Development of Cube Swarm for Search and Rescue Applications - Appendix A

Static Force Calculations of Cube Interactions

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Static Force Calculations of Cube Interactions

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April 25, 2024

Constants

$$\text{Pitch Diameter of all gears (Pd)} = 0.01524 \text{ meters}$$
$$\theta = 0.3$$
$$\beta = 34.38$$
$$\alpha = 34.86$$
$$q = 0.008636 \text{ meters}$$
$$\text{COMdist1} = 0.06985 \text{ meters}$$
$$\text{COMdist2} = 0.224282 \text{ meters}$$
$$\text{COMdist3} = 0.378714 \text{ meters}$$
$$l2 = 0.030988 \text{ meters}$$
$$l3 = 0.00508 \text{ meters}$$
$$l4 = 0.041148 \text{ meters}$$
$$l5 = 0.05588 \text{ meters}$$
$$l6 = 0.02413 \text{ meters}$$
$$\text{Mass Values} = 800, 810, 820, \ldots, 940, 950 \text{ grams}$$

Equations and FBD's

Using Motor Torque to Solve for f_{T4}

Mass = Mass Values

WeightCOM = Mass * 0.0098

Max Stall Torque of the Motor in Nm @ 4.8V = Tm

$$TorqueEquation: \ T_m = \frac{P_d}{2} \times -f_{T4}$$

Tm = 0.42 Newton-Meters

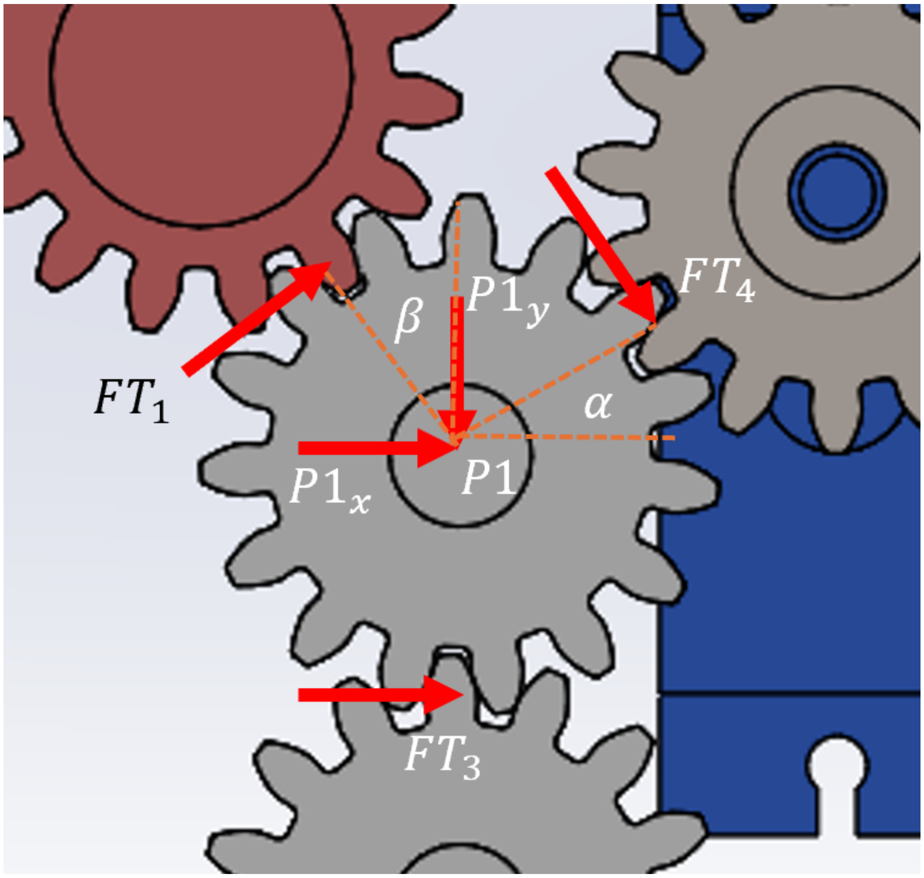


Figure 1: Spur Gear 1 Free Body Diagram

Spur Gear 1 Equations

Unknowns: $fT3, P1x, fT1, P1y$

$$F_{1x} = 0 = f_{T3} + f_{T1}\sin(\beta) + f_{T4} \cdot 0.95\cos(\alpha) + P_{1x}$$

$$F_{1y} = 0 = f_{T1}\cos(\beta) - f_{T4} \cdot 0.95\sin(\alpha) - P_{1y}$$

$$M_{p1} = 0 = f_{T3} \cdot \frac{P_d}{2} - f_{T1} \cdot \frac{P_d}{2} - f_{T4} \cdot \frac{P_d}{2}$$

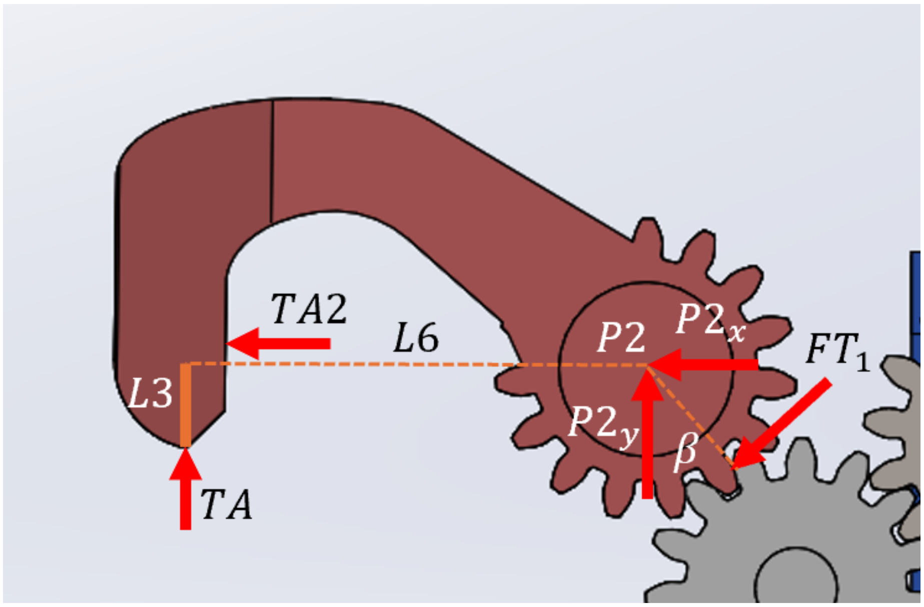


Figure 2: Upper Arm Free Body Diagram

Top Arm Equations

Unknowns: P2x, P2y

$$F_{2x} = 0 = T_{A2} - T_A \sin(\theta) - P_{2x} - f_{T1} \sin(\beta) \cdot 0.95 = 0$$

$$F_{2y} = 0 = T_A \cos(\theta) + P_{2y} - f_{T1} \cos(\beta) \cdot 0.95 = 0$$

$$M_{p2} = 0 = -f_{T1} \cdot 0.95 \cdot \frac{P_d}{2} - l_6 T_A \cos(\theta) - l_5 T_A \sin(\theta)$$

