MEM493 : LuMar – Lunar Autonomous Maintenance Robot

MEM Team 30

Advisor: Dr. Yousuff

May 2025

Overview

Team Member Responsibility

- Nhung – Software and documentation management
- Eddie – Chassis design and prototyping,
- Jordan – Systems engineering, component research
- Gill – Team Lead, Design, manufacturing and testing

Motivation

The inspiration for this project comes from NASA’s RASC-AL Competition that the team entered, which deals with applications on the lunar surface.

Stakeholders

Direct

- NASA
- Future lunar mission operators
- Other Potential funding agencies
  - Determine the scope of the project and dictate the cost/resources.

Indirect

- Academia
  - Aim to create a project which can be expanded upon for future senior design students
- Suppliers
  - Manufacture crucial components of the project which in turns affect time and cost.

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Problem Statement

- A lunar base requires semi-autonomous robotic systems to ensure continuous operation and maintenance in extreme conditions.
- This project aims to design a versatile robot capable of addressing challenges such as manipulating umbilicals or fittings, repairing and servicing structures, and maintaining or assisting other robots. The robot is designed with interchangeable end effectors, which can be manually swapped based on the required task. This modularity allows it to perform a range of operations, ultimately contributing to the longevity of the lunar habitat.

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Approach

1: singular robot – multifunctional
2: singular robot – specialized task
3: swarm of robots with specialized tasks
4: swarm of modular robots
*concepts based off RASC-AL Competition

Scale: 1-5 Worst to Greatest	Cost (Weight 5)	Capabilities/ usefulness (Weight 4)	Serviceability (Weight 3)	Potential for future expansion/upgrades (Weight 2)	Score
Concept 1	1x5 = 5	4x4 = 16	2x3 = 6	1x2 = 2	29
Concept 2	3x5 = 15	3x4 = 12	3x3 = 9	2x2 = 2	38
Concept 3	2x5 = 10	4x4 =16	3x3 = 9	3x2 = 6	31
Concept 4	4x5 = 20	5x4 = 20	5x3 = 15	5x2 = 10	65

Specifications and Standards

ID Number	Type	Specification
SPEC-1	Chassis Dimensions	The chassis dimensions will be 1m x 0.6m x .3m
SPEC-2	Drive Train	The drivetrain shall enable the robot to go ~ 2 kph while carrying a total mass of 40 kg.
SPEC-3	Chassis Materials	Use lightweight materials to balance strength and weight.
SPEC-4	Ground clearance	Ground clearance of the chassis is a minimum of 15 cm.
SPEC-5	Degrees of Freedom	The robotic arm will have 6 degrees of freedom.
SPEC-6	Base Arm Rotation	The base rotation of the arm shall be +/- 360 degrees.
SPEC-7	Arm Payload – Full Extension	The robotic arm shall be capable of lifting a payload of 0.5kg at its maximum extension.
SPEC-8	Arm Extension	The robotic arm shall have a standing reach extending at least 2 inches beyond the chassis boundary.
SPEC-9	Arm Speed	The robotic arm shall be capable of moving fully retracted position to the fully extended position in 3 seconds or less
SPEC-10	Arm Accuracy	The arm shall have a positional repeatability of +/- 5mm when commanded to a certain position.
SPEC-11	Max Load Capacity (Static)	The drivetrain and chassis shall support a static load of 50kg without structural deformation.
SPEC-12	Turn Radius	The robot shall have a turn radius of less than 1.5m.

- INOCSE Systems Engineering Handbook
- NASA Systems Engineering Handbook
- ASME Y14.5
- NASA-STD-8739.1
- ASTM Standards for Materials

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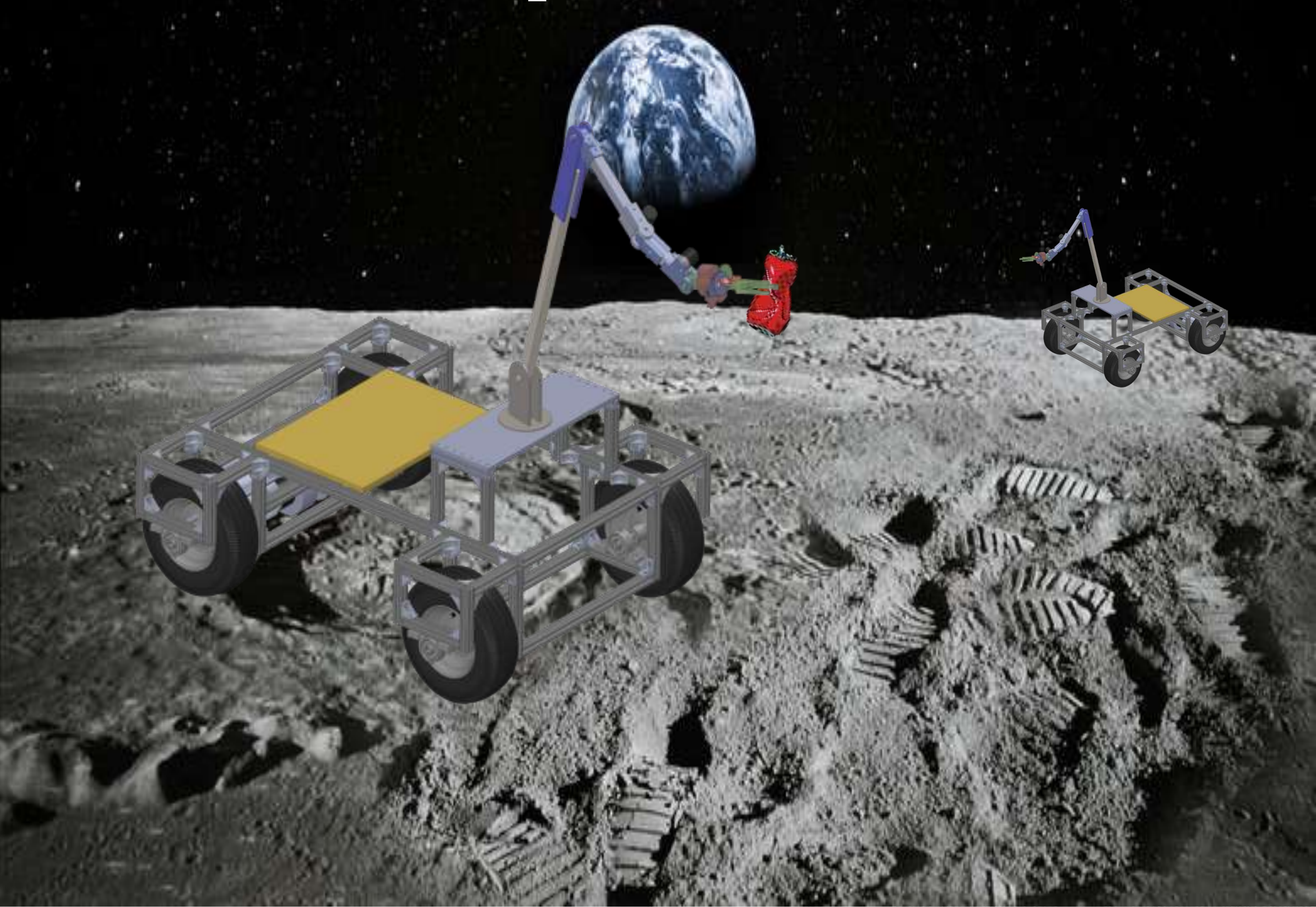
Overall product in action



Chassis Calcs

Motor Info								
	at max efficiency		at max power		at free spin		at stall	
efficiency	65.99%	unitless	n/a	unitless	n/a	unitless	n/a	unitless
torque	293.6	m-Nm	1210.2	m-Nm	n/a	m-Nm	2420.4	m-Nm
speed	4666	rpm	2655	rpm	5310	rpm	0	rpm
current	18.2	amps	66.9	amps	2.5	amps	131.2	amps
power output	143.4	watts	336.5	watts	n/a	watts	n/a	watts

Torque from Rotational MOI				
wheel mass (kg)	weight (N)	radius (m)	rotational MOI (m^4)	required torque to turn wheel (N*m)
2.18	21.39	0.152	0.02518336	0.003827871

Speed Numbers				
required speed (kph)	speed (m/s)	desired acceleration (m/s^2)	angular velocity (rad/s)	angular acceleration (rad/s^2)
2	0.556	0.556	3.658	3.658

Power and Torque Calculations							
Estimated bot mass (kg)	Payload from requirements (kg)	Total mass (kg)	Total weight (N)	Force to move up 15° incline (N)	Total torque to move mass up 15° incline, incluidng rotational inertia (N*m)	Total force for accelerating 0.556 m/s^2 up incline (N)	Total power for moving at 0.556 m/s up incline (W)
30	40.00	70.00	686.7	864.43	131.40	480.62	267.23

$F = m*a$

$Power = F*v$

$Angular\ vel = v/r$

$Angular\ accel = a/r$

$T = F*d = F*r = I*r$

$I = m*r^4$

- Batteries ruled out due to cost, did not want power consumption from chassis and arm electronics as a constraint
- With 4 motors, total torque is very low but power is good due to high speed
- If motors operate at max efficiency; torque output is 1.174 N*m, power output is 573.6W
  - To get proper torque, gearbox must have <u>reduction of at *least* 1:112</u>

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Transmission Calcs

For first stage (3);

