Development of Autonomous Excavation Algorithms

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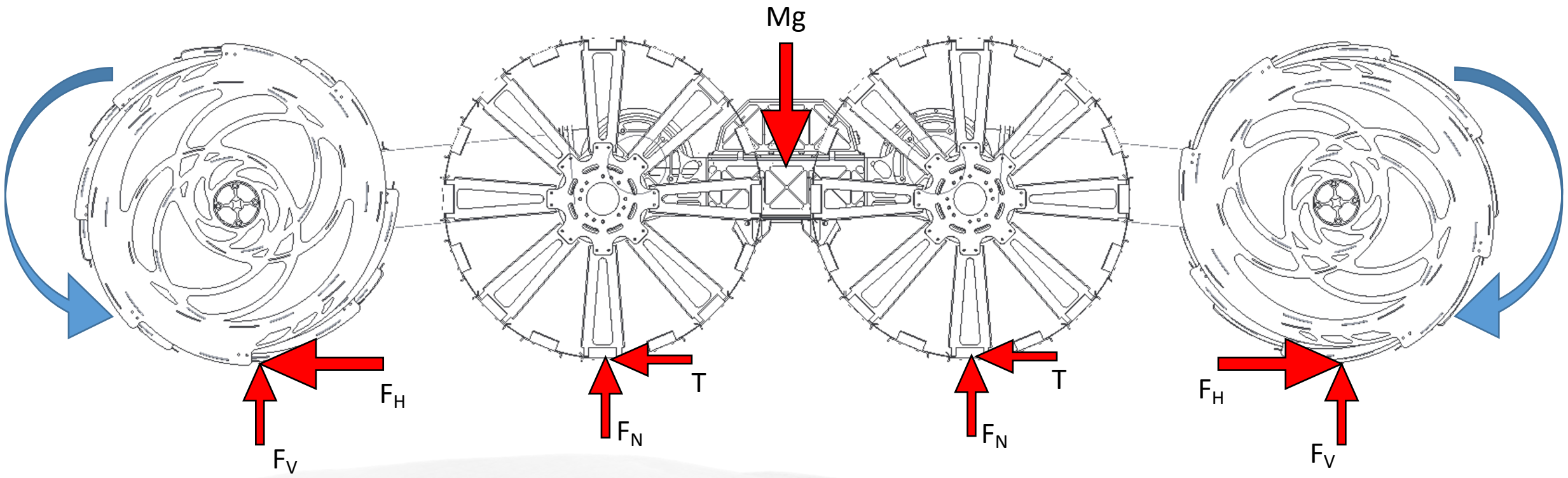
RASSOR 2.0 Prototype Excavation Rover

- RASSOR 2.0 is a prototype robotic excavator developed in the Granular Mechanics and Regolith Operations (GMRO) Lab at Kennedy Space Center
- Currently being used for development of excavation algorithms to inform the ISRU Pilot Excavator (iPEX) project
- iPEX is a NASA Game Changing Development (GCD) funded project to develop a flight ready robotic excavator to demonstrate lunar excavation.
- iPEX is planned to fly as a Commercial Lunar Payload Service (CLPS) payload