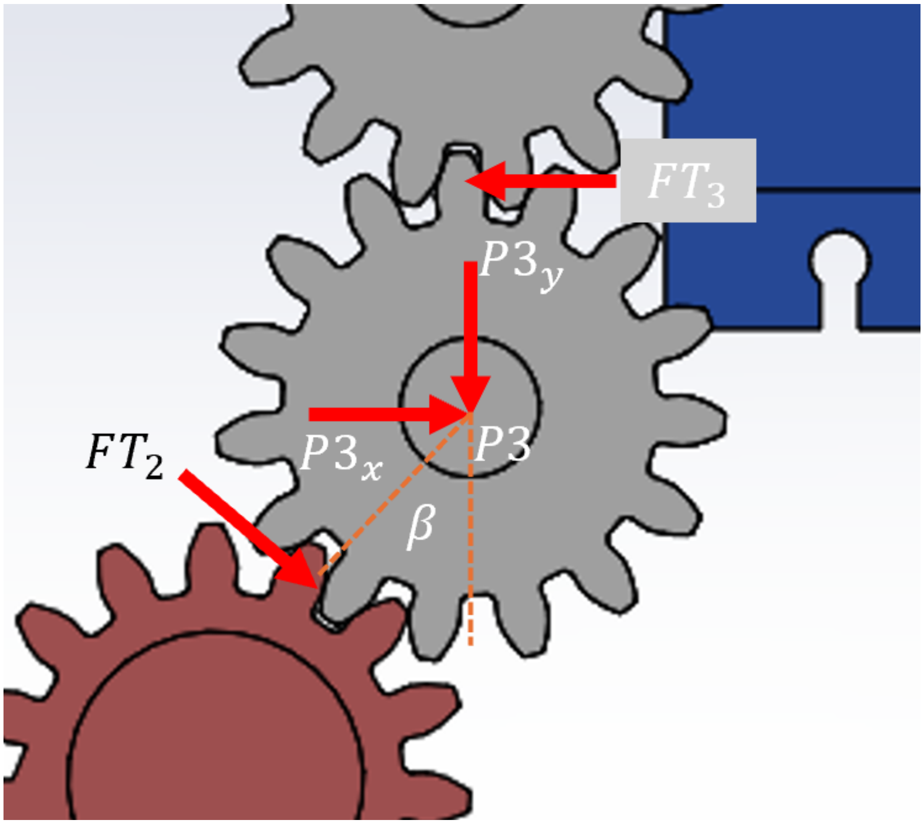


Figure 3: Spur Gear 2 Free Body Diagram

Spur Gear 2 Equations (Bottom)

Unknowns: fT3, P3x, fT2, P3y

$$F_{3x} = 0 = P_{3x} + f_{T2}\sin(\beta) - f_{T3} \cdot 0.95$$

$$F_{3y} = 0 = P_{3y} - f_{T2}\cos(\beta)$$

$$M_{p3} = 0 = f_{T3} \cdot 0.95 \cdot \frac{P_d}{2} + f_{T2} \cdot \frac{P_d}{2}$$

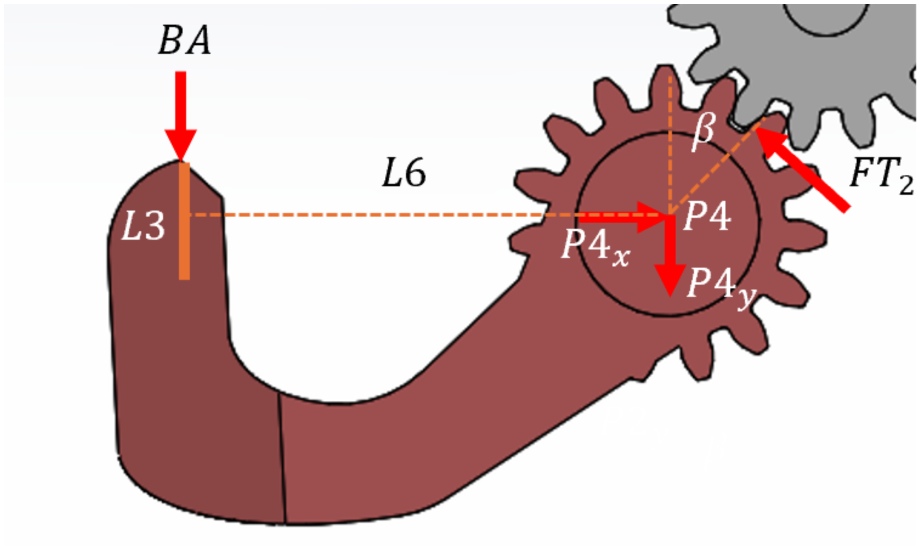


Figure 4: Bottom Arm Free Body Diagram

Bottom Arm Equations

Unknowns: P4x, P4y, fT2

$$F_{4x} = 0 = P_{4x} - f_{T2} \cdot 0.95\cos(\beta) + B_A \sin(\theta)$$

$$F_{4y} = 0 = -P_{4y} + f_{T2} \cdot 0.95\sin(\beta) - B_A \cos(\theta)$$

Sum of moments about point P4

$$M_{p4} = 0 = f_{T2} \cdot 0.95 \cdot \frac{P_d}{2} - l_5 B_A \sin(\theta) + l_6 B_A \cos(\theta)$$

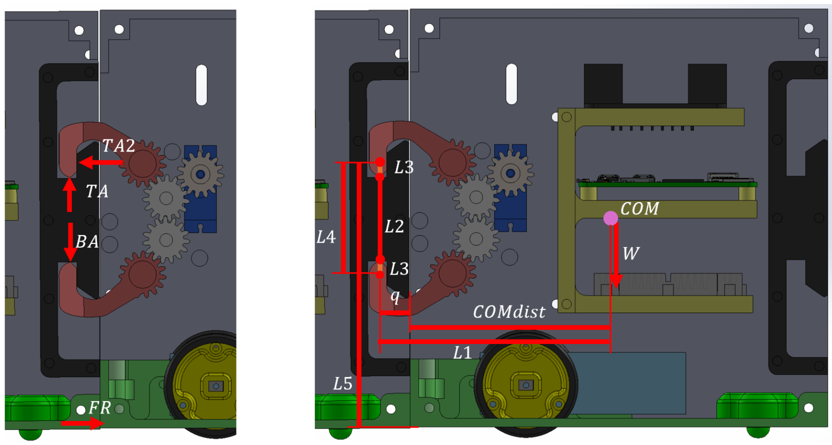


Figure 5: Full System Free Body Diagrams
*Note: The bottom arm does not interact with the receiver in the X direction when loaded

Full System Equations

$$F_{5x} = 0 = B_A \sin(\theta) - T_A \sin(\theta) + T_{A2} - F_R \cos(\theta)$$

$$F_{5y} = 0 = -B_A \cos(\theta) + T_A \cos(\theta) - W_{\text{COM}} - F_R \sin(\theta)$$

Sum of moments about point BA:

$$M_{p5} = 0 = -q \cdot F_R \cos(\theta) + l_2 T_A \cos(\theta) - l_5 F_R \sin(\theta) + W_{\text{COM}}(\text{COMdist1}) - l_4 T_{A2}$$

Solving Parameters

Using MATLAB's syms and solve functions, the 15 equations associated with the Free Body Diagrams above were used to solve for the 15 unknown values. These equations were then iterated through with masses of 800 grams to 950 grams in increments of 10. In addition, the actual gripper system has two servo motors driving the gripper arms. However, because the math was done in two dimensions and not three, the sum of the motor's torque output was used to solve for the forces throughout the system.