No.	Description	Sun gear A z_a	Planet gear B z_b	Internal gear C z_c	Carrier D
1	Rotate sun gear once while holding carrier	$+1$	$-\frac{z_a}{z_b}$	$-\frac{z_a}{z_c}$	0
2	System is fixed as a whole while rotating	$+\frac{z_a}{z_c}$	$+\frac{z_a}{z_c}$	$+\frac{z_a}{z_c}$	$+\frac{z_a}{z_c}$
3	Sum of 1 and 2	$1+\frac{z_a}{z_c}$	$\frac{z_a}{z_c}-\frac{z_a}{z_b}$	0 (fixed)	$+\frac{z_a}{z_c}$

Gear	#teeth
Sun Gear, Z_a	16
Planet Gear, Z_b	32
Planet Carrier	96
static ring, Z_c	80
output ring, Z_d	83

Multi-stage planetary chosen for compactness and high reduction

For second stage;

divide number of teeth on output ring by number of planet gears (all calculations done with three planet gears)

$$\frac{Z_d}{N_b} = \frac{83}{3} = 27.667$$

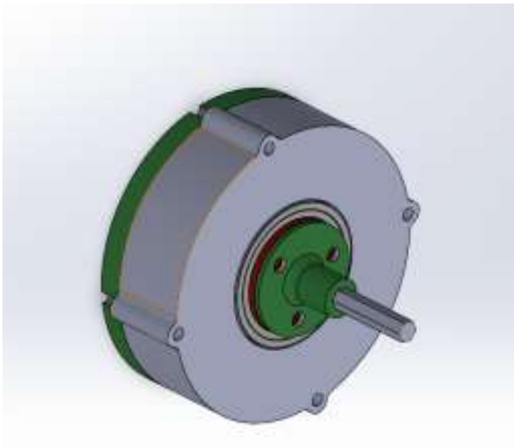
For Final Drive;

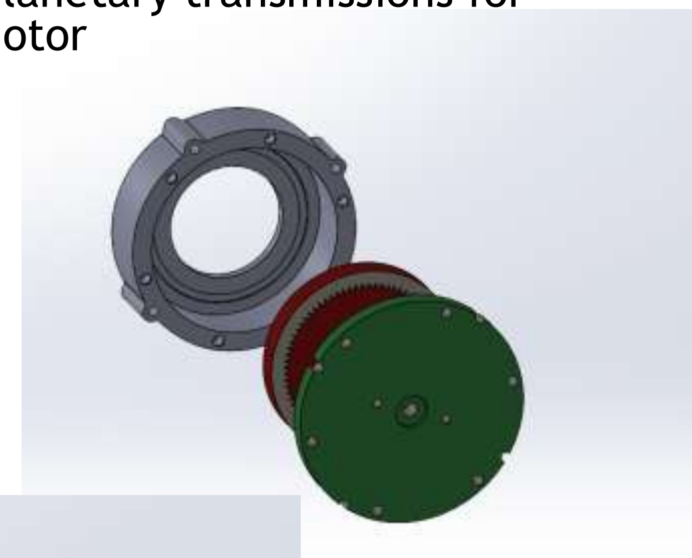
multiply first and second stages

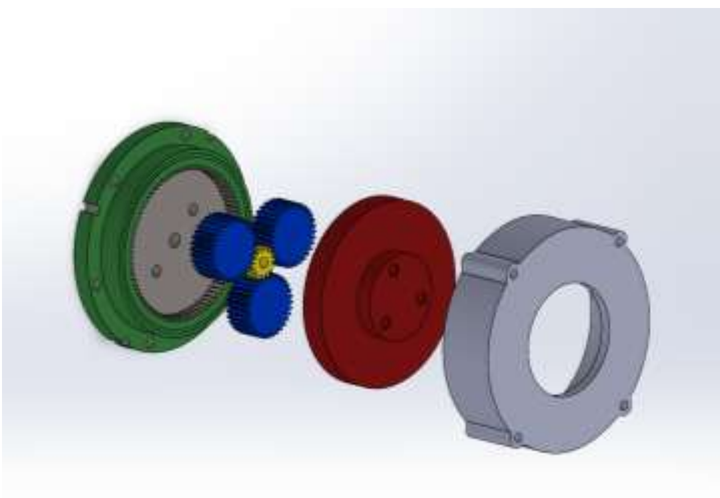
Ratio			
sun-planets	0.166667 :1	or, 1:	6.000
planets-output	0.03614 :1	or, 1:	27.667
final drive	0.006024 :1	or, 1:	166.000

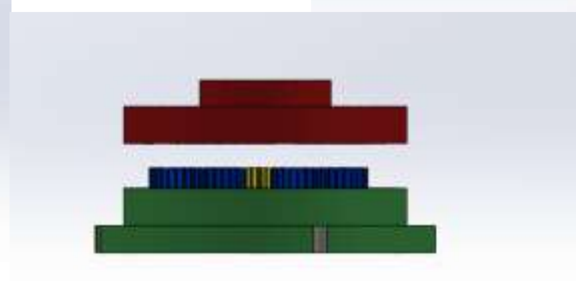
Transmission Design

- 2x 2.5" CIM Motors hooked up to individual PWM Module
- 3-D Printed 166:1 reduction two-stage planetary transmissions for each motor









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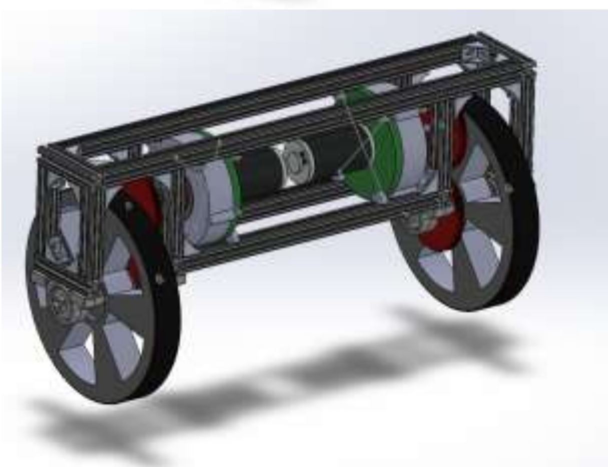
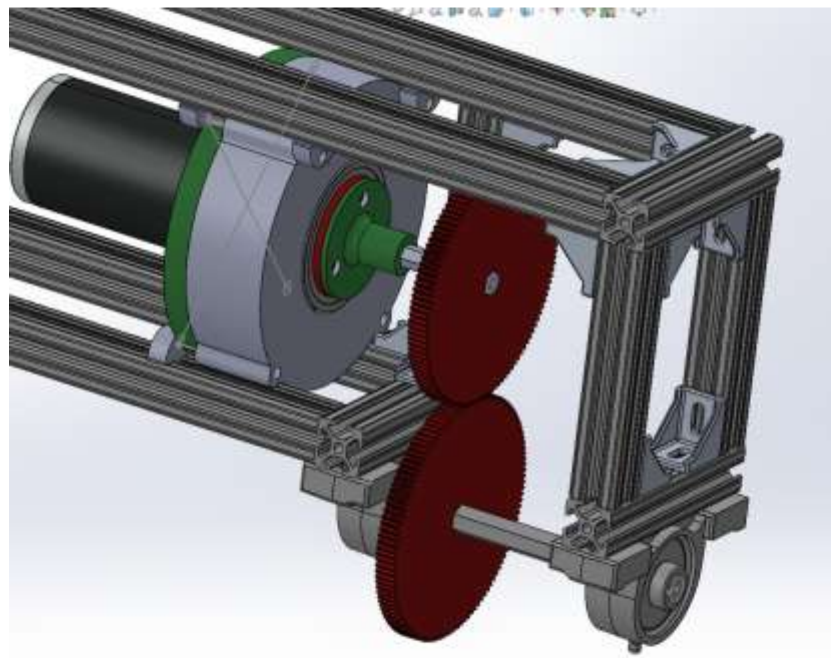
Chassis Design

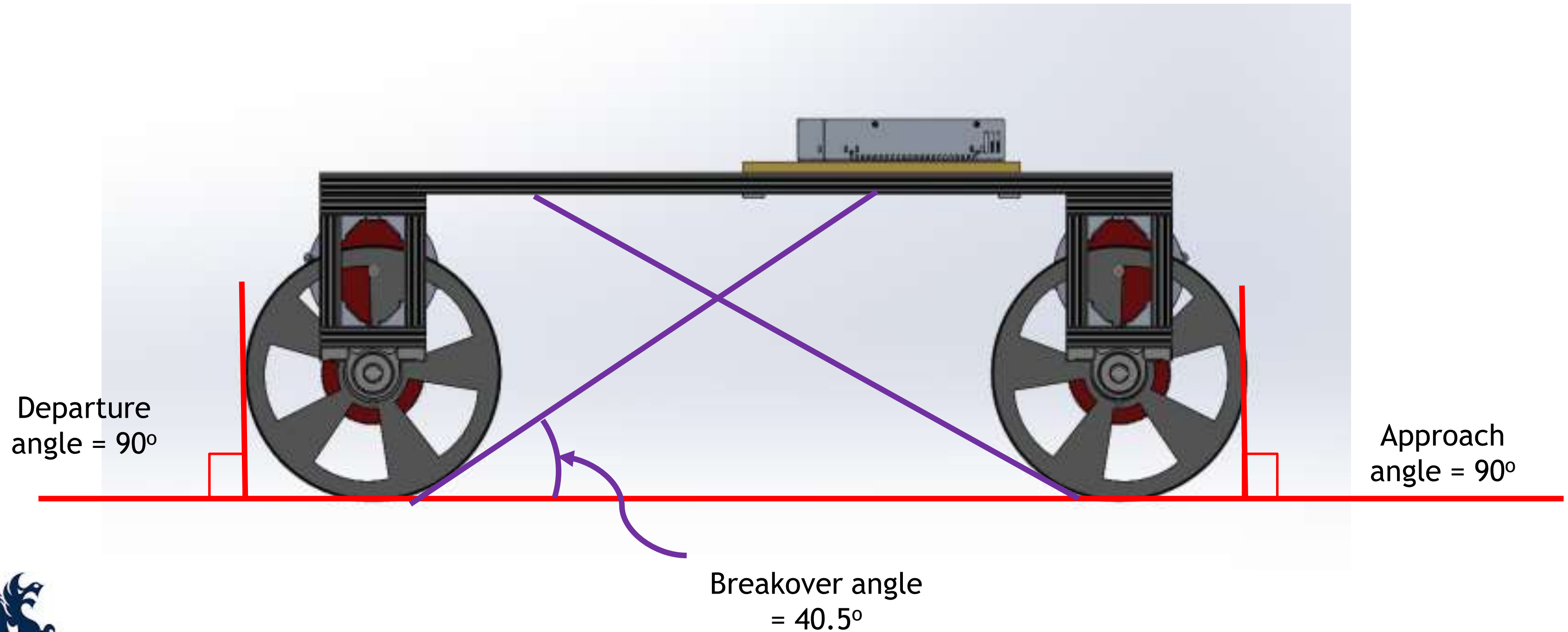


- Constructed of 1010 aluminum extrusion and brackets
- Easy-to-remove modular drivetrain carriers
- Total mass of 23.45 kg



