Optimization of a Spherical Parallel Manipulator for Enhanced Performance in Human-Centric Environments

ME6103 Final Project, Spring 2025

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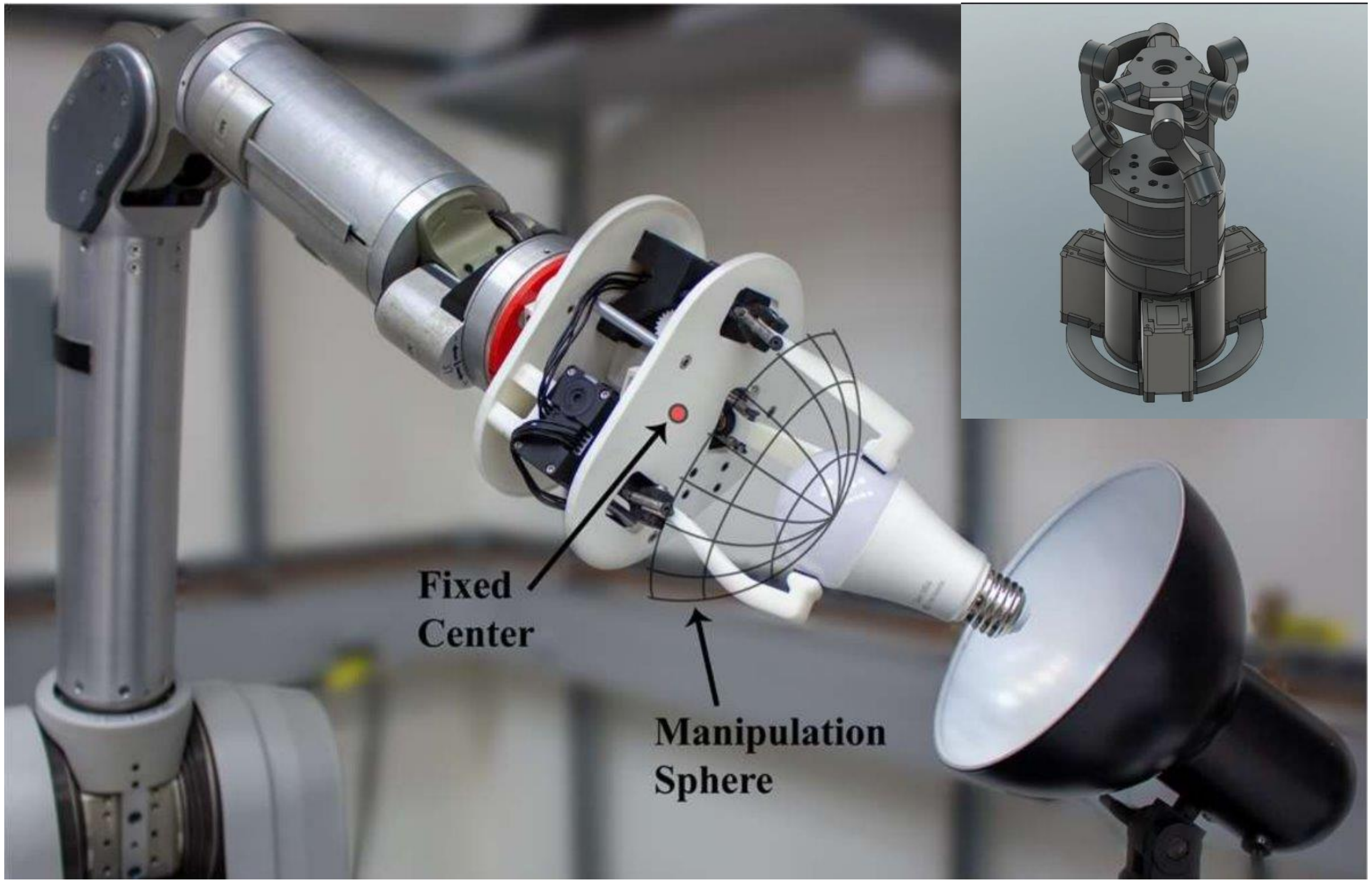
Introduction

What is a Spherical Parallel Manipulator?

- A spherical Parallel Manipulator is a type of parallel robot with 3 degrees of rotational freedom
- Effectively this allows it to rotate around a fixed center point
- This simple attachment can make a standard collaborative robot incredibly more dexterous
- The tools presented in this course provide an excellent means of analyzing the many parameters of this robot and optimize an initial concept design