While these equations are the force interactions for one cube's gripper assembly holding one cube up, these were then scaled to determine the forces on the gripper components when there are 2 and 3 robots overhanging.

To solve for 2 and 3 robot's overhanging, the only equation used from the 15 equations above is the full system sum of moments equation about point BA. Below are the iterations of the equations.

Sum of moments about point BA (2 Cube Overhang)

$$M_{p5} = 0 = -q \cdot F_R \cos(\theta) + l_2 T_A \cos(\theta) - l_5 F_R \sin(\theta) + W_{\mathrm{COM}}(\mathrm{COMdist1}) - l_4 T_{A2}$$

Sum of moments about point BA (3 Cube Overhang)

$$M_{p5} = 0 = -q \cdot F_R \cos(\theta) + l_2 T_A \cos(\theta) - l_5 F_R \sin(\theta) + W_{\mathrm{COM}}(\mathrm{COMdist1}) - l_4 T_{A2}$$

Force Results: One Cube

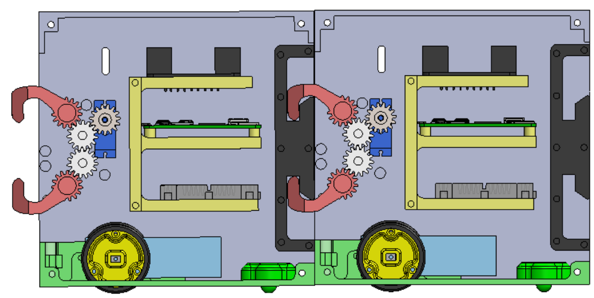
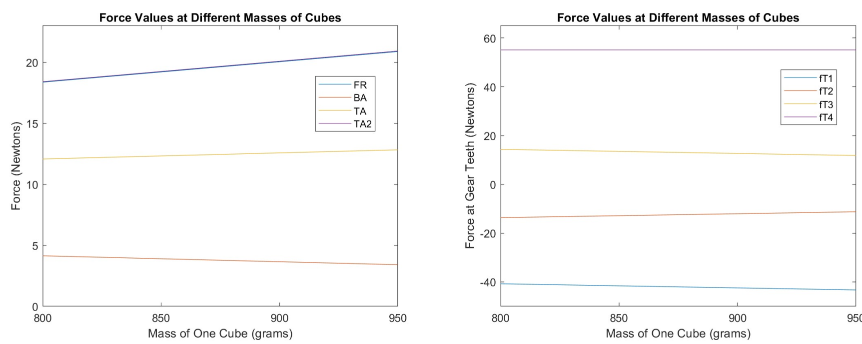


Figure 6: Example of 1 Cube held by One Gripper Assembly above



(a) External Forces on Gripper and Cube

(b) Forces at Gears

Figure 7: Forces the Gripper and Cube experience **Note: TA2 and FR have the same Force values (left plot)

Force Results: Multiple Cube's Held by Gripper

2 Cube Force Results

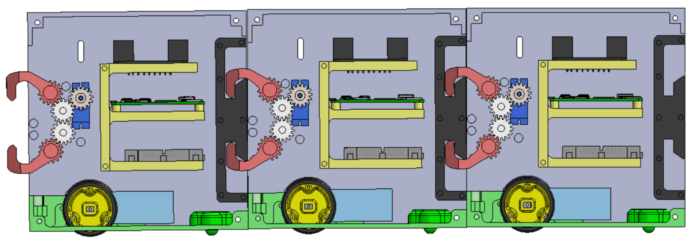
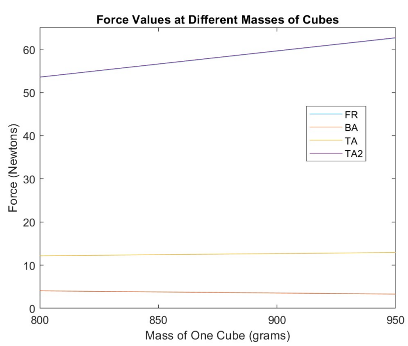
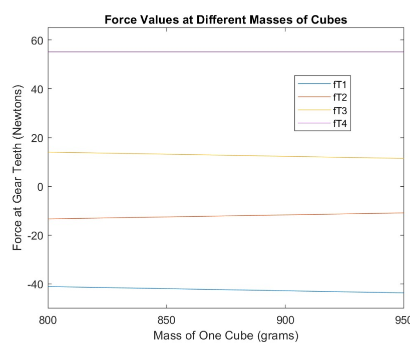


Figure 8: Example of 2 Cubes held by One Gripper Assembly



(a) External Forces on Gripper and Cube



(b) Forces at Gears

Figure 9: Forces the Gripper and Cube experience **Note: TA2 and FR have the same Force values (left plot)

3 Cube Force Results

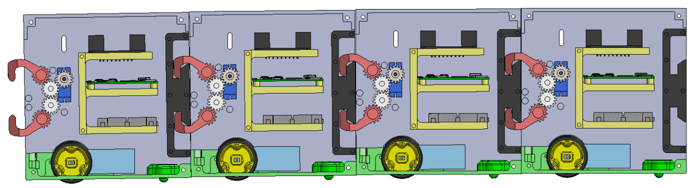
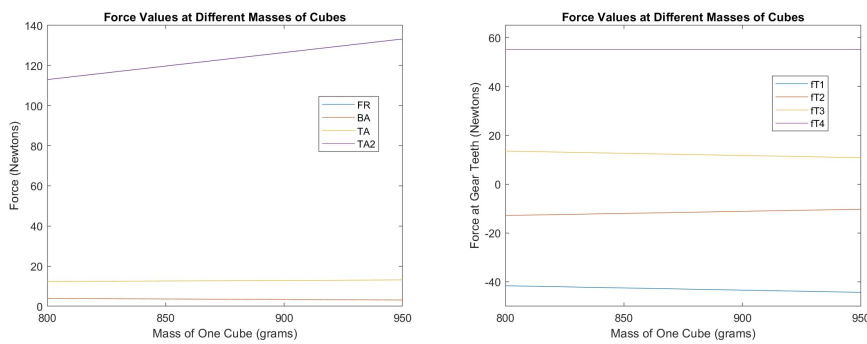


Figure 10: Example of 3 Cubes held by One Gripper Assembly



(a) External Forces on Gripper and Cube

(b) Forces at Gears

Figure 11: Forces the Gripper and Cube experience **Note: TA2 and FR have the same Force values (left plot)

Force Results Summary

The more cubes that one gripper assembly/cube try to hold up the greater the forces are on the gripper arms (TA, TA2, BA), cube face (FR), and gripper assembly gears (fT1, fT2, fT3, fT4). The graphs show large jumps in force values with each additional cube added, this is due to the moment that the cubes generate. The more cubes, the longer the moment arm, and in turn larger forces on the gripper.

The force values seen across these plots for the gears, arms, and cube frame were used in Solidworks FEA to better understand how the forces the parts will theoretically experience and the part's max force it can withstand before reaching maximum yield.