Chassis Design

- Since wheels stick forward and behind total chassis length, approach and departure angles are not a concern
- Breakover angle, beta = 2*arctan(2*ground clearance / wheelbase) = 2arctan(2*0.165m/0.898m) = 40.5°
  - Can be increased by shortening wheelbase



Arm Calcs

	End	J7	J6	J5	J4	J3	J2
Distance from base (m)	1.4	1.3	1.15	1	0.75	0.2	0
Distance from joint to en	0	0.1	0.25	0.4	0.65	1.2	1.4
weight from material	0	0.06	0.15	0.24	0.39	0.72	0.84
Force from material	0	0.5886	1.4715	2.3544	3.8259	7.0632	8.2404
Force From End Effector	4.905	-	-	-	-	-	-
Force From J7	-	2.943	-	-	-	-	-
Force From J6	-	-	2.943	-	-	-	-
Force From J5	-	-	-	5.886		-	-
Force From J4	-	-	-	-	5.886	-	-
Force From J3	-	-	-	-	-	5.886	-
Force From J2	-	-	-	-	-	-	5.886
Force From J1	-	-	-	-	-	-	-
Distance between joints	0	0.1	0.15	0.15	0.25	0.55	0.2

Moment at J7	-	0.51993	0.44145	0.8829	1.61865	3.2373	3.8259
Moment at J6	-	-	1.851638	0.44145	1.1772	2.79585	3.38445
Moment at J5	-	-	-	3.75723	1.4715	4.7088	5.886
Moment at J4	-	-	-	-	8.699018	3.2373	4.4145
Moment at J3	-	-	-	-	-	24.10317	1.1772
Moment at J2	-	-	-	-	-	-	31.32333
Moment at J1	-	-	-	-	-	-	-

Specs — **Holding Weight**

Weights — **Of Material and motor**

Forces — **F=m*g**

Moments — **M=Σ(F*d)**

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Arm Design

- Arm & Electronics
  - 7 joints (radial & axial)
  - J3, J4, J5, J6: Controlled by motors and potentiometers
  - J7: End effector – servo
- J3: -90° to 130°
- J4: -75° to 75°
- J5: -80° to 80°
- J6: -180° to 180°
- J7: 0° to 100°
- Arm stretches 23.5 cm past chassis with J3 at 90°

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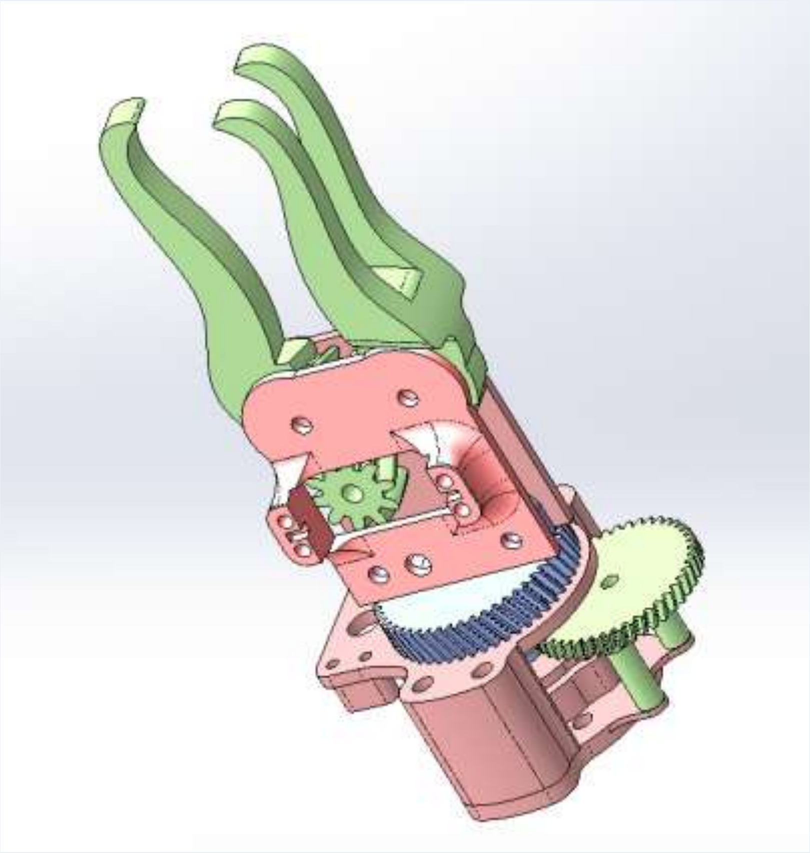
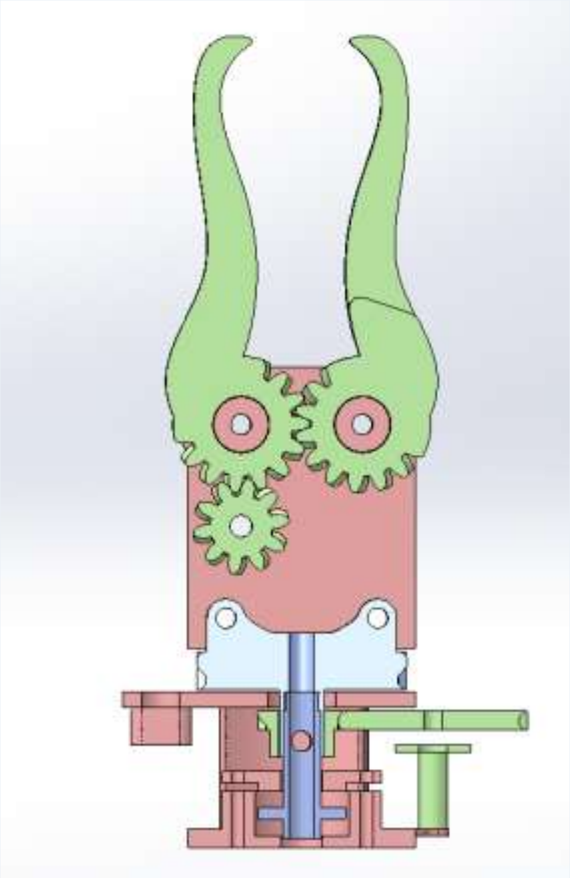
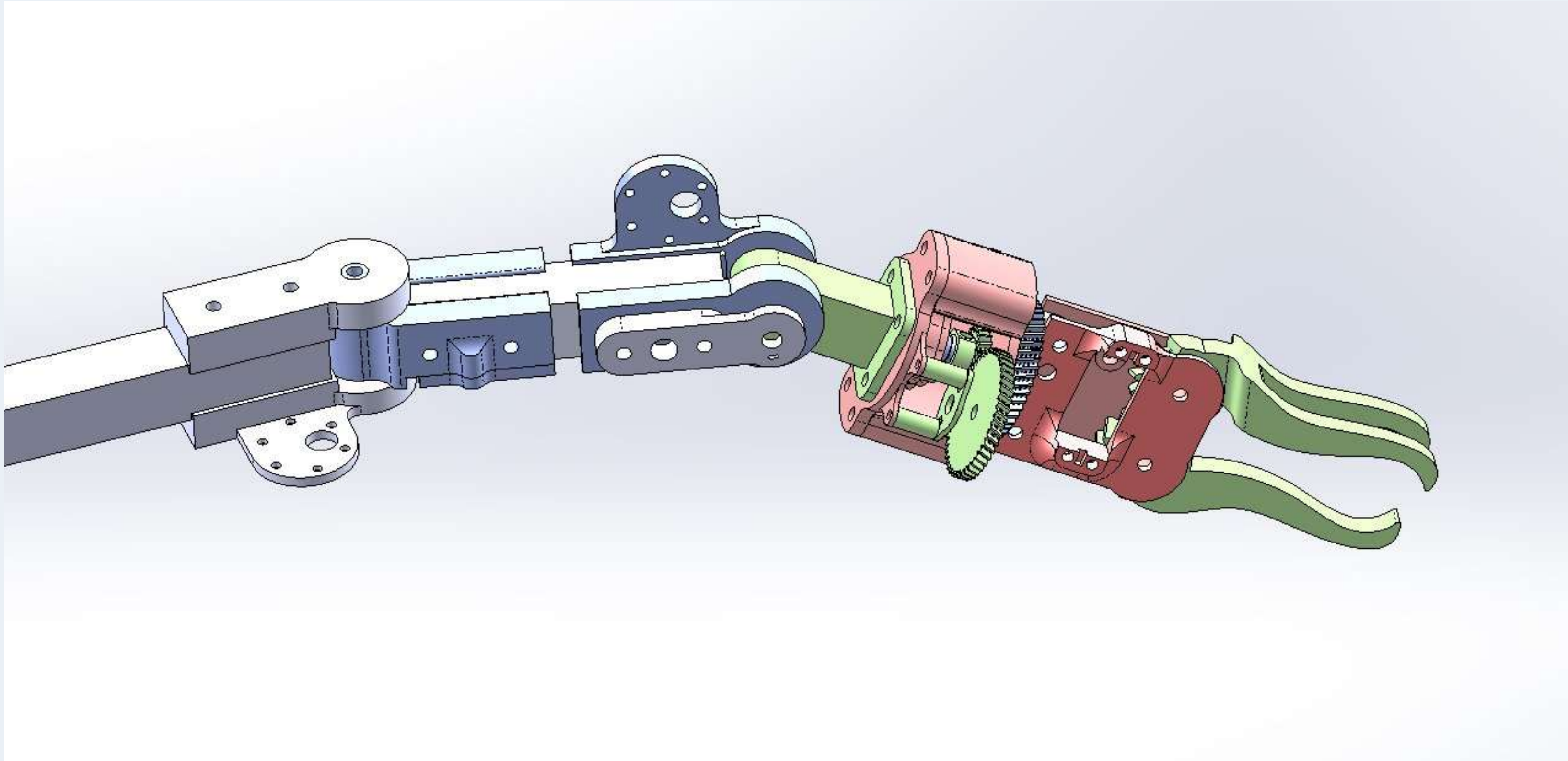
End Effector