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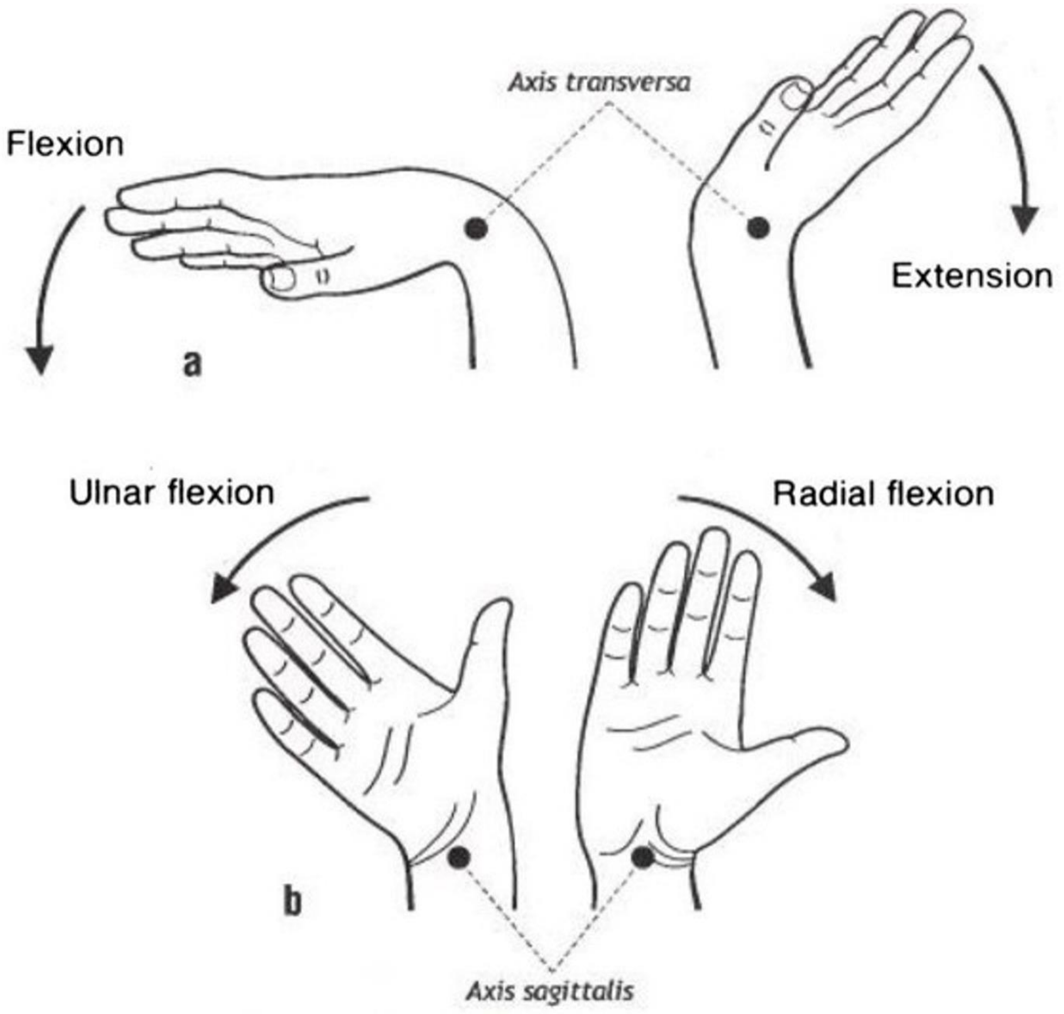
Point of Reference

- The human wrist effectively serves a an immediate comparison of what the mechanism can achieve
- However rather than being limited in a direction such as ulnar flexion the SPM can achieve large rotation in all directions
- With robots being more prevalent in human centric environments excellent dexterity and orientation adjustment without needing to have large robot repositions is paramount