The forces that one gripper holding 3 other cubes up experiences far exceeds what the part's maximum yield is (based on Solidworks FEA). These calculations serve as a way to understand theoretically what is the "max" load one gripper/cube system can endure. However, the theoretical math does not account for the fact, the gripper will not be continuously "gripping" the receiver. The gripper actuation is for the purpose of move the arms into the "connected" position on the receiver. Once in this place, the gripper no longer requires actuation. This is because the receiver and gripper were designed in a way that once "connected" the cube faces keep the cubes locked together. Additionally, when completing the demonstration, at minimum the same number of cubes overhanging while crossing the gap will be connected to each other on a flat surface.

Static Force Calculations of Wheels

Constants

$$\text{WheelRadius} = 0.022225 \text{ meters} = 0.875\text{inches}$$
$$\text{Max Torque for Blue Motors} = 0.146 \text{ Newton-Meters @ 11.1 Volts}$$
$$\text{1 Cube: Mass Values} = 0.80, 0.81, 0.82, \ldots, 0.94, 0.95 \text{ kilograms}$$
$$\text{2 Cubes: Mass Values} = 1.60, 1.62, 1.63, \ldots, 1.88, 1.90 \text{ kilograms}$$
$$\text{2 Cubes: Mass Values} = 2.40, 2.43, 2.46, \ldots, 2.82, 2.85 \text{ kilograms}$$
$$\text{Gravity} = 9.8 \text{ m/s}^2$$
$$\text{Weight} = \text{Mass Values} \times \text{Gravity}$$

Static Coefficients of Friction

$$\text{Soft Rubber on Dry Wood: SRonDW} = \mu 1 = 0.95$$
$$\text{Soft Plastic on Dry Wood: SPonDW} = \mu 1 = 0.7$$
$$\text{Soft Rubber on Dry Concrete: SRonDC} = \mu 1 = 0.6$$
$$\text{Soft Plastic on Dry Concrete: SPonDC} = \mu 1 = 0.85$$

FBD

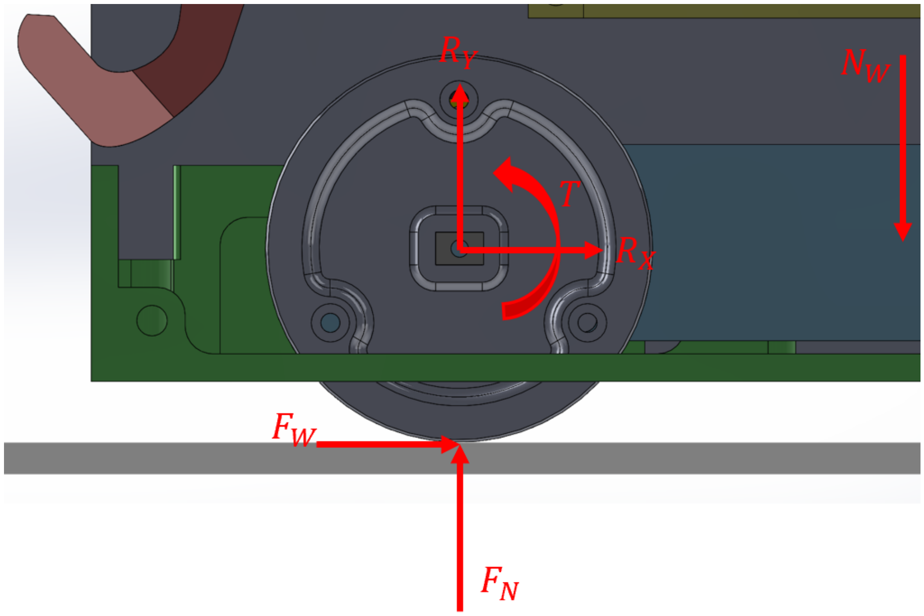


Figure 12: Wheel Free Body Diagram

Fw = Friction Force acting on the wheel
FN = Normal Force Acting on the wheel
Ry and Rx are the pin forces acting on the wheel's hub/axle
Nw is the net weight of the cube acting down due to gravity

This FBD shows all forces that the wheel experiences, internal and external. The sum of force equations and sum of moment equations are not needed to solve for the Torque value that would result in wheel slippage.

Instead, knowing when the force experienced at the wheel (Fw) is greater than the coefficient of friction * the weight of the cube, slippage occurs in combination with the equation Torque = Force*radius the torque value output by the blue motors that causes slippage can be calculated.

Force Equations

*Fw must be Less than or Equal to μ * Weight*
All values for one of the two wheels
All values in Nm

Force Equations for Fw: Soft Rubber on Dry Wood

$$\text{Fw1} = \frac{SRonDW \times \text{Weight}}{2}$$

Force Equations for Fw: Soft Plastic on Dry Wood

$$\text{Fw2} = \frac{SPonDW \times \text{Weight}}{2}$$

Force Equations for Fw: Soft Plastic on Dry Concrete

$$\text{Fw3} = \frac{SRonDC \times \text{Weight}}{2}$$

Force Equations for Fw: Soft Plastic on Dry Concrete

$$\text{Fw4} = \frac{SPonDC \times \text{Weight}}{2}$$

Torque Equations

Max Torque (Nm) before experiencing slippage for (one of the two wheels) for different material combinations

Torque Equations for T: Soft Rubber on Dry Wood

$$T1 = \text{WheelRadius} \times \text{Fw1}$$

Torque Equations for T: Soft Plastic on Dry Wood

$$T2 = \text{WheelRadius} \times \text{Fw2}$$

Torque Equations for T: Soft Rubber on Dry Concrete

$$T3 = \text{WheelRadius} \times \text{Fw3}$$

Torque Equations for T: Soft Plastic on Dry Concrete

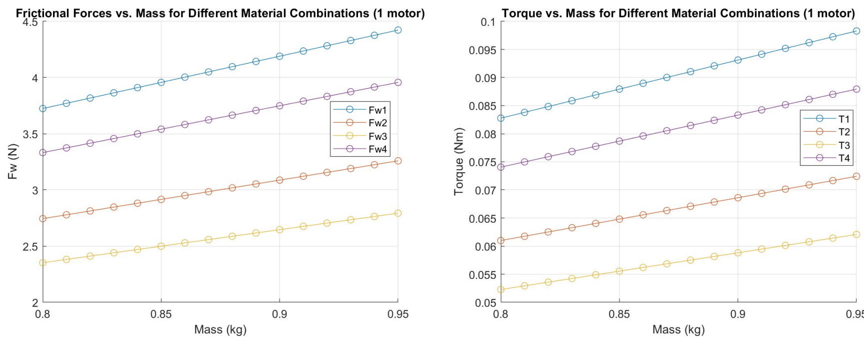
$$T4 = \text{WheelRadius} \times \text{Fw4}$$

Solving Parameters

To generate the equations above, it was assumed that all cube weight values were only acting on one wheel directly above its axle. This allowed for analysis of what the blue motors were capable of moving if one of the two motors were to stop functioning. In addition, the mass of one cube was iterated from 800 grams to 950 grams to detail the flexibility the robot has if the weight were to fluctuate during design changes. To complete the calculations, these assumptions were made. If one robot was pushing/pulling another, the second and/or third robot's masses would be directly over the axles. Therefore, not generating a moment, nor having the force of friction increase from the driving robot dragging the other robots wheels.

Using these results, the forces and torques were extrapolated to for understanding what the force and torque values would be when the weight is distributed to the two drive wheels. The marble/caster wheel on the back of the robot was not considered for load distribution in the calculations.