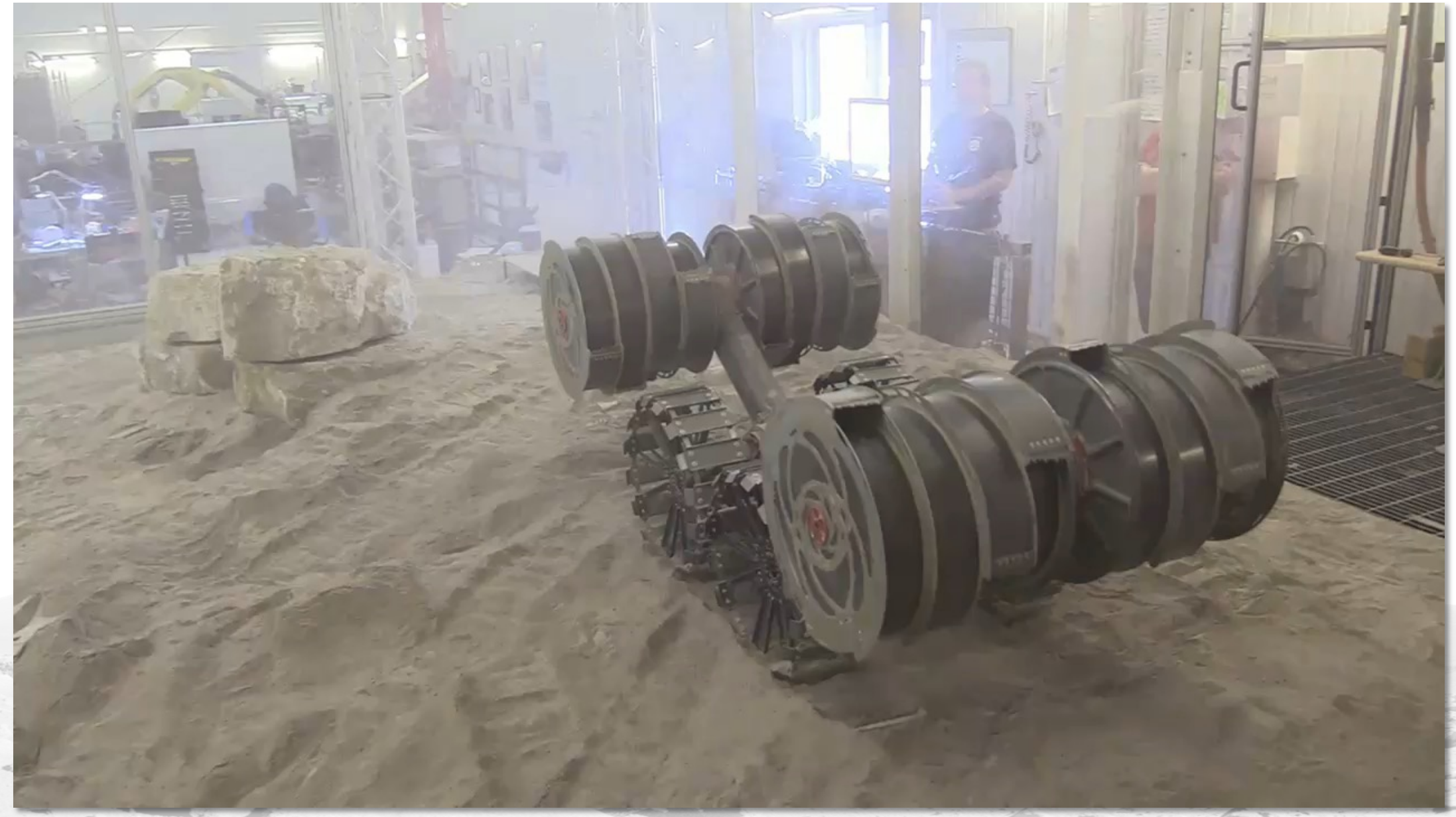
Excavation Free Body Diagram



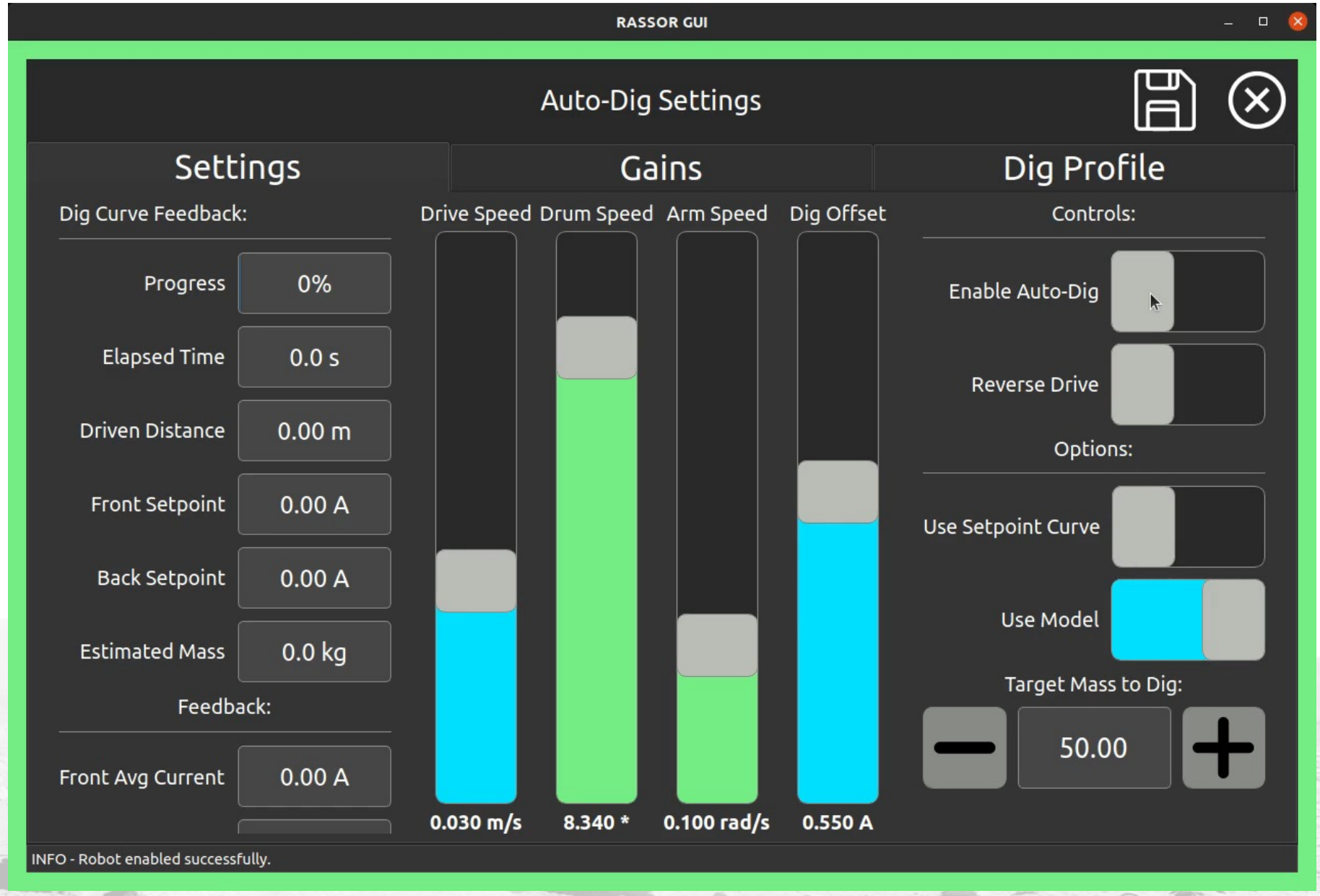
Excavation Concept

- Reduced gravity and mass limitations limit the traction of the vehicle
- Need to be able to excavate without a large reaction force
- Counter rotating bucket drums cancel the horizontal digging forces
- In order for the forces to be continually balanced, we need autonomy
- We call the control loop that enables this autonomy “autodig”