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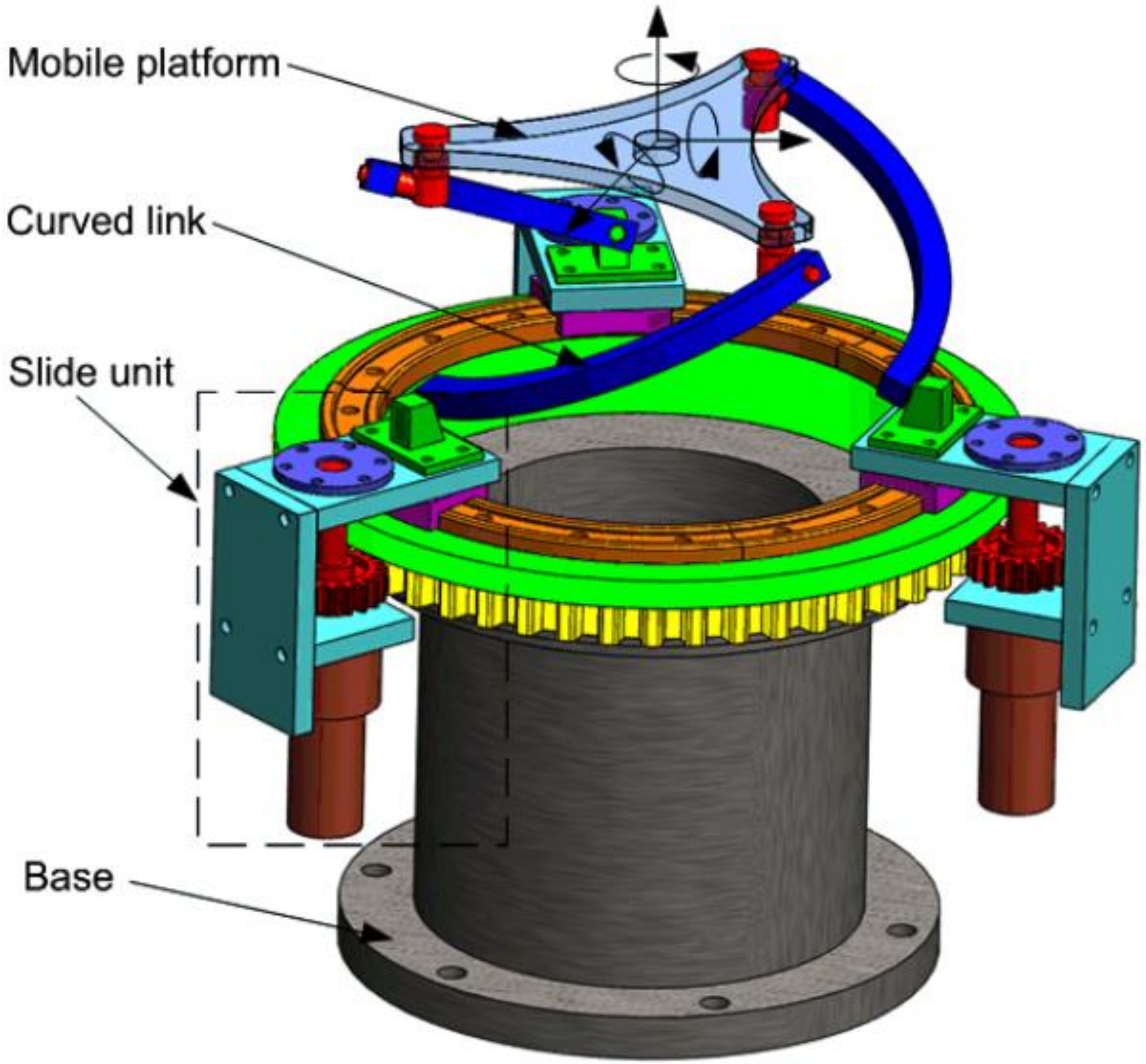
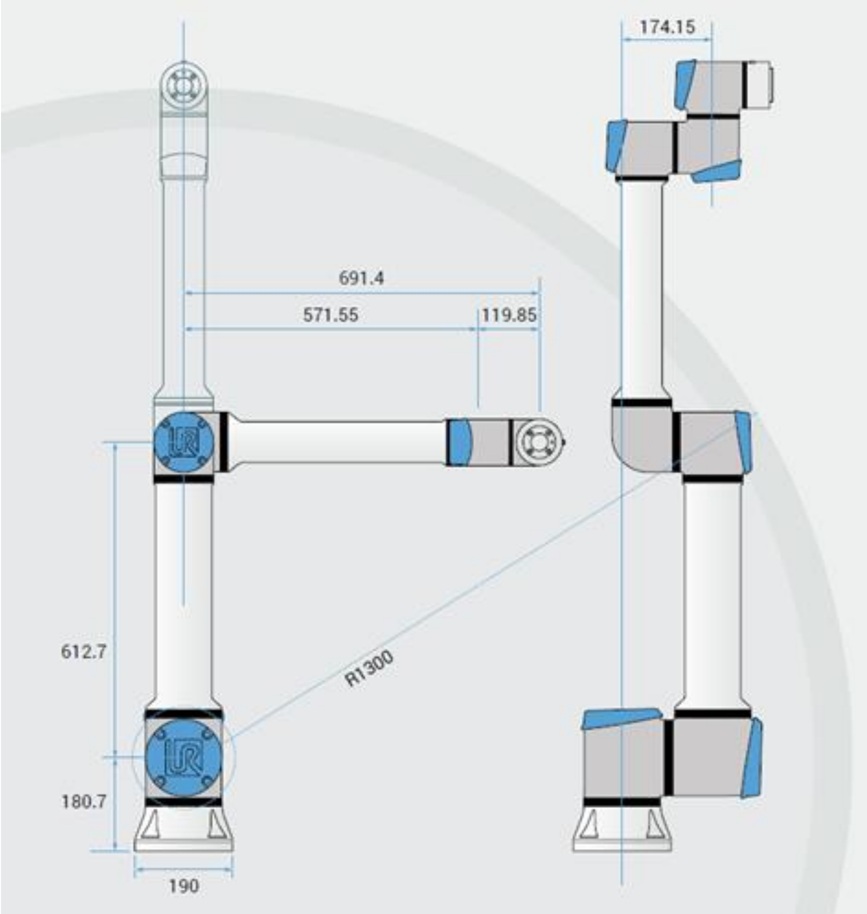
Reference Design