Joint Assembly



Demonstration

Development & Integration

Rapid Prototyping

The project settled on 3D printed parts as it was the fastest and most efficient way to prototype it.

Also allowed the team to make modifications easily.

Modular Design

Designed to allow systems to be tested/sections changed out easily (i.e. arm end effector, drivetrain carrier)

Room for easy future expansion (sectional code, easy to find materials, simple mounting with t-slots)

Fabrication

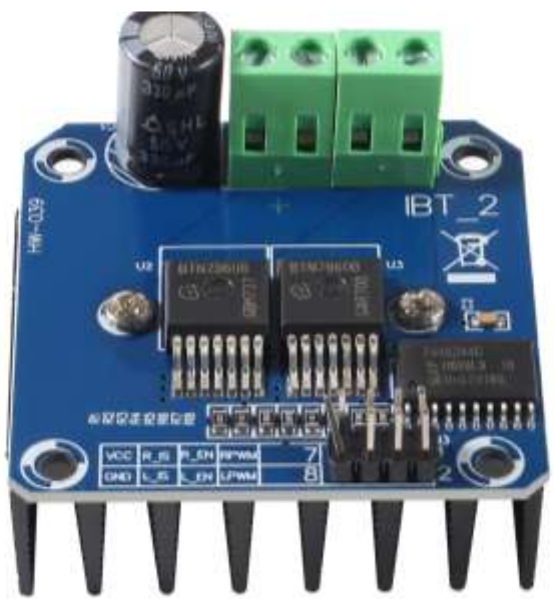
- 1010 Aluminum was cut on a band saw, no extra tooling needed
- Most moving components 3-D printed
- Transmissions were prototyped in multiple stages
- Gear mesh worked first try with marginally tight fitment

Fabrication

- Ran into issues with printing, so a full transmission prototype has not been completed

Electronics (Drivetrain)

- **Central control from RPI**
- **Drive Motors**
  - 2x 2.5" DC CIM Motors
    - Powers Arm HV
- **30a PWM Modules**
  - Dual H-Bridge Motor Drivers
    - Allows for precise bi-directional movement



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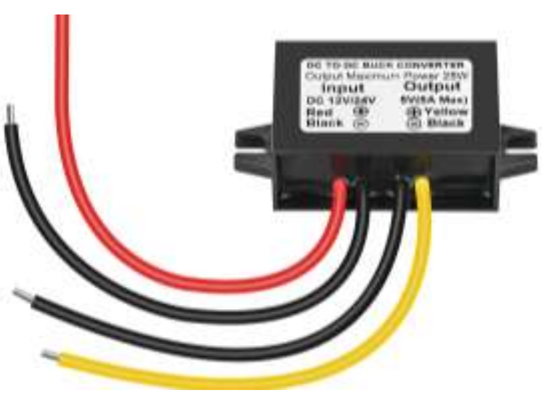
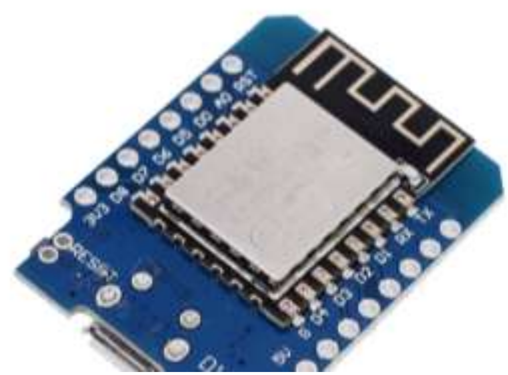


Electronics (Power and Central Node)

- **Power Supplies**
  - 120V AC to 24V DC
    - Powers Arm HV
- **Buck Converters**
  - 24V DC to 12V DC
    - Powers drive motors
  - 24V DC to 5V DC
    - Powers RPI and Arm LV
- **Raspberry Pi 4b**
  - Internal Logic
  - Host Wi-Fi for Arm

Electronics (Arm Side)

- **ESP2866**
  - Microcontroller – handles internal Logic
  - Communicates with other joints via Wi-Fi
- **Potentiometer**
  - Reads Joint Position
- **37D Gearmotor**
  - Moves Joint



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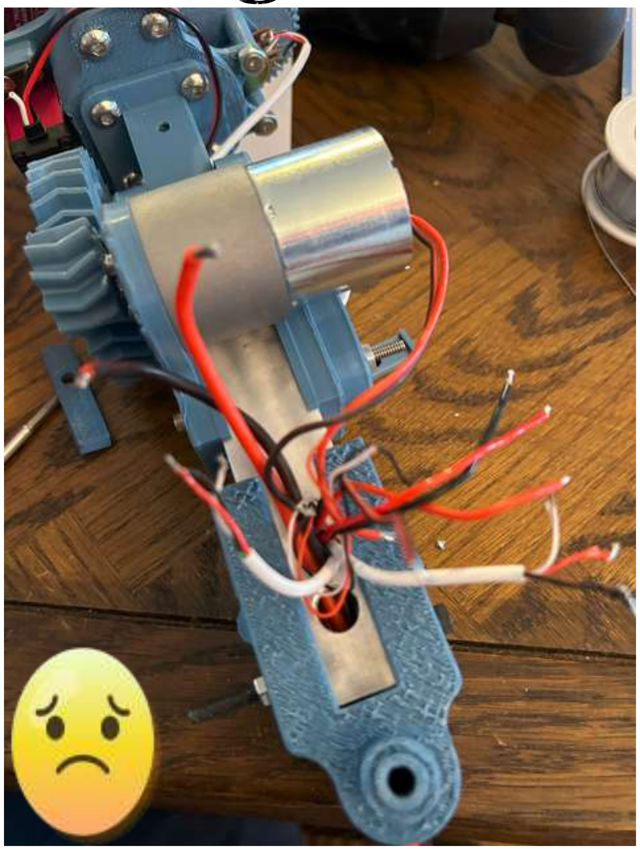
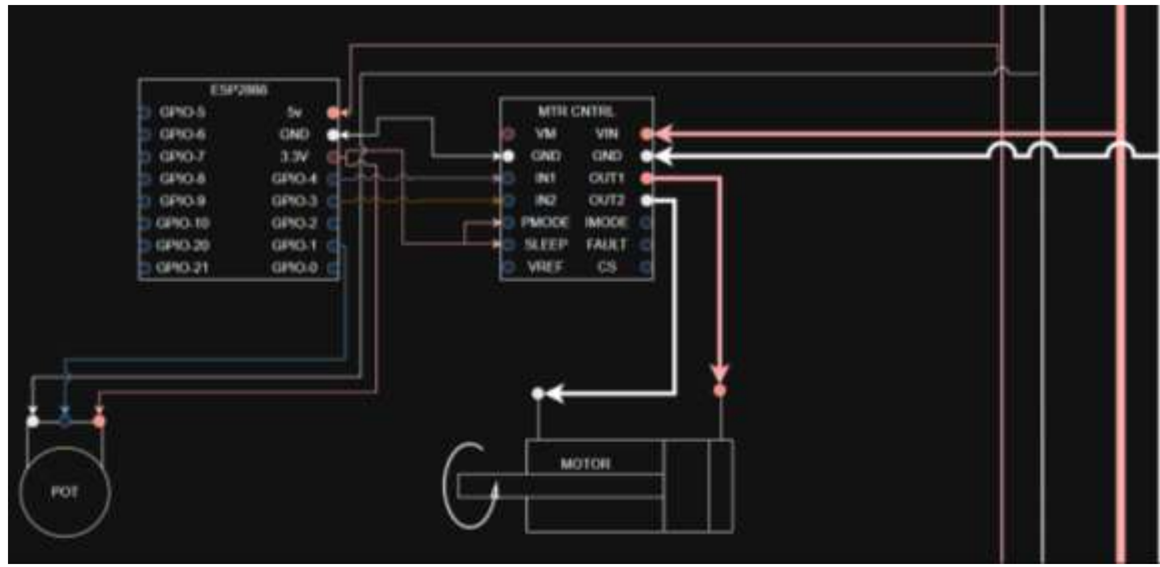
Joint Wiring Diagram