Iterating Mass of 1 Cube: Friction Force, Torque, and Percent Stall Torque Results



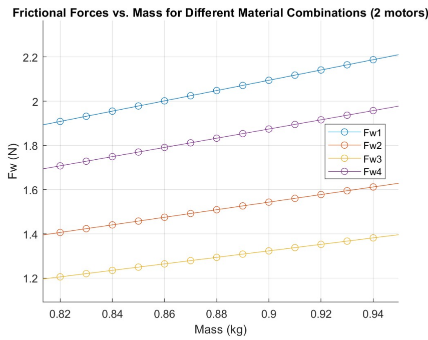
(a) 1 Cube 1 Wheel/Motor

(b) 1 Cube 1 Wheel/Motor

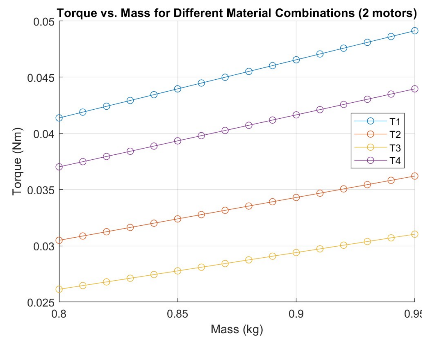
Figure 13: Max Friction Force and Torque Plots Before Wheel Slippage Based on Varying 1 Cube Mass

		Force Per Blue Motor (1 Motor)				Torque Per Blue Motor (1 Motor)			
		1 Cube FORCES (N)				1 Cube TORQUES (Nm)			
	Cube Mass (kg)	SR on DW	SP on DW	SR on DC	SP on DC	SR on DW	SP on DW	SR on DC	SP on DC
	0.8	3.7240	2.7440	2.3520	3.3320	0.0828	0.0610	0.0523	0.0741
	0.81	3.7706	2.7783	2.3814	3.3737	0.0838	0.0617	0.0529	0.0750
	0.82	3.8171	2.8126	2.4108	3.4153	0.0848	0.0625	0.0536	0.0759
	0.83	3.8637	2.8469	2.4402	3.4570	0.0859	0.0633	0.0542	0.0768
	0.84	3.9102	2.8812	2.4696	3.4986	0.0869	0.0640	0.0549	0.0778
	0.85	3.9568	2.9155	2.4990	3.5403	0.0879	0.0648	0.0555	0.0787
	0.86	4.0033	2.9498	2.5284	3.5819	0.0890	0.0656	0.0562	0.0796
1 Cube Mass	0.87	4.0499	2.9841	2.5578	3.6236	0.0900	0.0663	0.0568	0.0805
	0.88	4.0964	3.0184	2.5872	3.6652	0.0910	0.0671	0.0575	0.0815
	0.89	4.1430	3.0527	2.6166	3.7069	0.0921	0.0678	0.0582	0.0824
	0.9	4.1895	3.0870	2.6460	3.7485	0.0931	0.0686	0.0588	0.0833
	0.91	4.2361	3.1213	2.6754	3.7902	0.0941	0.0694	0.0595	0.0842
	0.92	4.2826	3.1556	2.7048	3.8318	0.0952	0.0701	0.0601	0.0852
	0.93	4.3292	3.1899	2.7342	3.8735	0.0962	0.0709	0.0608	0.0861
	0.94	4.3757	3.2242	2.7636	3.9151	0.0972	0.0717	0.0614	0.0870
	0.95	4.4223	3.2585	2.7930	3.9568	0.0983	0.0724	0.0621	0.0879

Figure 14: 1 Cube 1 Wheel/Motor Friction Force and Torque Values
**If a box is red: Indicates more than 50 Percent of Blue Motor Stall Torque is being used*



(a) 1 Cube 2 Wheels/Motors



(b) 1 Cube 2 Wheels/Motors

Figure 15: Max Friction Force and Torque Plots Before Wheel Slippage Based on Varying 1 Cube Mass

		Force Per Blue Motor (2 Motors)				Torque Per Blue Motor (2 Motors)			
		1 Cube FORCES (N)				1 Cube TORQUES (Nm)			
	Cube Mass (kg)	SR on DW	SP on DW	SR on DC	SP on DC	SR on DW	SP on DW	SR on DC	SP on DC
1 Cube Mass	0.8	1.8620	1.3720	1.1760	1.6660	0.0414	0.0305	0.0261	0.0370
	0.81	1.8853	1.3892	1.1907	1.6868	0.0419	0.0309	0.0265	0.0375
	0.82	1.9086	1.4063	1.2054	1.7077	0.0424	0.0313	0.0268	0.0380
	0.83	1.9318	1.4235	1.2201	1.7285	0.0429	0.0316	0.0271	0.0384
	0.84	1.9551	1.4406	1.2348	1.7493	0.0435	0.0320	0.0274	0.0389
	0.85	1.9784	1.4578	1.2495	1.7701	0.0440	0.0324	0.0278	0.0393
	0.86	2.0017	1.4749	1.2642	1.7910	0.0445	0.0328	0.0281	0.0398
	0.87	2.0249	1.4921	1.2789	1.8118	0.0450	0.0332	0.0284	0.0403
	0.88	2.0482	1.5092	1.2936	1.8326	0.0455	0.0335	0.0288	0.0407
	0.89	2.0715	1.5264	1.3083	1.8534	0.0460	0.0339	0.0291	0.0412
	0.9	2.0948	1.5435	1.3230	1.8743	0.0466	0.0343	0.0294	0.0417
	0.91	2.1180	1.5607	1.3377	1.8951	0.0471	0.0347	0.0297	0.0421
	0.92	2.1413	1.5778	1.3524	1.9159	0.0476	0.0351	0.0301	0.0426
	0.93	2.1646	1.5950	1.3671	1.9367	0.0481	0.0354	0.0304	0.0430
	0.94	2.1879	1.6121	1.3818	1.9576	0.0486	0.0358	0.0307	0.0435
	0.95	2.2111	1.6293	1.3965	1.9784	0.0491	0.0362	0.0310	0.0440

Figure 16: 1 Cube 2 Wheels/Motors Friction Force and Torque Values
**If a box is red: Indicates more than 50 Percent of Blue Motor Stall Torque is being used*

PERCENT OF STALL TORQUE 0.146 Nm (1 Motor)				
1 Cube TORQUES (Nm)				
Cube Mass (kg)	SR on DW	SP on DW	SR on DC	SP on DC
0.8	56.69%	41.77%	35.80%	50.72%
0.81	57.40%	42.29%	36.25%	51.36%
0.82	58.11%	42.82%	36.70%	51.99%
0.83	58.81%	43.34%	37.15%	52.62%
0.84	59.52%	43.86%	37.59%	53.26%
0.85	60.23%	44.38%	38.04%	53.89%
0.86	60.94%	44.90%	38.49%	54.53%
0.87	61.65%	45.43%	38.94%	55.16%
0.88	62.36%	45.95%	39.38%	55.79%
0.89	63.07%	46.47%	39.83%	56.43%
0.9	63.78%	46.99%	40.28%	57.06%
0.91	64.48%	47.51%	40.73%	57.70%
0.92	65.19%	48.04%	41.17%	58.33%
0.93	65.90%	48.56%	41.62%	58.96%
0.94	66.61%	49.08%	42.07%	59.60%
0.95	67.32%	49.60%	42.52%	60.23%