UR10 Cobot Arm



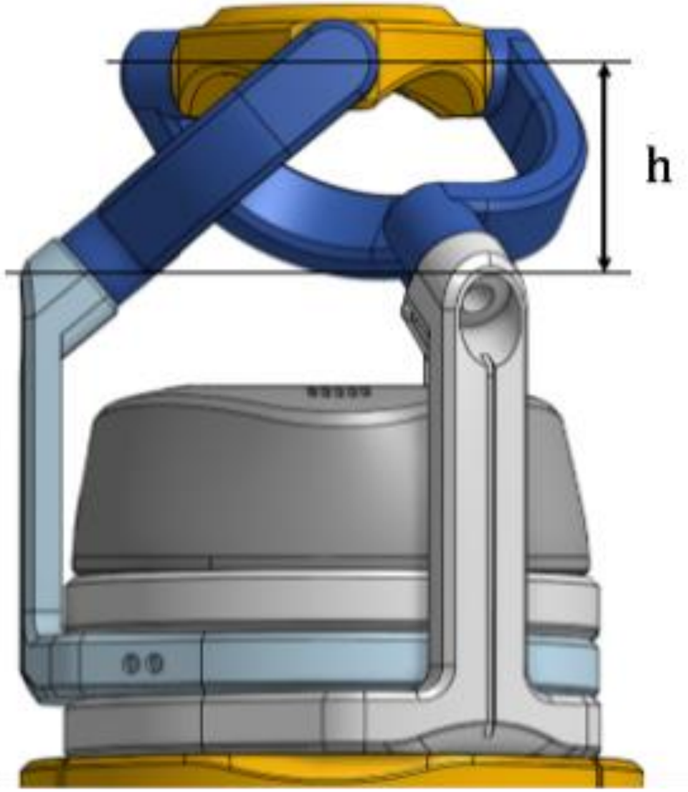
Optimization Goals

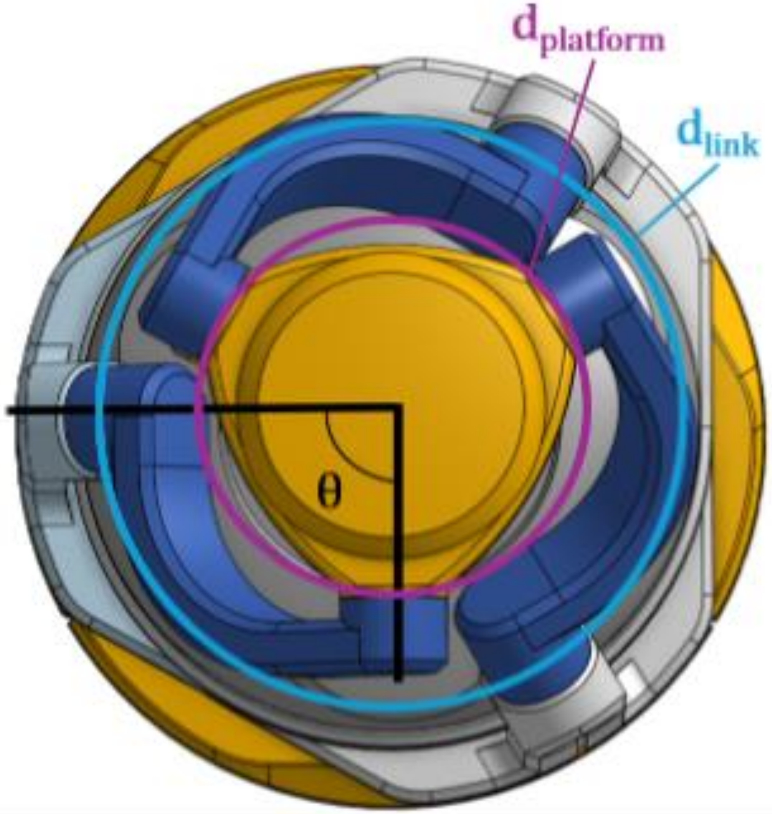
Minimize:

$$f_1(\bar{x}) = 3(m_{actuator} + m_{linkage})$$
$$f_2(\bar{x}) = -GCI$$

Subject to:

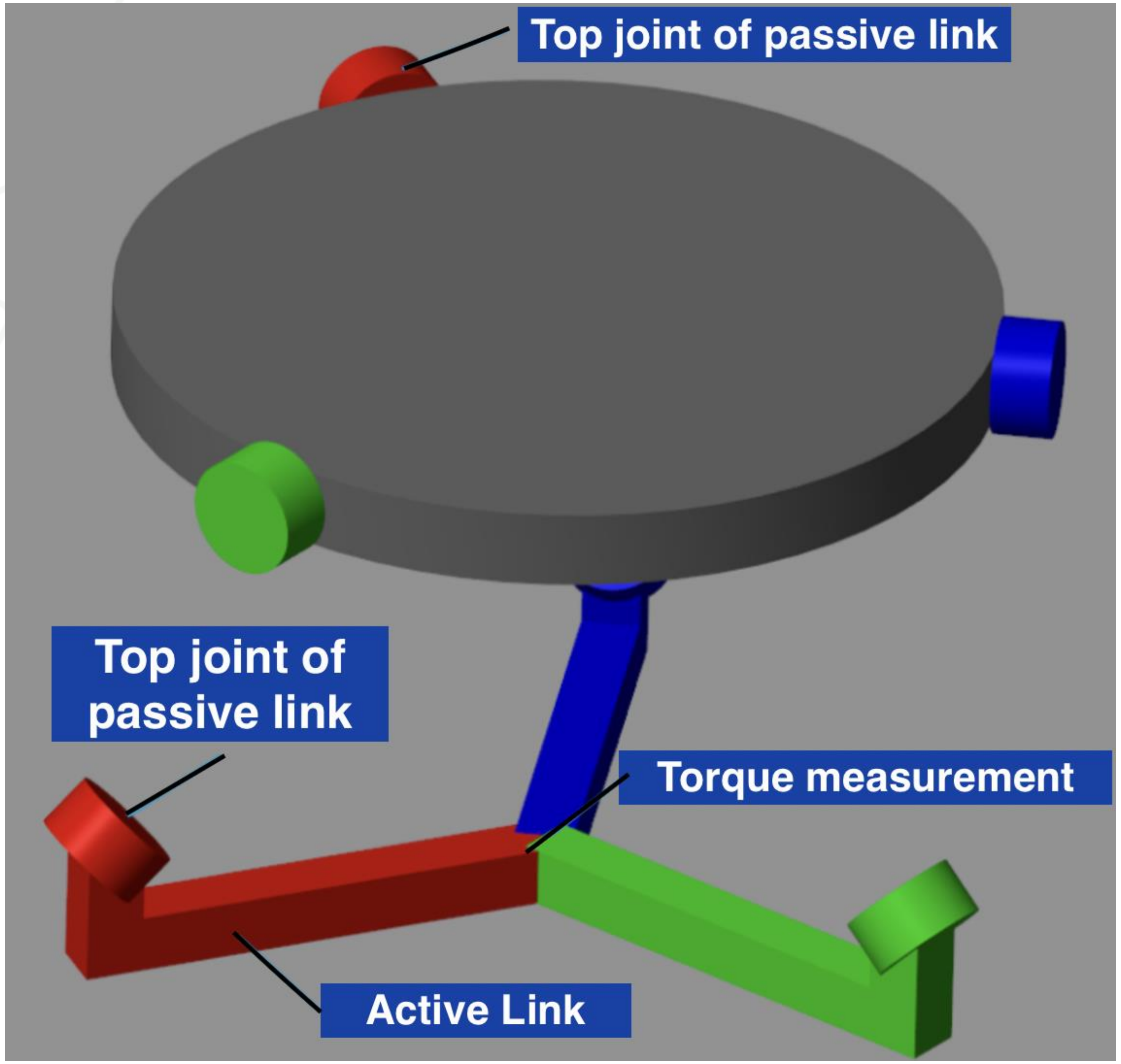
$$\delta_{linkage} \leq 0.5\text{mm}$$
$$\tau_{actuator} \geq 2\tau_{min}$$
$$10\text{mm} \leq h \leq 100\text{mm}$$
$$30° \leq \theta \leq 150°$$
$$95\text{mm} \leq d_{platform} \leq 125\text{mm}$$
$$d_{link} = 90\text{mm}$$