- High Voltage (24V)
- Low Voltage (5V)





Software On Raspberry Pi

Procedure:

↓

Host Wi-Fi

↓

Create Desired and Actual Bracket,

↓

Receive actual data and apply to Actual Bracket

↓

Wait for input from user or controller and put in desired bracket to send to arm

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Software on Esp 2866

Memory:

- Wi-Fi Credentials
- Joint Number
- Joint Pot Values for regression

Procedure:

- Connect to Wi-Fi
- Apply Pot value to regression and send Actual Angle
- Wait for desired angle, apply to regression and apply PID to move joint

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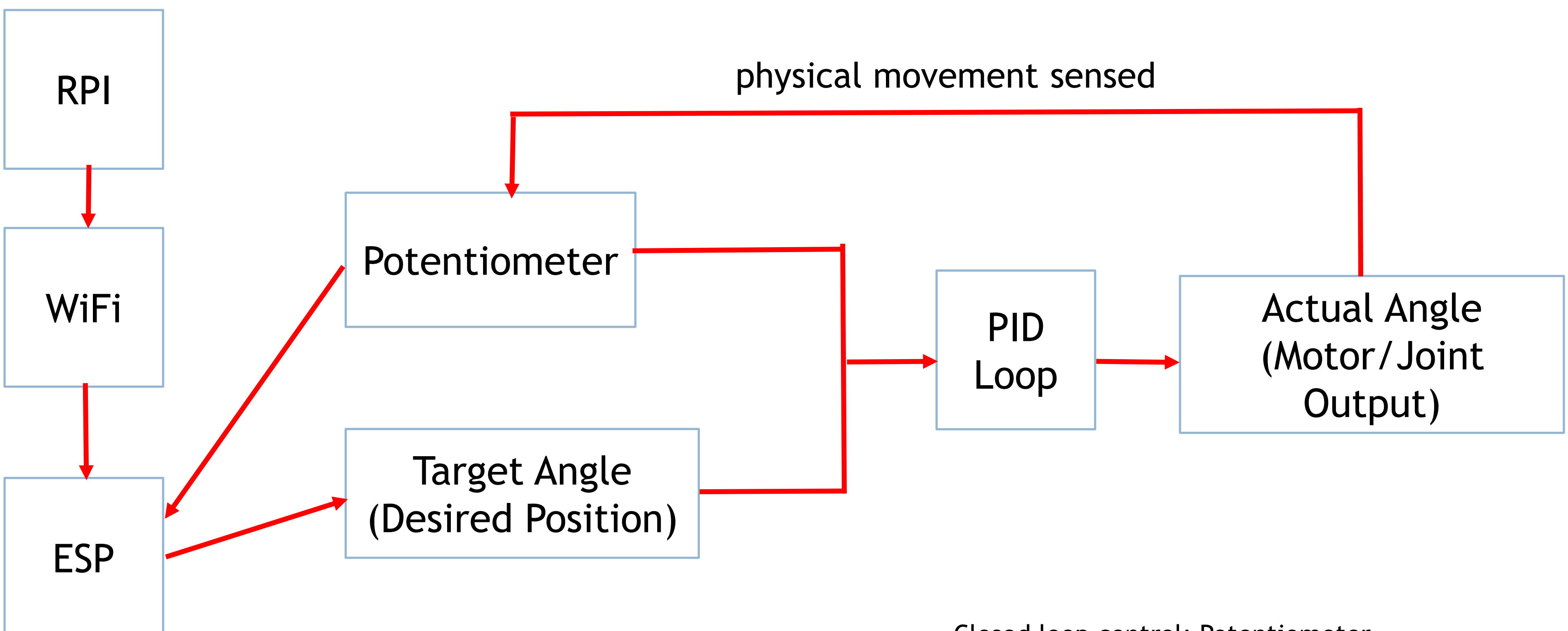
Communication, Control and Software Design



Closed loop control: Potentiometer – PID loop – actual angle – back to potentiometer

```
MODE    : Position
MASTER  : ['0.00', '0.00', '0.00', '0.00', '0.00', '0.00', '15']
ACTUAL  : ['X', 'X', '85.86', '-2.17', '-5.79', '-10.13', 'X']
DESIRED : ['0.00', '0.00', 'P80.00', 'V0.00', 'V0.00', 'V0.00', '15']

===== ROBOT ARM STATUS =====
MODE    : Position
MASTER  : ['0.00', '0.00', '0.00', '0.00', '0.00', '0.00', '15']
ACTUAL  : ['X', 'X', '85.86', '-2.17', '-5.79', '-10.13', 'X']
DESIRED : ['0.00', '0.00', 'P80.00', 'V0.00', 'V0.00', 'V0.00', '15']

===== ROBOT ARM STATUS =====
MODE    : Position
MASTER  : ['0.00', '0.00', '0.00', '0.00', '0.00', '0.00', '15']
ACTUAL  : ['X', 'X', '85.86', '-2.17', '-5.79', '-9.56', 'X']
DESIRED : ['0.00', '0.00', 'P80.00', 'V0.00', 'V0.00', 'V0.00', '15']

===== ROBOT ARM STATUS =====
MODE    : Position
MASTER  : ['0.00', '0.00', '0.00', '0.00', '0.00', '0.00', '15']
ACTUAL  : ['X', 'X', '85.86', '-2.17', '-5.79', '-9.56', 'X']
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p
===== ROBOT ARM STATUS =====
MODE    : Position
MASTER  : ['0.00', '0.00', '0.00', '0.00', '0.00', '0.00', '15']
ACTUAL  : ['X', 'X', '85.86', '-2.39', '-5.79', '-9.56', 'X']
DESIRED : ['0.00', '0.00', 'P80.00', 'V0.00', 'V0.00', 'V0.00', '15']

===== ROBOT ARM STATUS =====
MODE    : Position
MASTER  : ['0.00', '0.00', '0.00', '0.00', '0.00', '0.00', '15']
ACTUAL  : ['X', 'X', '85.86', '-2.17', '-5.79', '-9.56', 'X']
DESIRED : ['0.00', '0.00', 'P80.00', 'V0.00', 'V0.00', 'V0.00', '15']

===== ROBOT ARM STATUS =====
MODE    : Position
MASTER  : ['0.00', '0.00', '0.00', '0.00', '0.00', '0.00', '15']
ACTUAL  : ['X', 'X', '85.86', '-2.17', '-5.79', '-10.13', 'X']
DESIRED : ['0.00', '0.00', 'P80.00', 'V0.00', 'V0.00', 'V0.00', '15']
```

Desired Data:
Where we want the arm to be, 7 term bracket

Position Format:
P[DL,DR,J3,J4,J5,J6,G] (Angles)

Velocity Format:
V[DL,DR,J3,J4,J5,J6,G] (-1 to 1 Velocity)

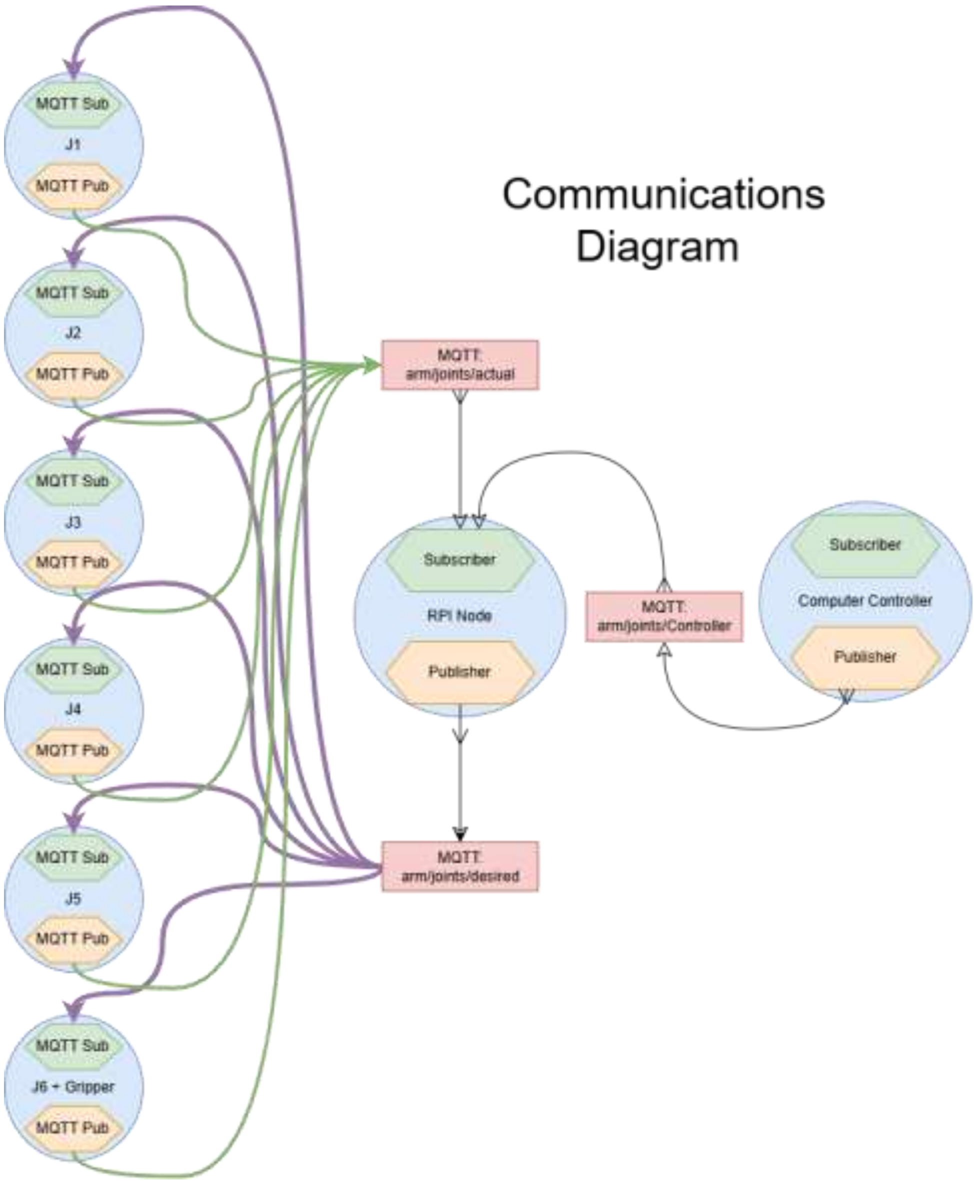
ex: [0.00,0.80,25,32.4,-45,20,30]

