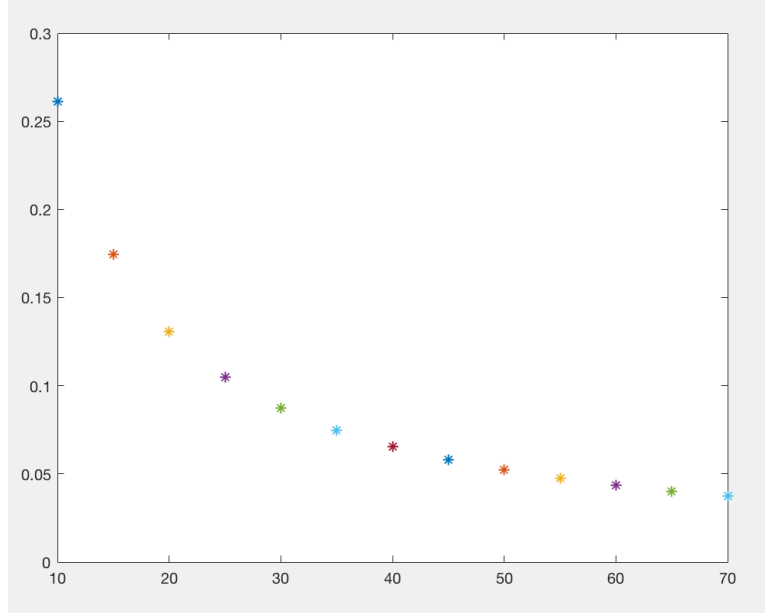


Figure 38: Slip(cm) as a function of bed radius(cm).

Using this plot, a compromise between minimizing both slip and bed radius was struck at 30cm, which equates to 0.0872cm of slip at each tip of the grouser. It was decided by the design team that these two values achieve both the goal of keeping the footprint small, and approximating linear motion.

For complete Matlab code, see section [9.0.1](#)

4.4 Motor Selection

To select a motor to drive the rotation of the bed calculations were done to predict the torque and power output required from the motor. To accomplish this an equation for the torque and power required was derived for the engine start-up period, as well as the continuous velocity period. From these equations it was concluded that a value for tine drag would have to be experimentally determined prior to selecting a motor.

4.4.1 Input Variables

RR = rolling resistance

TD = Tine drag

r_1 = outer radius of bed

r_2 = inner radius of bed

ω_w = angular velocity of wheel

rw = radius of wheel

ρ_s = soil density

ρ_b = density of material used to build bed

T_b = thickness of bed material

T_s = soil depth

H = height of bed walls

t = time required to get bed up to desired rotational speed

4.4.2 Calculated Variables

$mass_b$ = mass of bed

$mass_s$ = mass of soil

$mass_{ttl}$ = total mass

I_{ttl} = total rotational inertia of system

α_{req} = angular acceleration required to get bed up to speed in desired Δ time

4.4.3 Output Variables

ts_{req} = torque required for startup

tm_{req} = torque required for maintaining speed

Ps_{avg} = average power required during startup

Ps_{max} = max power required during startup

Pm = power required for maintaining speed

4.4.4 Derivation

$$\omega_b = \omega_w * ((r_1 + r_2)/2)/r_w)$$

$$\alpha_{req} = \omega_b/t$$

$$mass_b = ((\pi * r_1^2 - \pi * r_2^2) * T_b + 2 * \pi * r_1 * H * T_b) * \rho_b$$