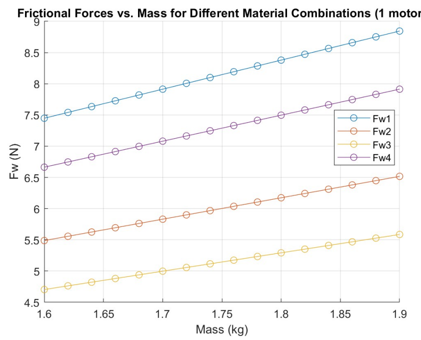
(a) 1 Cube 1 Wheel/Motor

PERCENT OF STALL TORQUE 0.146 Nm (2 Motors)				
1 Cube TORQUES (Nm)				
Cube Mass (kg)	SR on DW	SP on DW	SR on DC	SP on DC
0.8	28.34%	20.89%	17.90%	25.36%
0.81	28.70%	21.15%	18.13%	25.68%
0.82	29.05%	21.41%	18.35%	25.99%
0.83	29.41%	21.67%	18.57%	26.31%
0.84	29.76%	21.93%	18.80%	26.63%
0.85	30.12%	22.19%	19.02%	26.95%
0.86	30.47%	22.45%	19.24%	27.26%
0.87	30.82%	22.71%	19.47%	27.58%
0.88	31.18%	22.97%	19.69%	27.90%
0.89	31.53%	23.24%	19.92%	28.21%
0.9	31.89%	23.50%	20.14%	28.53%
0.91	32.24%	23.76%	20.36%	28.85%
0.92	32.60%	24.02%	20.59%	29.16%
0.93	32.95%	24.28%	20.81%	29.48%
0.94	33.30%	24.54%	21.03%	29.80%
0.95	33.66%	24.80%	21.26%	30.12%

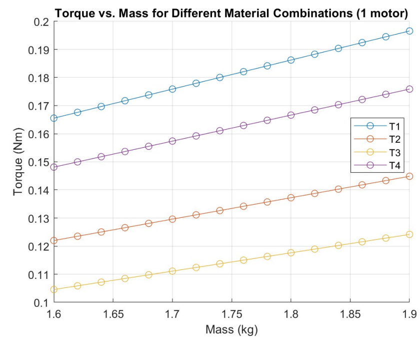
(b) 1 Cube 1 Wheel/Motor

Figure 17: Percent Stall Torque Used for Different Material Combinations
**If a box is red: Indicates more than 50 Percent of Blue Motor Stall Torque is being used*

Iterating Mass of 2 Cubes: Friction Force, Torque, and Percent Stall Torque Results



(a) 2 Cubes 1 Wheel/Motor

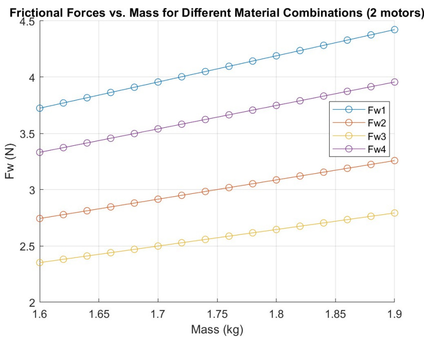


(b) 2 Cubes 1 Wheel/Motor

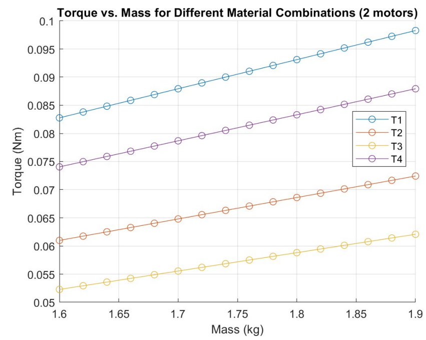
Figure 18: Max Friction Force and Torque Plots Before Wheel Slippage Based on Varying 2 Cube Mass

		Force Per Blue Motor (1 Motor)				Torque Per Blue Motor (1 Motor)			
		2 Cube FORCES (N)				2 Cube TORQUES (Nm)			
	Cube Mass (kg)	SR on DW	SP on DW	SR on DC	SP on DC	SR on DW	SP on DW	SR on DC	SP on DC
2 Cube Mass	1.6	7.4480	5.4880	4.7040	6.6640	0.1655	0.1220	0.1045	0.1481
	1.62	7.5411	5.5566	4.7628	6.7473	0.1676	0.1235	0.1059	0.1500
	1.64	7.6342	5.6252	4.8216	6.8306	0.1697	0.1250	0.1072	0.1518
	1.66	7.7273	5.6938	4.8804	6.9139	0.1717	0.1265	0.1085	0.1537
	1.68	7.8204	5.7624	4.9392	6.9972	0.1738	0.1281	0.1098	0.1555
	1.7	7.9135	5.8310	4.9980	7.0805	0.1759	0.1296	0.1111	0.1574
	1.72	8.0066	5.8996	5.0568	7.1638	0.1779	0.1311	0.1124	0.1592
	1.74	8.0997	5.9682	5.1156	7.2471	0.1800	0.1326	0.1137	0.1611
	1.76	8.1928	6.0368	5.1744	7.3304	0.1821	0.1342	0.1150	0.1629
	1.78	8.2859	6.1054	5.2332	7.4137	0.1842	0.1357	0.1163	0.1648
	1.8	8.3790	6.1740	5.2920	7.4970	0.1862	0.1372	0.1176	0.1666
	1.82	8.4721	6.2426	5.3508	7.5803	0.1883	0.1387	0.1189	0.1685
	1.84	8.5652	6.3112	5.4096	7.6636	0.1904	0.1403	0.1202	0.1703
	1.86	8.6583	6.3798	5.4684	7.7469	0.1924	0.1418	0.1215	0.1722
	1.88	8.7514	6.4484	5.5272	7.8302	0.1945	0.1433	0.1228	0.1740
	1.9	8.8445	6.5170	5.5860	7.9135	0.1966	0.1448	0.1241	0.1759

Figure 19: 2 Cubes 1 Wheel/Motor Friction Force and Torque Values
**If a box is red: Indicates more than 50 Percent of Blue Motor Stall Torque is being used*



(a) 2 Cubes 2 Wheels/Motors



(b) 2 Cubes 2 Wheels/Motors

Figure 20: Max Friction Force and Torque Plots Before Wheel Slippage Based on Varying 2 Cube Mass