Actual Data:
Where the arm is

Format: [J1,J2,J3,J4,J5,J6]

ex: [NA,NA,25.3,31.8,-46.4,20.0,]

*Gripper is not included because servo does not have feedback

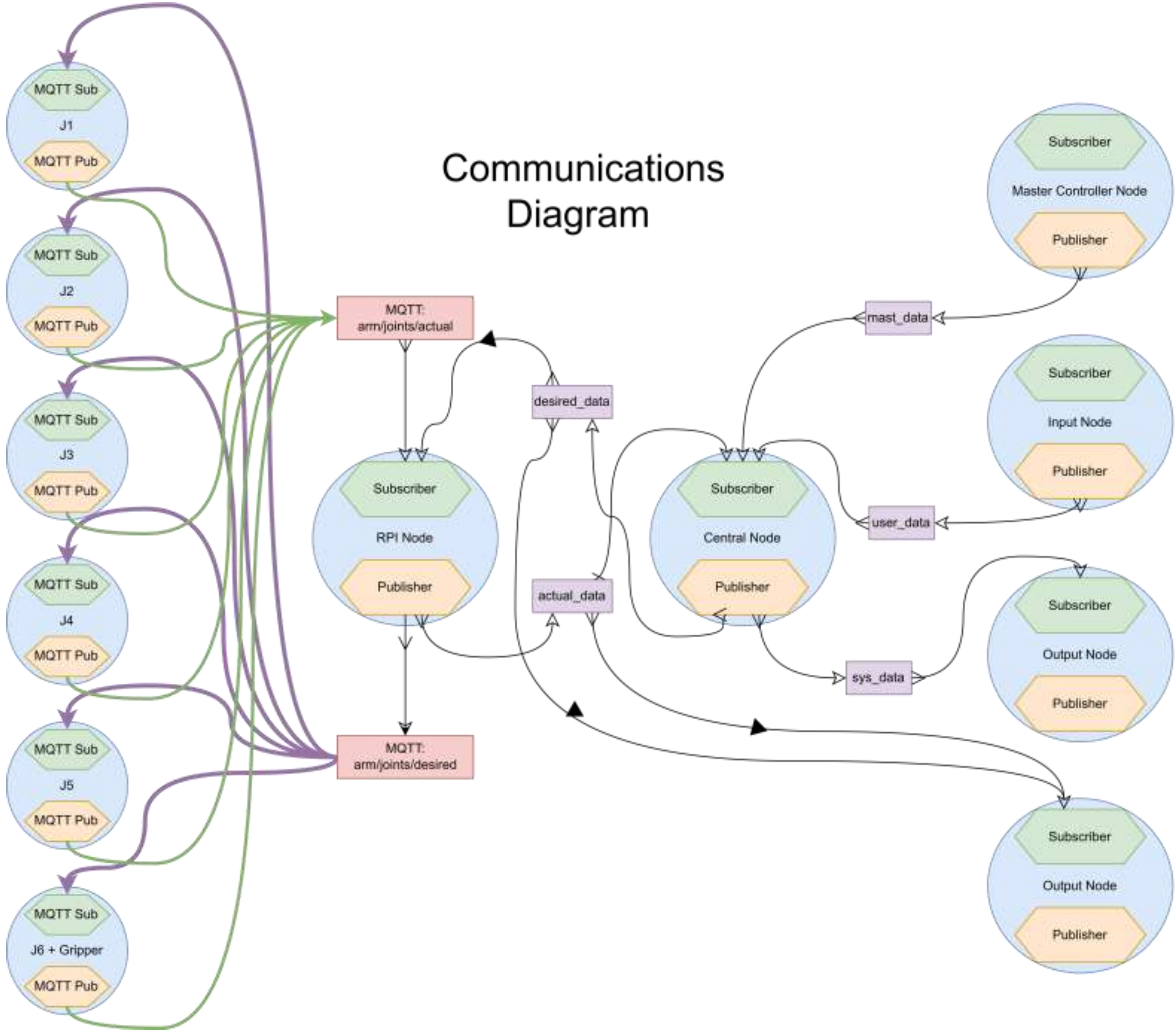


Current Communication Diagram

Notable Features

- RPI Host Wifi
- 3 data Pipelines
  - Actual
  - Desired
  - Controller

Communications Diagram



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Wireless Control

- Integrated an Xbox Controller for intuitive arm and gearbox manipulation
  - 2 modes: Arm and Drive
- Wired to computer, talks to robot through WiFi
- Computer wirelessly communicates to RPI
- Custom software bridges joystick inputs to actuator commands
- Real-time control through Bluetooth interface
- Enhances ease of testing, demo, and ground-based simulation
- Right joystick:J3 and J4   Left joystick: J5 and J6

Interpret Data

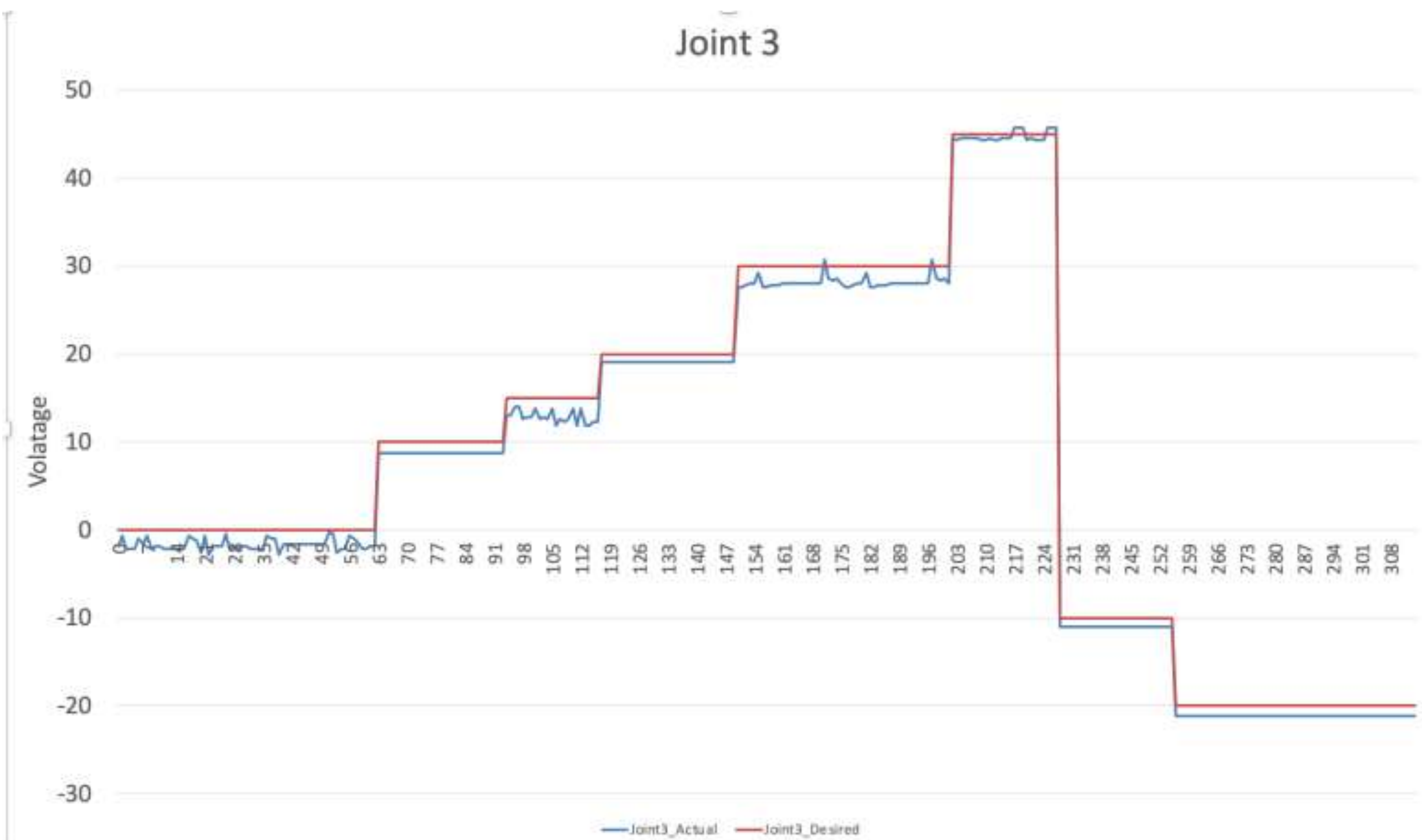
- Data Procedure: set each joint to the same angle and gathered data for approximately 5 seconds of its actual position.