$$mass_s = ((\pi * r_1^2 - \pi * r_2^2) * T_s) * \rho_s$$

$$mass_{ttl} = mass_b + mass_s$$

$$I_{ttl} = (1/2) * (mass_{ttl}) * (r_2^2 + r_1^2)$$

$$ts_{req} = RR + (TD * ((r_1 + r_2)/2)) + I_{ttl} * \alpha_{req}$$

$$tm_{req} = RR + (TD * ((r_1 + r_2)/2))$$

$$Ps_{avg} = ts_{req} * (\omega_b/2)$$

$$Ps_{max} = ts_{req} * (\omega_b)$$

$$Pm = tm_{req} * (\omega_b)$$

4.4.5 Conclusions

As shown above, the desired outputs are a function of twelve variables, of which all but tine drag and rolling resistance are known. It is hypothesized that the rolling resistance of the bed's rotation may be insignificant relative to that of the tine drag, potentially bringing to unknown variable count down to one. However, this would still leave the equation unsolvable without a value for tine drag. To find a value for this variable, calculations were done using two approaches. The first was based on frictional calculations of the estimated tine/soil interaction, and the second was done by approximating the soil as a fluid and the tines as a permeable dam. These two methods each required a significant amount of assumptions and estimates, and predictable yielded drastically different results (variance of greater than 99%). For this reason, it was concluded that the value for tine drag would have to be determined experimentally.

For complete Matlab code, see section [9.0.2](#)

4.4.6 Software Equations

The quantities this tester wants to collect are drawbar pull, slippage, and sinkage. Sinkage is taken directly from the a linear potentiometer, but drawbar pull and sinkage must be calculated from other measured values. The equations for finding each of these quantities are below.

$$DP = \frac{\tau}{4.44822(9.25 + z)}$$

4

$$Slippage = \frac{r_b \omega_b - r_w \omega_w}{r_b \omega_b}$$

4

In Figures 39 through 43 the analysis that the software performs are shown. There are five sensors that must be converted to meaningful data (two rotary encoders, string potentiometer, accelerometer, torque sensor). The string potentiometer, torque sensor and accelerometer all provided analog voltages, so the software calls functions to read values from the external ADC and then converts to meaningful units via info from the datasheets and personal calibration. The rotary encoders provide digital logic so pins directly on the pi measure these values.

```
def calcTorque(rawVal):
    #ADC pin 5, index 4 in ADC vector #V/in-lb
    cal=.9246/140.43
    return ADCBitsToVoltage(rawVal)/cal #returns in-lbs
```

Figure 39: Solving for torque in the software

```
def calcAcceleration(acc):
    global neutral
    calcAcc=[0,0,0]
    for count in range(3):
        calcAcc[count]=ADCBitsToVoltage(acc[count]-neutral[count])/.3
    return calcAcc
```

Figure 40: Solving for the acceleration in the software

```
def calcSinkage(rawVal):
    #5.25 full extension, 0 extension returns a binary value of 6
    extension=(rawVal-6)/1017.0*5.25
    zero=2
    return extension - zero
```

Figure 41: Solving for sinkage in the software


```

def getBedRPM():
    eventsPerShaftRevolution=34607.472  #8651.868 cycles per shaft revolution
    testbedEvents=0
    lastAState=0
    lastBState=0
    testbedTimeA=time.time()
    for check in range(100000):
        if GP.input(24)!=lastAState:
            lastAState=GP.input(24)
            testbedEvents=testbedEvents+1
        if GP.input(23)!=lastBState:
            lastBState=GP.input(23)
            testbedEvents=testbedEvents+1
    testbedTimeB=time.time()
    return testbedEvents/eventsPerShaftRevolution/(testbedTimeB-testbedTimeA)*60.0/2.0

```

Figure 42: Solving for bed RPM in the software

```

def getWheelRPM():
    eventsPerShaftRevolution=17700.624 #48 events for pre-gearbox shaft
    wheelEvents=0
    lastAState=0
    lastBState=0
    wheelTimeA=time.time()
    for check in range(100000):
        if GP.input(16)!=lastAState:
            lastAState=GP.input(16)
            wheelEvents=wheelEvents+1
        if GP.input(20)!=lastBState:
            lastBState=GP.input(20)
            wheelEvents=wheelEvents+1
    wheelTimeB=time.time()
    return wheelEvents/eventsPerShaftRevolution/(wheelTimeB-wheelTimeA)*60.0/7.5

```

Figure 43: Solving for wheel RPM in the software

Refer to the technical document for the full script.