Autodig Demonstration Video



Autodig Software Demonstration Video



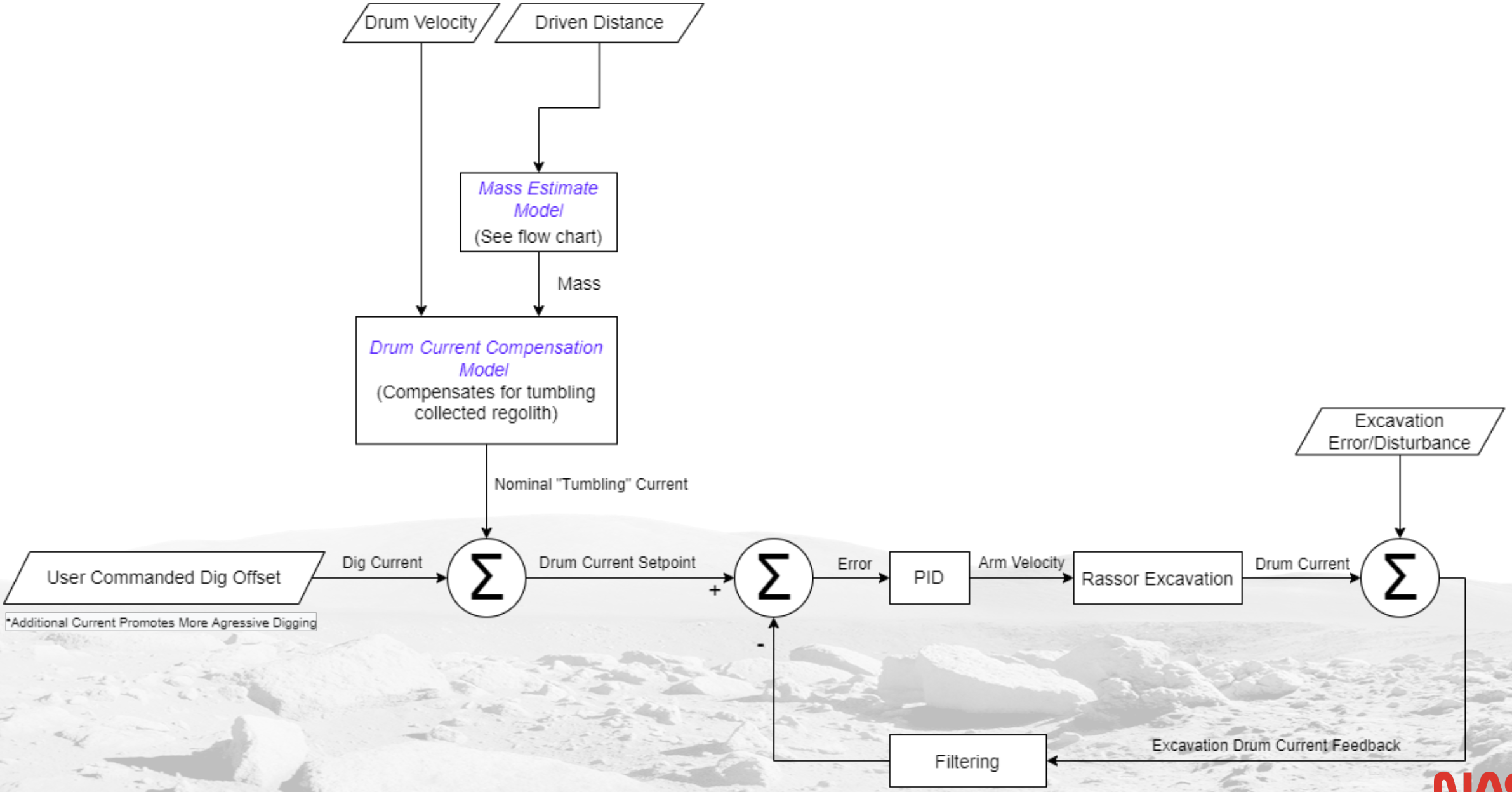
Excavation Concept Continued

- A PID loop is used to maintain matching currents (torque) on the front and rear drum
- The arms servo up and down to increase/decrease the depth of cut and engagement of the soil
- This increases or decreases the resultant torque on the drum
- As regolith is collected and stored in the drum, additional current is required to compensate for the increased torque from “tumbling” the regolith inside
- The current required to tumble a known mass in free air with no excavation is referred to as the “*nominal tumbling current*”