An example of the data printed out when setting all joints to 0:

- Enter command (e.g., 'j5 45', 'm', 'p'): p
- Position printing enabled
- Enter command (e.g., 'j5 45', 'm', 'p'):
- ===== ROBOT ARM STATUS =====
- ACTUAL : ['X', 'X', '-1.87', '-0.43', '0.25', '2.31', 'X']
- DESIRED : ['0.00', '0.00', '0.00', '0.00', '0.00', '0.00', '0.00']

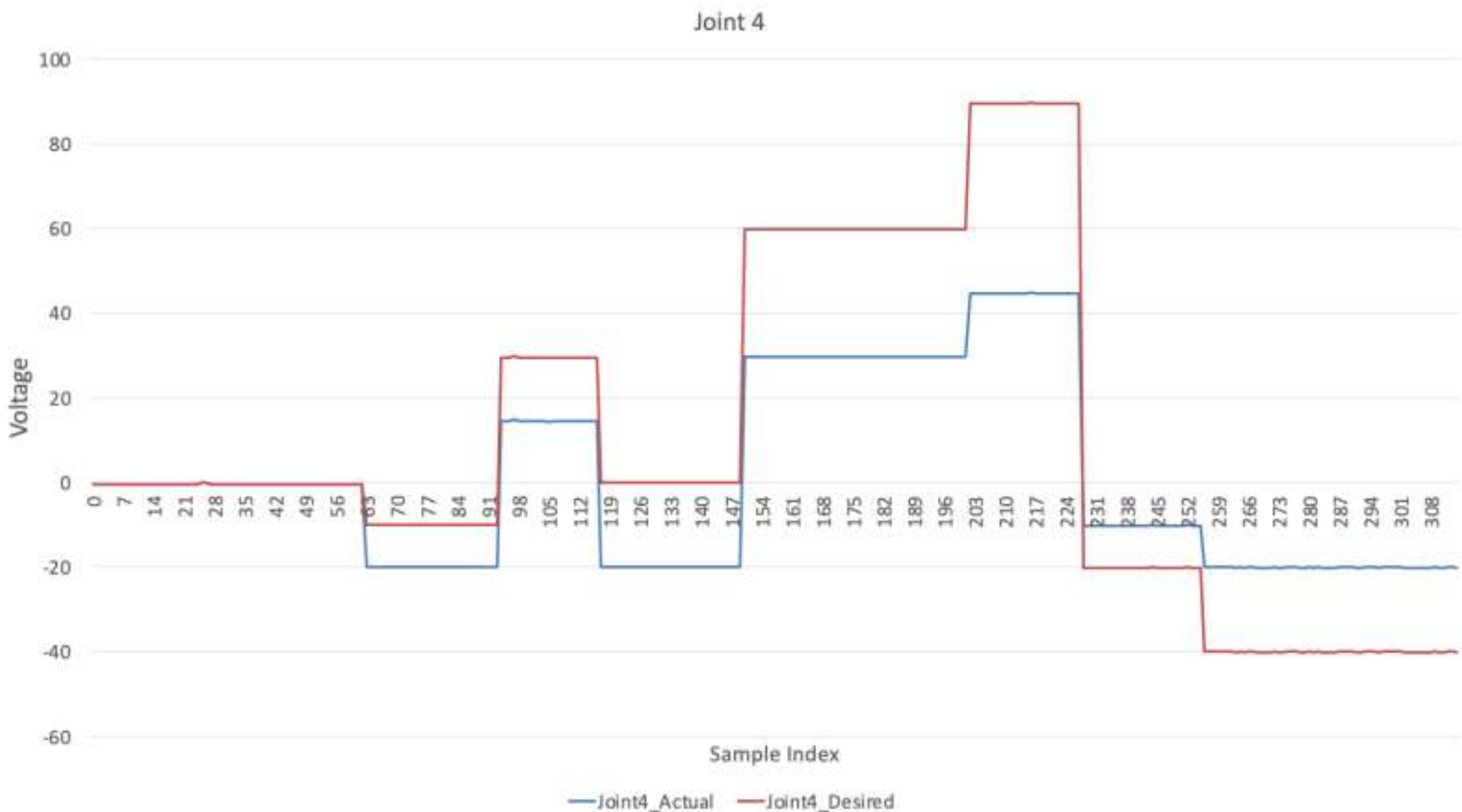
- These numbers were then converted to voltages

Joints 3



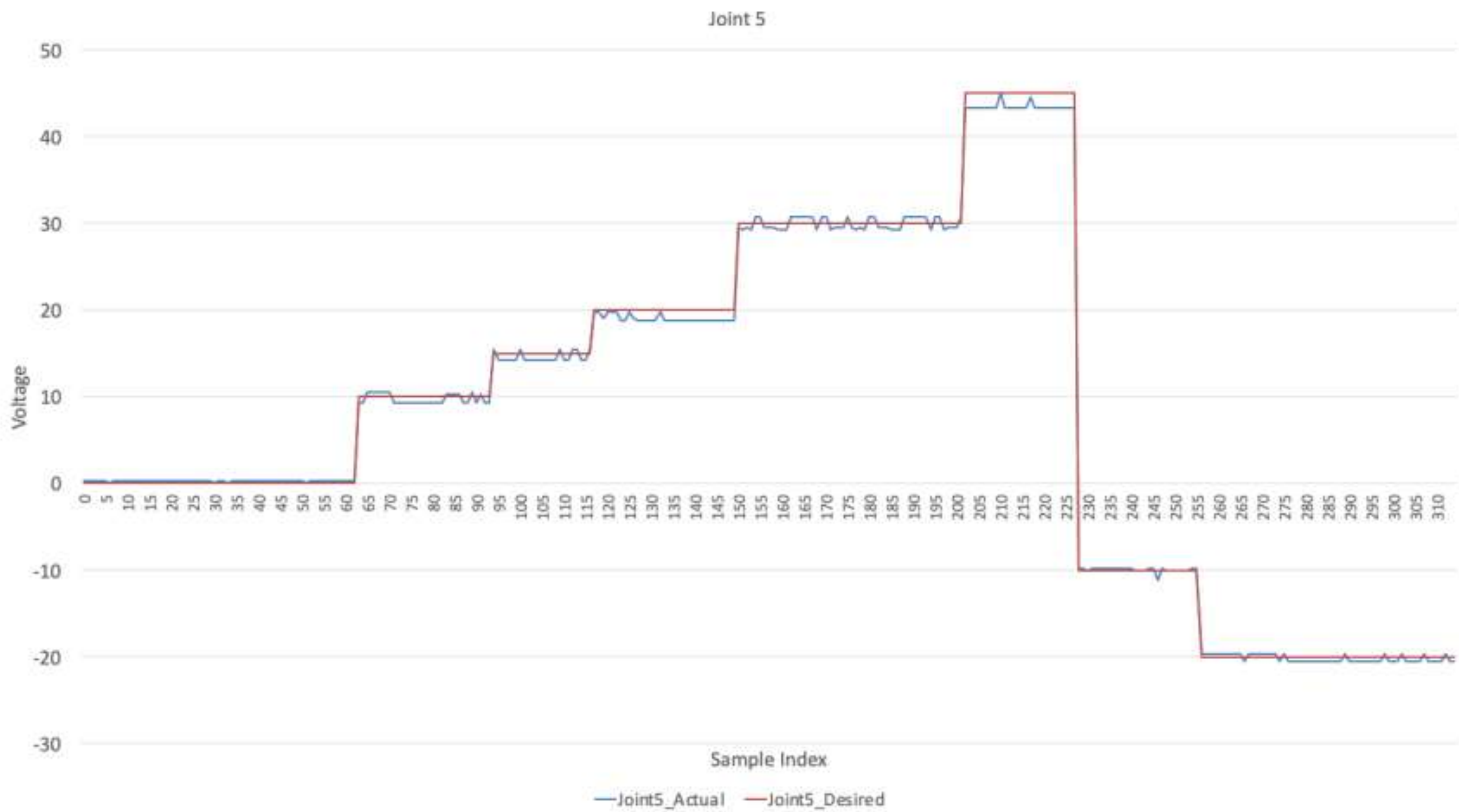
Joint 3
50
40
30
20
10
0
-10
-20
-30
Volatage
63
70
77
84
91
98
105
112
119
126
133
140
147
154
161
168
175
182
189
196
203
210
217
224
231
238
245
252
259
266
273
280
287
294
301
308
Joint3_Actual
Joint3_Desired