		Force Per Blue Motor (2 Motors)				Torque Per Blue Motor (2 Motors)			
		2 Cube FORCES (N)				2 Cube TORQUES (Nm)			
	Cube Mass (kg)	SR on DW	SP on DW	SR on DC	SP on DC	SR on DW	SP on DW	SR on DC	SP on DC
2 Cube Mass	1.6	3.7240	2.7440	2.3520	3.3320	0.0828	0.0610	0.0523	0.0741
	1.62	3.7706	2.7783	2.3814	3.3737	0.0838	0.0617	0.0529	0.0750
	1.64	3.8171	2.8126	2.4108	3.4153	0.0848	0.0625	0.0536	0.0759
	1.66	3.8637	2.8469	2.4402	3.4570	0.0859	0.0633	0.0542	0.0768
	1.68	3.9102	2.8812	2.4696	3.4986	0.0869	0.0640	0.0549	0.0778
	1.7	3.9568	2.9155	2.4990	3.5403	0.0879	0.0648	0.0555	0.0787
	1.72	4.0033	2.9498	2.5284	3.5819	0.0890	0.0656	0.0562	0.0796
	1.74	4.0499	2.9841	2.5578	3.6236	0.0900	0.0663	0.0568	0.0805
	1.76	4.0964	3.0184	2.5872	3.6652	0.0910	0.0671	0.0575	0.0815
	1.78	4.1430	3.0527	2.6166	3.7069	0.0921	0.0678	0.0582	0.0824
	1.8	4.1895	3.0870	2.6460	3.7485	0.0931	0.0686	0.0588	0.0833
	1.82	4.2361	3.1213	2.6754	3.7902	0.0941	0.0694	0.0595	0.0842
	1.84	4.2826	3.1556	2.7048	3.8318	0.0952	0.0701	0.0601	0.0852
	1.86	4.3292	3.1899	2.7342	3.8735	0.0962	0.0709	0.0608	0.0861
	1.88	4.3757	3.2242	2.7636	3.9151	0.0972	0.0717	0.0614	0.0870
	1.9	4.4223	3.2585	2.7930	3.9568	0.0983	0.0724	0.0621	0.0879

Figure 21: 2 Cubes 2 Wheels/Motors Friction Force and Torque Values
**If a box is red: Indicates more than 50 Percent of Blue Motor Stall Torque is being used*

PERCENT OF STALL TORQUE 0.146 Nm (1 Motor)				
2 Cube TORQUES (Nm)				
Cube Mass (kg)	SR on DW	SP on DW	SR on DC	SP on DC
1.6	113.38%	83.54%	71.61%	101.44%
1.62	114.80%	84.59%	72.50%	102.71%
1.64	116.21%	85.63%	73.40%	103.98%
1.66	117.63%	86.67%	74.29%	105.25%
1.68	119.05%	87.72%	75.19%	106.52%
1.7	120.46%	88.76%	76.08%	107.78%
1.72	121.88%	89.81%	76.98%	109.05%
1.74	123.30%	90.85%	77.87%	110.32%
1.76	124.72%	91.90%	78.77%	111.59%
1.78	126.13%	92.94%	79.66%	112.86%
1.8	127.55%	93.98%	80.56%	114.12%
1.82	128.97%	95.03%	81.45%	115.39%
1.84	130.38%	96.07%	82.35%	116.66%
1.86	131.80%	97.12%	83.24%	117.93%
1.88	133.22%	98.16%	84.14%	119.20%
1.9	134.64%	99.21%	85.03%	120.46%

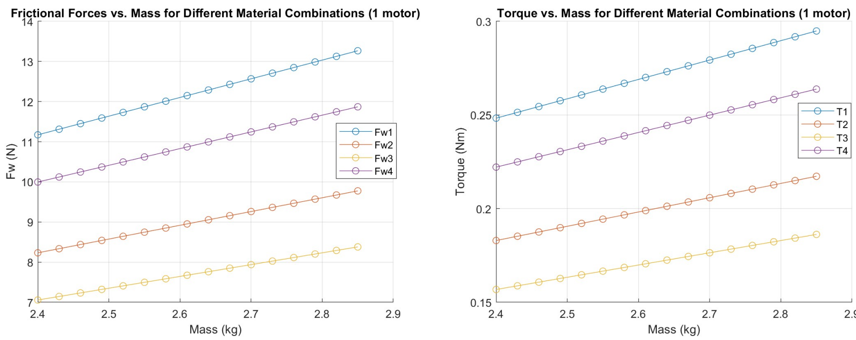
(a) 2 Cubes 1 Wheel/Motor

PERCENT OF STALL TORQUE 0.146 Nm (2 Motors)				
2 Cube TORQUES (Nm)				
Cube Mass (kg)	SR on DW	SP on DW	SR on DC	SP on DC
1.6	56.69%	41.77%	35.80%	50.72%
1.62	57.40%	42.29%	36.25%	51.36%
1.64	58.11%	42.82%	36.70%	51.99%
1.66	58.81%	43.34%	37.15%	52.62%
1.68	59.52%	43.86%	37.59%	53.26%
1.7	60.23%	44.38%	38.04%	53.89%
1.72	60.94%	44.90%	38.49%	54.53%
1.74	61.65%	45.43%	38.94%	55.16%
1.76	62.36%	45.95%	39.38%	55.79%
1.78	63.07%	46.47%	39.83%	56.43%
1.8	63.78%	46.99%	40.28%	57.06%
1.82	64.48%	47.51%	40.73%	57.70%
1.84	65.19%	48.04%	41.17%	58.33%
1.86	65.90%	48.56%	41.62%	58.96%
1.88	66.61%	49.08%	42.07%	59.60%
1.9	67.32%	49.60%	42.52%	60.23%

(b) 2 Cubes 2 Wheels/Motors

Figure 22: Percent Stall Torque Used for Different Material Combinations
**If a box is red: Indicates more than 50 Percent of Blue Motor Stall Torque is being used*

Iterating Mass of 3 Cubes: Friction Force, Torque, and Percent Stall Torque Results

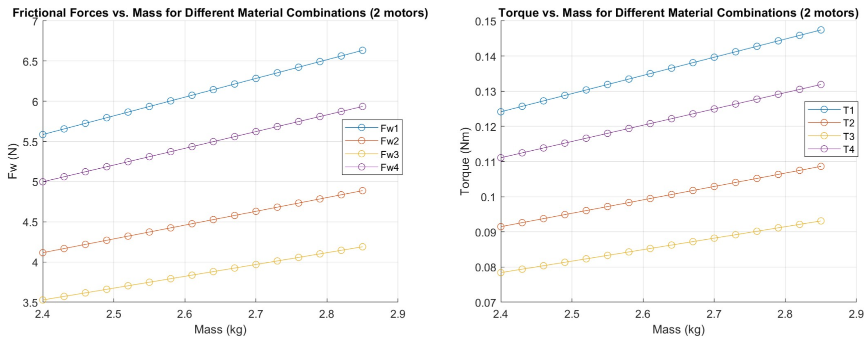


(a) 3 Cubes 1 Wheel/Motor (b) 3 Cubes 1 Wheel/Motor

Figure 23: Max Friction Force and Torque Plots Before Wheel Slippage Based on Varying 3 Cube Mass