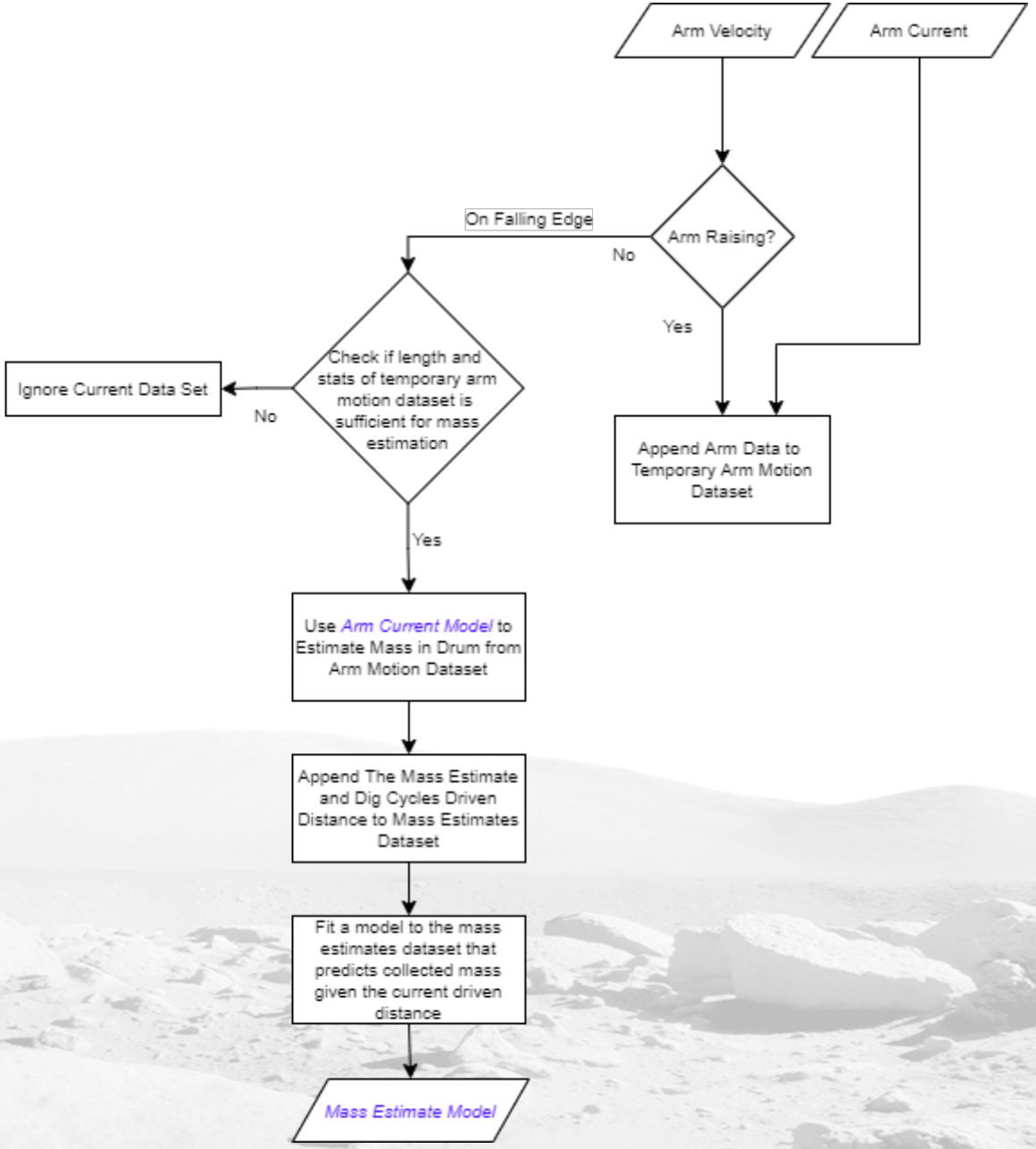
Excavation Concept Continued

- Since our goal is to excavate, we need additional torque beyond what it takes to just tumble the mass in the drum
- The current setpoint for the PID becomes:
  - Current Setpoint = Nominal Tumbling Current + Dig Offset
- Where the dig offset is a commanded value that encourages digging
- A higher dig offset will result in deeper cuts and more “aggressive” digging

Autodig Algorithm Block Diagram



Mass Estimate Model Generation



Arm Current Model

- Arm Current Model
  - Estimates the mass in a drum based off current during an upward movement
  - Function of arm position, arm current
  - An array of previous sensor readings from the arm is used
  - Computes:

$$current_{average} = \frac{\sum \cos(position_{arm}) * current_{arm}}{num_datapoints}$$

  - Then, uses the linear function:

$$mass\ estimate = 4.0629 * current_{average} - 17.432$$

  - The linear coefficients were determined by gathering data with the robot lifting known masses and fitting the first order polynomial to the data
  - The trend was observed to be nearly perfectly linear