Joint 4

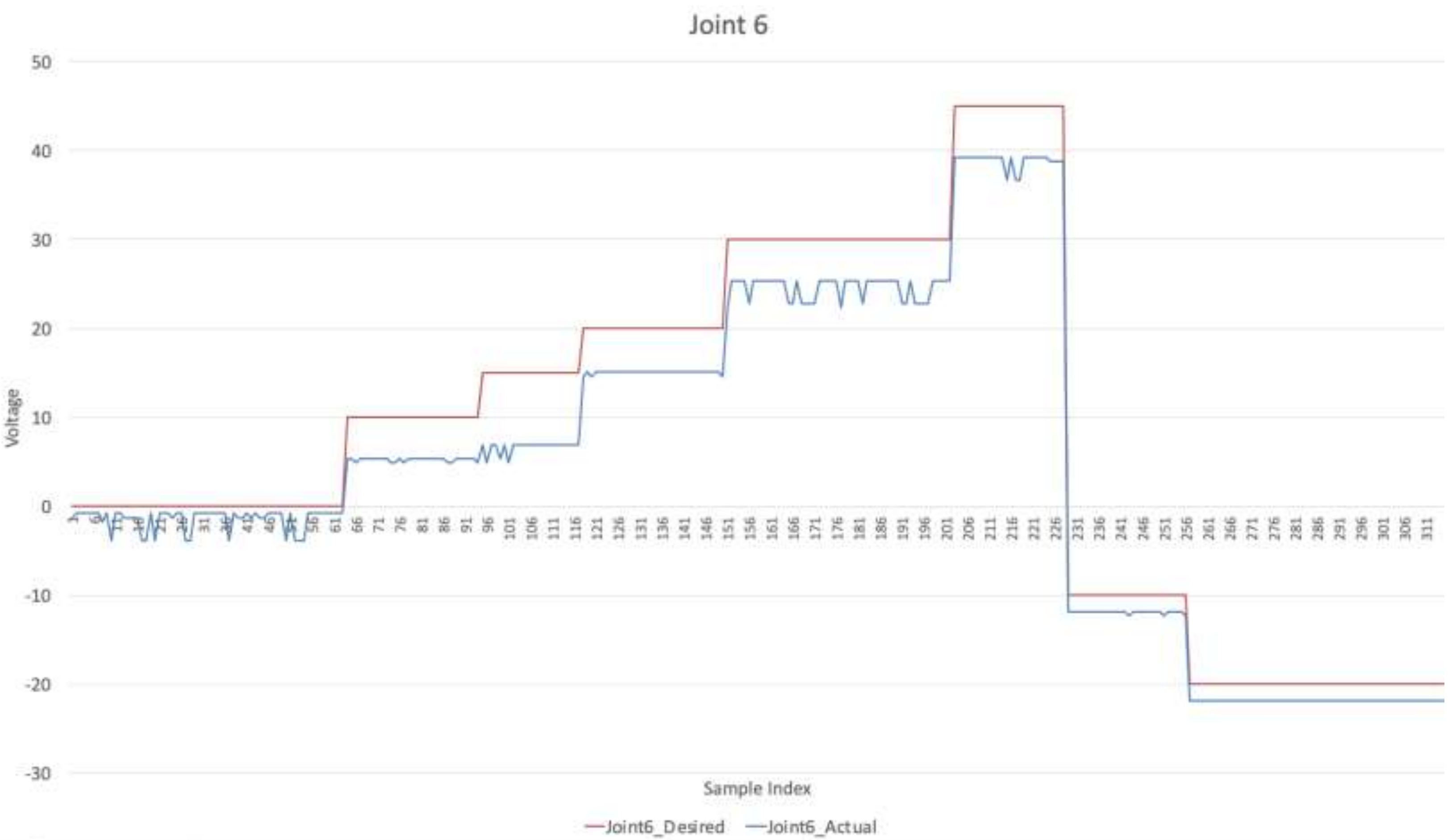


Joint 4
Voltage
Sample Index
100
80
60
40
20
0
-20
-40
-60
0
7
14
21
28
35
42
49
56
63
70
77
84
91
98
105
112
119
126
133
140
147
154
161
168
175
182
189
196
203
210
217
224
231
238
245
252
259
266
273
280
287
294
301
308
Joint4_Actual
Joint4_Desired

Joints 5


Joint 5
50
40
30
20
10
0
-10
-20
-30
Voltage
Sample Index
Joint5_Actual
Joint5_Desired

Joint 6



Impact

Social

- Advancing Technological Innovation
- Inspires Stem research

Technical

- Modularity
- Autonomy

Economical

- Cost Reduction
- Job Creation
- Inspiring Long-term Investment

Ethical

- Protecting Astronauts

Environmental

- Preserving Lunar Environment

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What we learned

When prototyping the arm, it's difficult to account for how the weight distribution will affect the joints/gears when multiple motors are running and signals are being sent, hence the deviation between the actual and desired values.

Setting realistic requirements for the robot and learning how to add and adjust as aspects of the design changes is important.

Prototyping is best done in multiple stages. Because the gearbox had multiple parts with their own tolerancing requirements, it was easier to print a few parts first, make sure they fit, then print other parts

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Future Work

Continue prototyping drivetrain (transmission & other components)

Prepare documentation for future students expanding upon LuMAR

Collect all CAD models and drawings

Outline current capabilities

Detail current software suite

Provide some ideas for projects, but still leave open ended for future students

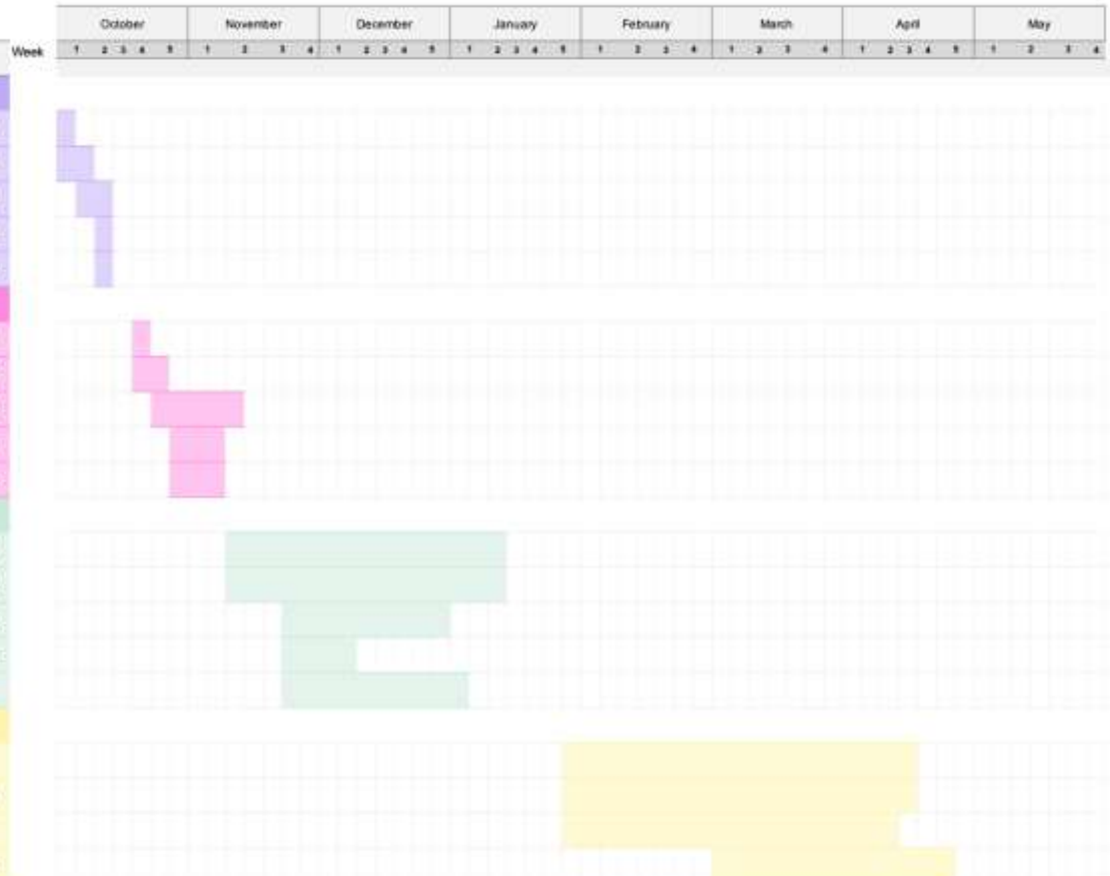
Project Management

LuMar

VanArsdel, Ltd

Project start: **Tue, 10/1/2024**

TASK	PROGRESS	START	END
Initiation			
Define goals	100%	10/1/24	10/4/24
Conduct studies	100%	10/5/24	10/12/24
Establish communication	100%	10/10/24	10/14/24
Project charter	100%	10/10/24	10/15/24
Set up team	100%	10/10/24	10/12/24
Planning and design			
Create schedule	100%	10/20/24	10/25/24
Identify deliverables	100%	10/21/24	10/31/24
Develop budget	100%	10/21/24	11/20/24
Define scope	100%	11/1/24	11/22/24
Identify risks	100%	11/1/24	11/22/24
Design			
Design Robot Arm	100%	11/1/24	12/31/24
Design Chassis	100%	11/11/24	12/31/24
Order Parts	100%	12/1/22	12/31/22
Progress Report	100%	11/15/24	12/5/22
Electronics Design	100%	11/15/24	1/4/25
Build and Testing			
Build Chassis	100%	2/1/25	4/7/25
Build Arm	100%	2/1/25	4/12/25
Track expenses	100%	2/1/25	4/2/25
Testing	100%	3/1/25	4/20/25



Final Budget

Final Budget		
	Items	Price
Electronics	Raspberry Pi	90.00
	Chassis motor controllers	39.98
	Arm motors	125.00
	Arm motor controllers	32.84
	Servo motors	29.66
Assembly Hardware	1010 Hardware	50.87
	Heat-set inserts	40.99
	Screws, nuts, bolts	30.97
Raw Material	1010 Aluminum	149.97
	3D Print Filament	87.38
	1x1in aluminum bars	50.98
Machine Components	Bearings	70.97
Other	Misc electronics	120
Total	$1,001.30	

- We would like to thank the Philadelphia chapter of ASME, Drexel University and the NASA Pennsylvania Space Grant for funding this project.

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- (2) Ren, F., Li, A., Shi, G., Wu, X., & Wang, N. (2020). The effects of the planet–gear manufacturing eccentric errors on the dynamic properties for Herringbone Planetary Gears. *Applied Sciences, 10*(3), 1060. https://doi.org/10.3390/app10031060
- (3) "Gear Systems." *KHK Gears*, khkgears.net/new/gear_knowledge/gear_technical_reference/gear_systems.html
- (4) Sterling, F. B. *Basic and Mechanical Properties of the Lunar Soil Estimated From Surveyor Touchdown Data* , NASA Jet Propulsion Laboratory, 15 Mar. 1970, ntrs.nasa.gov/api/citations/19700014154/downloads/19700014154.pdf

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