5 Metrics for Success

	Design shall be safely mounted and portable per ICD 1.1	The reduced gravity testbed shall enable wheel-soil interactions	Design shall allow for comparison of data acquired at 1G, ½ G, and 1.8 G	The design shall be composed of several sub-assemblies that interface with each other in a manner that allows functionality
unsatisfactory	Size > 10x10x10 ft Weight > 500 lbs	0 out of 3 interaction states is allowed	Cannot acquire data	Assemblies do not interface with eachother
just tolerable	Size = 10x10x10 ft. Weight = 500 lbs Regolith is able to escape	1 out of 3 interaction states are allowed	Can only visually inspect sinkage	Mechanical assemblies interface with eachother but not with electrical system
adequate	Size <= 10x10x10 ft. Weight <= 350 lbs Interfaces per ICD 1.1 but regolith is able to escape	2 out of 4 interaction states are allowed	Raw data from sensors acquired	Assemblies interface with eachother but impede eachother's performance
good	Size <= 8x8x8 ft. Weight <= 200 lbs Interfaces with ICD 1.1 and regolith is safely contained	3 out of 3 interaction states are allowed	Can manipulate raw data and to obtain drawbar pull, sinkage, slippage at .	Assemblies interface with eachother with no interference but do not meet all the requirements of the interface documents
very good	Size <= 6x6x6 ft. Weight <= 150 lbs Regolith is safely contained and footprint is small enough to allow other experiements to fit in the 10X10X10 testing space	All interaction states are allowed and compaction zone generated does not exceed the boundaries of the soil	Can display real-time feedback from trials	Assemblies interface with eachother with no interference and meet all requirements of interface documents
Verification Method	Measure/Weigh Testbed, test electrical systems for compatibility per ICD 1.1	Testing	Testing	Testing
Verification Description	Metric Verification Test Results	Metric Verification Test Results	Metric Verification Test Results	Metric Verification Test Results
Verification Document	Metric Verification Test Results	Metric Verification Test Results and Compaction Propagation Test Results (RF 1)	Metric Verification Test Results	Metric Verification Test Results
Status (Green, Yellow, Red)	Green	Green	Yellow	Green
Result	Footprint and weight significantly below requirements, meeting electrical requirements	Dimensions set after compaction zone testing so compaction zone will not exceed boundaries of soil, interaction states not yet allowed		
Client Satisfaction	very good	very good	adequate	adequate
Notes			Team will only be able to test at 1 G	

6 System Requirements

Top Level Requirements

1. Design shall be safely mounted and operated in a Zero-G Corporation aircraft per ICD 1.1
2. The design shall be composed of several sub-assemblies that interface with each other in a manner that allows functionality
3. The reduced gravity testbed shall enable wheel-soil interactions in $\frac{1}{6}$ G
4. Design shall allow for comparison of data acquired at 1G and $\frac{1}{6}$ G

Top level requirements should encompass the design in its entirety. All other requirements will flow down in some way from the top level requirements listed above. Requirements 1 and 2 involve all external interfacing, including mechanical, electrical, and software connections with the device's environment and user and internal interfacing within the design itself. All requirements for the mechanical and electrical function of the testbed are placed under Requirement 3. Data collection and monitoring requirements flow down from Requirement 4.

Requirement Flow Down

From Requirement 1: (External Interfacing)

- Shall interface mechanically with the plane per ICD 1.1
 - Shall fit in cargo hold of 10 x 10 x 10 ft
 - Shall be a small scale design
 - Shall not exceed the maximum allowable payload of 200 pounds
 - Design shall be contained in a man-rated flight-safe case and no regolith shall be allowed to escape into environment
 - The testbed shall be able to withstand the macro-G forces generated during parabolic arcs of the plane
- Shall interface electrically with the plane per ICD 1.1

- The electronic system shall provide sufficient power for the testbed to function
- The power plug shall interface with the plane via ICD 1 provided by Zero G.
- Shall have surge protection
- Shall have an emergency shutoff
- Shall interface with the user
 - The controls shall interface with the user such that they are intuitive to use, and provide all control needed.
 - The monitor shall interface with the user such that all information needed by the user is provided.