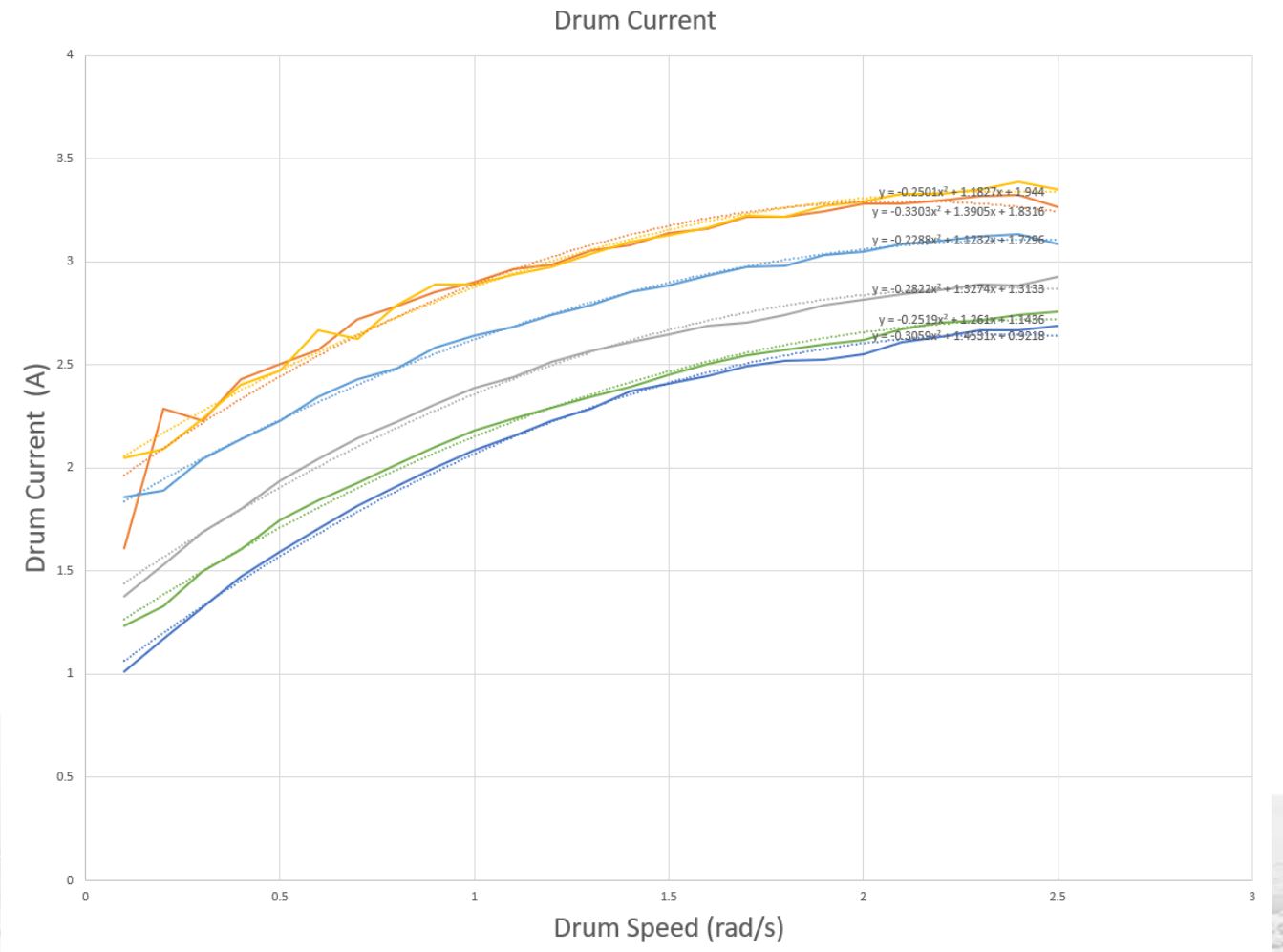
Mass Estimate Model

- Mass Estimate Model
  - Periodic mass estimates are provided by the Arm Current Model
  - These typically happen every few seconds
  - We could use the latest estimate for our drum compensation until we get a new one, Or…

- We can interpolate between each new mass estimate:
  - This provides smoother and more consistent digging,
  - Added benefit of filtering some of the error in mass estimations
  - The excavation rate is assumed to be constant with constant drive speed
  - Each time we get a new mass estimate, we add that to a dataset with the corresponding distance that has been driven during the dig cycle
  - A first order polynomial is refit with each estimate
  - In real-time, the autodig algorithm evaluates the polynomial at its current driven distance and uses the computed mass estimate for drum current compensation

Drum Current Compensation Model

- A test was conducted where a known mass is spun in the drum in free air, while the drum was ramped through a range of drum speeds
- This test was conducted for multiple known masses
- The corresponding plots provided insight to the trends
- The same trend was observed across drums speeds for all masses
- The regolith mass contributed to a Y-offset of the 2nd order polynomial



Drum Current Compensation Model Continued

- Drum Current Compensation Model
  - Predicts the nominal tumbling current for a given mass
  - Is a function of:
    - regolith mass
    - drum speed
  - Takes the form of:

$$nominal = a1 * \mathrm{speed_{drum}}^2 + \mathrm{a_2} * \mathrm{speed_{drum}} + \mathrm{b_1} * \mathrm{mass_{regolith}} + \mathrm{c_1}$$

  - Fit to the complete dataset using the scipy library for Python:

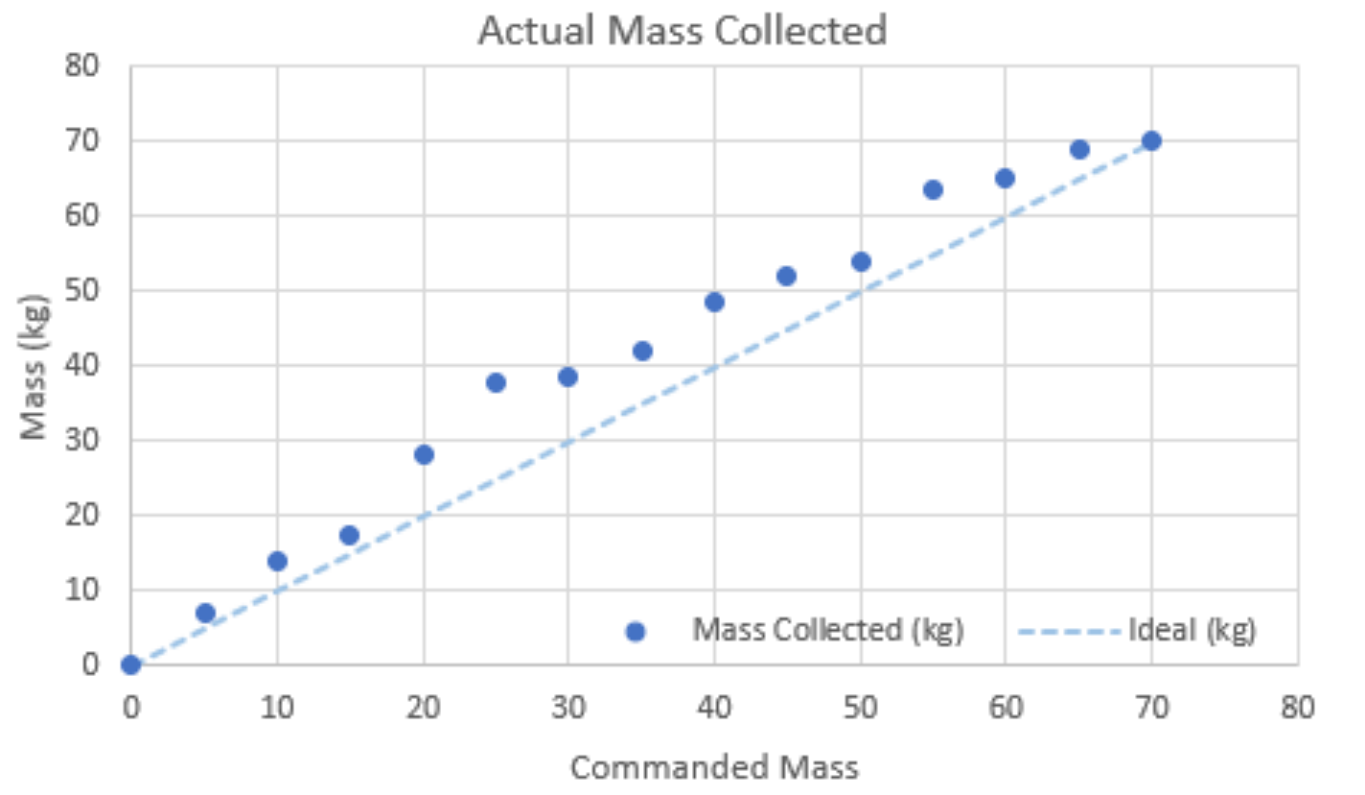
```python
def func(x, a, b, c, d):
    return a*x[:,0]**2 + b*x[:,0] + c*x[:,1] + d

xdata = data[:,0:2]
ydata = data[:,2]

initialParameters = [1.0, 1.0, 1.0, 1.0]
fittedParameters, pcov = scipy.optimize.curve_fit(func, xdata, ydata, p0=initialParameters)
```

Autodig Performance

- Testing of the prototype algorithm showed
  - Consistency in cut depth
  - A constant excavation rate
  - Acceptable accuracy in predicting the collected mass
  - Responsiveness to disturbances and variation in terrain
  - Overall, provided reliable excavation
- Improvements
  - Many of the models can be improved
  - Very small data sets were used for fitting models, use larger datasets
  - Additional logic, filtering, and intelligence can be added to the algorithm

Autodig Performance Continued

- A test was conducted where a range of masses to collect was commanded
- The excavator automatically stops when it reaches its target
- The actual collected regolith was weighed and plotted



Autodig Performance Continued

- Some outliers were observed, but improvement of models will help with this
- It was observed that the error decreased at higher masses

Future Work

- Continue development of the autodig algorithm
- Improve the models used in the algorithm
- Develop automatic calibration routines to tune the various models
- Enhance the hazard and rock encounter capabilities
- Develop rock clearing algorithms based off of autodig