		Force Per Blue Motor (1 Motor)				Torque Per Blue Motor (1 Motor)			
		3 Cube FORCES (N)				3 Cube TORQUES (Nm)			
	Cube Mass (kg)	SR on DW	SP on DW	SR on DC	SP on DC	SR on DW	SP on DW	SR on DC	SP on DC
	2.4	11.1720	8.2320	7.0560	9.9960	0.2483	0.1830	0.1568	0.2222
	2.43	11.3117	8.3349	7.1442	10.1210	0.2514	0.1852	0.1588	0.2249
	2.46	11.4513	8.4378	7.2324	10.2459	0.2545	0.1875	0.1607	0.2277
	2.49	11.5910	8.5407	7.3206	10.3709	0.2576	0.1898	0.1627	0.2305
	2.52	11.7306	8.6436	7.4088	10.4958	0.2607	0.1921	0.1647	0.2333
	2.55	11.8703	8.7465	7.4970	10.6208	0.2638	0.1944	0.1666	0.2360
	2.58	12.0099	8.8494	7.5852	10.7457	0.2669	0.1967	0.1686	0.2388
3 Cube Mass	2.61	12.1496	8.9523	7.6734	10.8707	0.2700	0.1990	0.1705	0.2416
	2.64	12.2892	9.0552	7.7616	10.9956	0.2731	0.2013	0.1725	0.2444
	2.67	12.4289	9.1581	7.8498	11.1206	0.2762	0.2035	0.1745	0.2472
	2.7	12.5685	9.2610	7.9380	11.2455	0.2793	0.2058	0.1764	0.2499
	2.73	12.7082	9.3639	8.0262	11.3705	0.2824	0.2081	0.1784	0.2527
	2.76	12.8478	9.4668	8.1144	11.4954	0.2855	0.2104	0.1803	0.2555
	2.79	12.9875	9.5697	8.2026	11.6204	0.2886	0.2127	0.1823	0.2583
	2.82	13.1271	9.6726	8.2908	11.7453	0.2917	0.2150	0.1843	0.2610
	2.85	13.2668	9.7755	8.3790	11.8703	0.2949	0.2173	0.1862	0.2638

Figure 24: 3 Cubes 1 Wheel/Motor Friction Force and Torque Values
**If a box is red: Indicates more than 50 Percent of Blue Motor Stall Torque is being used*



(a) 3 Cube 2 Wheels/Motors

(b) 2 Cube 2 Wheels/Motors

Figure 25: Max Friction Force and Torque Plots Before Wheel Slippage Based on Varying 3 Cube Mass

		Force Per Blue Motor (2 Motors)				Torque Per Blue Motor (2 Motors)			
		3 Cube FORCES (N)				3 Cube TORQUES (Nm)			
	Cube Mass (kg)	SR on DW	SP on DW	SR on DC	SP on DC	SR on DW	SP on DW	SR on DC	SP on DC
3 Cube Mass	2.4	5.5860	4.1160	3.5280	4.9980	0.1241	0.0915	0.0784	0.1111
	2.43	5.6558	4.1675	3.5721	5.0605	0.1257	0.0926	0.0794	0.1125
	2.46	5.7257	4.2189	3.6162	5.1230	0.1273	0.0938	0.0804	0.1139
	2.49	5.7955	4.2704	3.6603	5.1854	0.1288	0.0949	0.0814	0.1152
	2.52	5.8653	4.3218	3.7044	5.2479	0.1304	0.0961	0.0823	0.1166
	2.55	5.9351	4.3733	3.7485	5.3104	0.1319	0.0972	0.0833	0.1180
	2.58	6.0050	4.4247	3.7926	5.3729	0.1335	0.0983	0.0843	0.1194
	2.61	6.0748	4.4762	3.8367	5.4353	0.1350	0.0995	0.0853	0.1208
	2.64	6.1446	4.5276	3.8808	5.4978	0.1366	0.1006	0.0863	0.1222
	2.67	6.2144	4.5791	3.9249	5.5603	0.1381	0.1018	0.0872	0.1236
	2.7	6.2843	4.6305	3.9690	5.6228	0.1397	0.1029	0.0882	0.1250
	2.73	6.3541	4.6820	4.0131	5.6852	0.1412	0.1041	0.0892	0.1264
	2.76	6.4239	4.7334	4.0572	5.7477	0.1428	0.1052	0.0902	0.1277
	2.79	6.4937	4.7849	4.1013	5.8102	0.1443	0.1063	0.0912	0.1291
	2.82	6.5636	4.8363	4.1454	5.8727	0.1459	0.1075	0.0921	0.1305
	2.85	6.6334	4.8878	4.1895	5.9351	0.1474	0.1086	0.0931	0.1319

Figure 26: 3 Cube 2 Wheels/Motors Friction Force and Torque Values
**If a box is red: Indicates more than 50 Percent of Blue Motor Stall Torque is being used*

PERCENT OF STALL TORQUE 0.146 Nm (1 Motor)				
3 Cube TORQUES (Nm)				
Cube Mass (kg)	SR on DW	SP on DW	SR on DC	SP on DC
2.4	170.07%	125.31%	107.41%	152.17%
2.43	172.19%	126.88%	108.75%	154.07%
2.46	174.32%	128.45%	110.10%	155.97%
2.49	176.44%	130.01%	111.44%	157.87%
2.52	178.57%	131.58%	112.78%	159.77%
2.55	180.70%	133.14%	114.12%	161.68%
2.58	182.82%	134.71%	115.47%	163.58%
2.61	184.95%	136.28%	116.81%	165.48%
2.64	187.07%	137.84%	118.15%	167.38%
2.67	189.20%	139.41%	119.49%	169.28%
2.7	191.33%	140.98%	120.84%	171.19%
2.73	193.45%	142.54%	122.18%	173.09%
2.76	195.58%	144.11%	123.52%	174.99%
2.79	197.70%	145.68%	124.86%	176.89%
2.82	199.83%	147.24%	126.21%	178.79%
2.85	201.95%	148.81%	127.55%	180.70%

(a) 3 Cubes 1 Wheel/Motor

PERCENT OF STALL TORQUE 0.146 Nm (2 Motors)				
3 Cube TORQUES (Nm)				
Cube Mass (kg)	SR on DW	SP on DW	SR on DC	SP on DC
2.4	85.03%	62.66%	53.71%	76.08%
2.43	86.10%	63.44%	54.38%	77.03%
2.46	87.16%	64.22%	55.05%	77.98%
2.49	88.22%	65.01%	55.72%	78.94%
2.52	89.29%	65.79%	56.39%	79.89%
2.55	90.35%	66.57%	57.06%	80.84%
2.58	91.41%	67.36%	57.73%	81.79%
2.61	92.47%	68.14%	58.40%	82.74%
2.64	93.54%	68.92%	59.08%	83.69%
2.67	94.60%	69.71%	59.75%	84.64%
2.7	95.66%	70.49%	60.42%	85.59%
2.73	96.73%	71.27%	61.09%	86.54%
2.76	97.79%	72.05%	61.76%	87.49%
2.79	98.85%	72.84%	62.43%	88.45%
2.82	99.91%	73.62%	63.10%	89.40%
2.85	100.98%	74.40%	63.78%	90.35%

(b) 3 Cubes 2 Wheels/Motors

Figure 27: Percent Stall Torque Used for Different Material Combinations
**If a box is red: Indicates more than 50 Percent of Blue Motor Stall Torque is being used*

Force, Torque, Stall Torque Results Summary

Based on the plots and tables, the tire material and driving terrain material combinations that had the best outcomes were soft rubber on dry concrete (SR on DC) and soft plastic on dry wood (SP on DW). This held true for calculations where only one wheel/motor would be moving the weight of cubes, and for calculations with two wheels/motors moving the weight.

The blue motors were able to handle moving the weight of 2 cubes (varying from 800g to 950 gram individual cube mass), without exceeding 50 Percent of the motor's stall torque. Furthermore, all the torque values seen in the tables are the maximum torque value that can be used before the wheels experience slippage. Therefore, one cube robot, based on the math and assumptions made, can push/pull one additional cube.