From Requirement 2: (Internal Interfacing)

- The Electrical System shall interface with the wheel mounting system
 - Shall provide the necessary wheel speed for the set slip ratio
 - Shall provide the sinkage and RPMs of the wheel
- The Electrical System shall interface with the regolith housing
 - Shall provide the necessary regolith housing angular speed for the set slip ratio
 - Shall measure the RPM of the regolith housing
- The frame shall interface with the Regolith housing such that turbulence and other environmental noise should be minimized
- The regolith housing shall interface with the wheel mounting system
 - Shall provide unrestricted movement in the z direction
 - Shall measure the forces in the x and y direction

From Requirement 3: (Functional)

- Design shall implement sensors, controls, and storage
 - The system shall control the motors and sensors
 - * Shall allow user input
 - * The sensors shall collect and transmit data

- Design shall allow functionality of wheel
 - The design shall allow for testing of several slippage ratios
 - Wheel shall be driven
- Design shall allow functionality of testbed
 - Testbed shall house regolith
 - * The amount of soil relative to the size of the wheel shall be deep and wide enough such that the compaction zone generated does not exceed the boundaries of the soil.
 - * The container shall be large enough to securely hold the regolith
 - * Testbed shall allow for different testing simulants to be used
 - * The regolith shall remain within $\pm 100 \text{ kg/m}^3$ of its baseline for multiple tests
 - The design should reset the regolith to a level starting orientation between tests
 - The design should maintain the homogeneity of the regolith through multiple tests by resetting the regolith
 - Testbed shall be driven
 - * The testbed shall collect data continuously
 - * The reduced gravity testbed shall be resettable in between tests.

From Requirement 4: (Performance)

- Design shall operate at both 1G and $\frac{1}{6}$ G
 - The design should mechanically filter unwanted noise from data
 - * Shall account for vibrations from turbines
 - The design should electrically filter unwanted noise from data
 - Shall withstand the maximum force imposed by parabolic flight
- Design shall collect data
 - The rig shall record: sinkage, slippage, and drawbar pull
 - Shall allow for visual inspection of wheel-soil interaction

- Software shall manipulate data
 - Should have real time display of sinkage, slippage, and drawbar pull
 - Shall allow for final result of slippage vs. drawbar pull curve

All lowest level requirements inform the relevant design-to specifications shown in engineering drawings of parts, software flowcharts, electrical drawings, and final dimensions.

8 Conclusion

8.1 Recommended Future Steps

Based on the effectiveness of the prototype outlined in this report, it is recommended that a final build be made with a few design amendments.

- Include a metal mounting floor for increased ability (this build used a plastic floor that could not fully withstand the forces)
- Include a user friendly belt tensioner for the bed motor drive-train
- Redesign wheel mounting assembly for increased stability
- Create a more refined user interface

With this improvements made it is recommended that a round of testing be completed to confirm the repeatably and functionality of all aspects of the design. Upon successful testing the final product would then be recommended for use in a low gravity flight to analyze the effects of gravity on wheel-soil interactions.

8.2 Lessons Learned

Through this project the team has been exposed to a variety of new challenges that offered meaningful real-world lessons and opportunities for growth. One example was the importance of the planning stage of the project. When the team worked towards the SDR and PDR, we lacked the perspective to see how the work we were doing fit into the larger context of the project as a whole. For this reason, in hindsight, we feel we approached the these initial stages with a narrow perspective, simply aimed at generating the documents needed to meet the presentation's criteria. Now having completed the project, we have a better understanding of why the criteria is what it is, and how it is a critical piece in enabling a smooth and successful build.

Another subject we learned about was the process of working with external contractors. We were surprised to find a number of significant challenges with this process, such as meeting time lines, and maintaining quality. Were we to do this project again, we would make sure to clearly define expectations with all contractors, and plan on longer lead times than what is originally claimed.

Finally, we also gained great perspective on the role of personal responsibility within a group project. We experienced first hand how one persons missed assignment can have

effects that propagate throughout the group and end up being a hindrance to everyone's individual work. Having completed this project, we all now place a heightened importance on making sure we accomplish what we say we will, in the time we said we would.

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