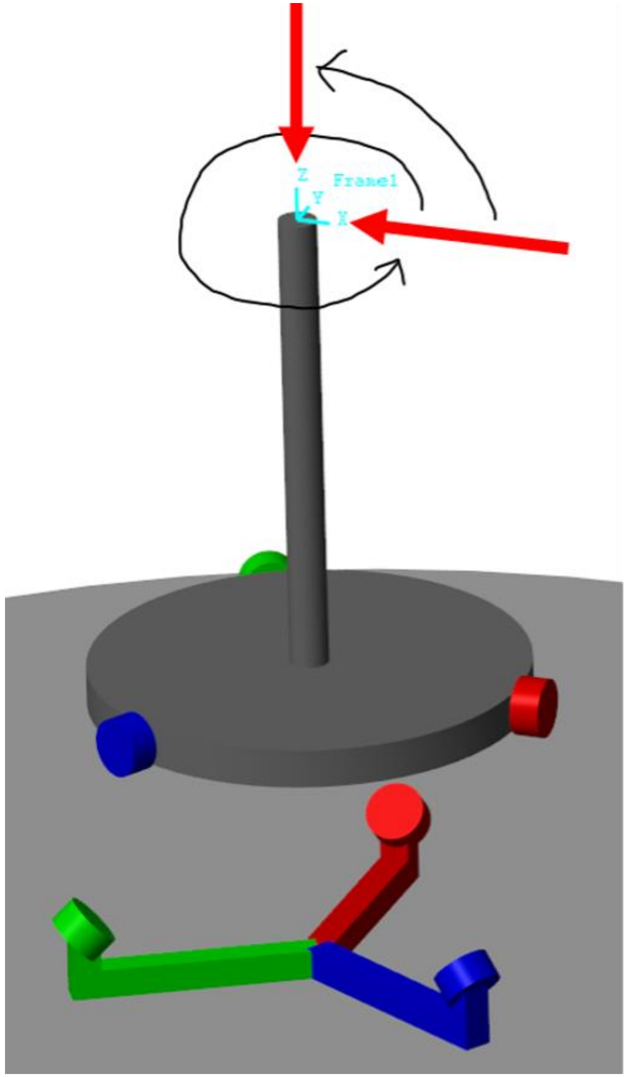




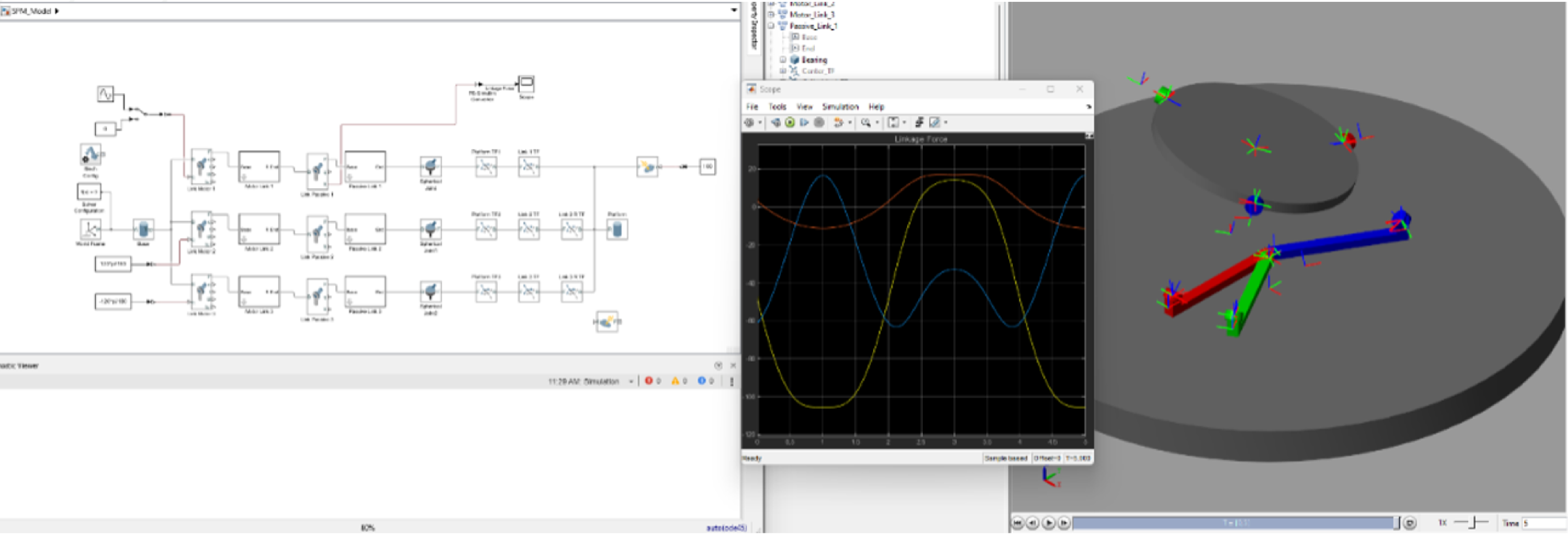
Methods

Design Space & Problem Formulation

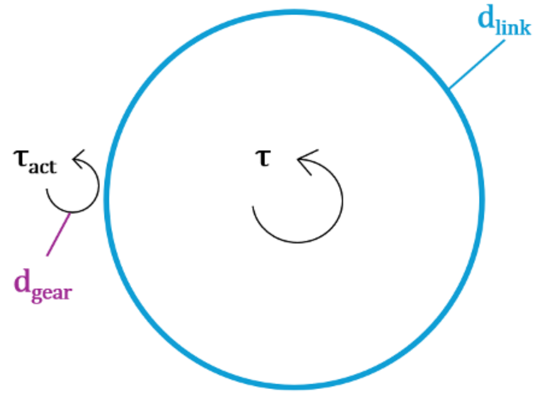




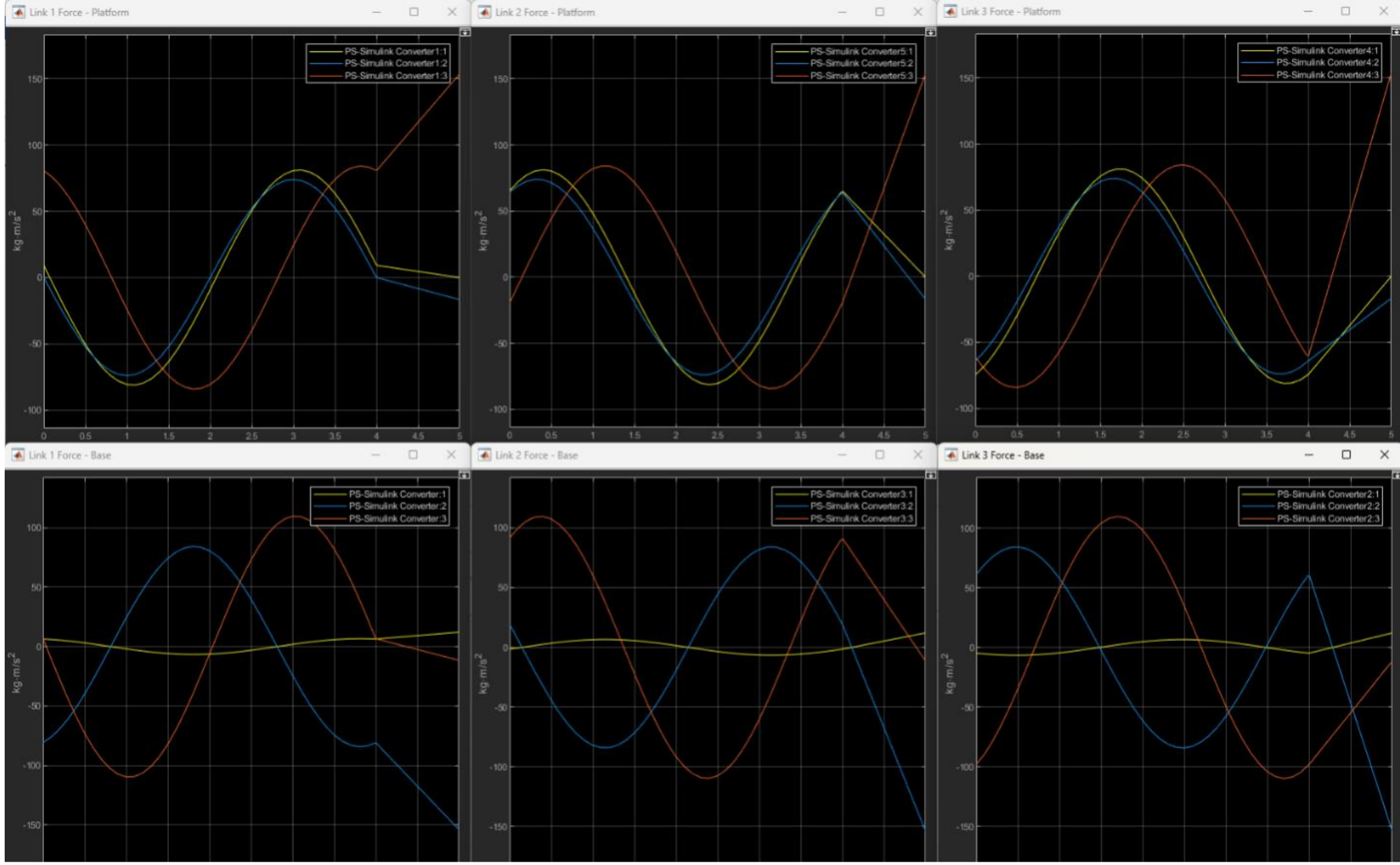
Simulink Model



Actuator Selection

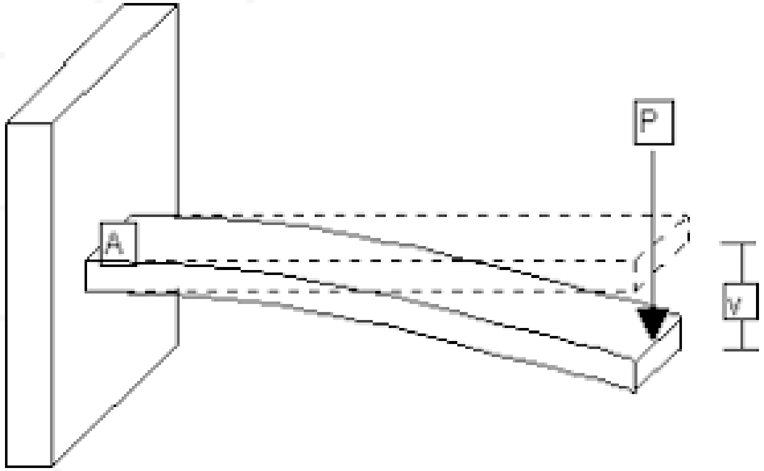


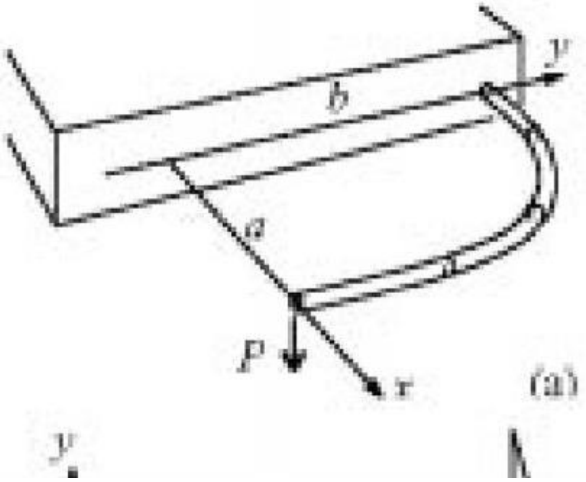
$$\tau_{act} = FoS\left(\frac{\tau d_{link}}{d_{gear}}\right)$$

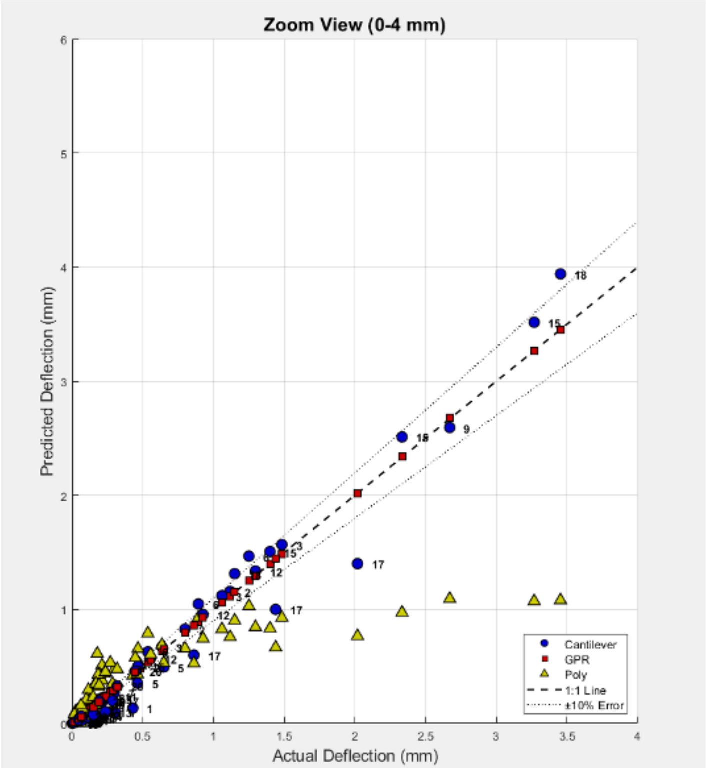


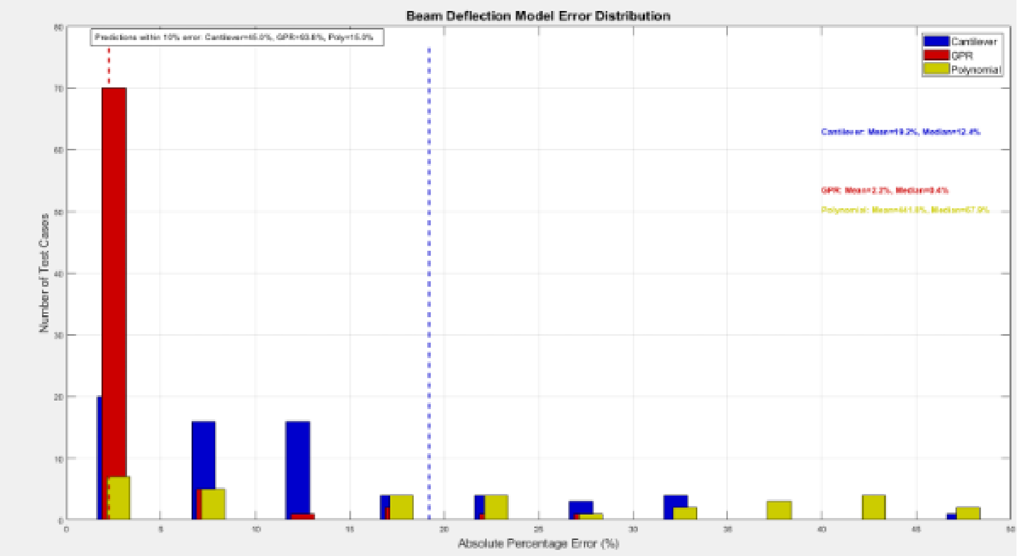
Part Number	Manufacturer	Motor Type	Rated Torque (Nm)	Max Torque (Nm)	Max Speed (rpm)	Diameter (mm)	Mass (g)	Torque Density (Nm/kg)	Cost
GL30 KV290	CubeMars	BLDC	0.080	0.280	2200	43	41	6.829268293	$ 55.99
GL35 KV100	CubeMars	BLDC	0.150	0.460	815	50	90	5.111111111	$ 54.99
GL40 KV70	CubeMars	BLDC	0.250	0.730	600	46.5	107	6.822429907	$ 91.90
RMD-L-4015 20T	MyActuator	BLDC Servo	0.220	0.490	1010	40	120	4.083333333	$103.00
722-401	Precision Micro Drives	BLDC	0.029	0.252	16380	22	122	2.062622951	$ 88.57
RMD-L-5010 35T	MyActuator	BLDC Servo	0.260	0.650	1015	50	135	4.814814815	$175.45
RO60 KV115-Lite	CubeMars	BLDC	0.800	2.400	5520	60	195	12.30769231	$ 77.90
G006984	iPower Motor	BLDC	0.392	0.392	400	60	207.8	1.887184133	$ 54.44
GL60 KV25	CubeMars	BLDC	0.600	1.750	516	69	230	7.608695652	$136.90
RO60 KV115	CubeMars	BLDC Servo	0.800	2.400	5520	60	248	9.677419355	$ 85.90
R60 KV115	CubeMars	BLDC	0.75	2.3	4150	60	248	9.274193548	$177.90
AKE60-8 KV80	CubeMars	BLDC Servo	5.000	12.500	240	60	260	48.07692308	$272.90
RB-Blu-303	Blue Robotics	BLDC	0.500	0.500	9400	40	282	1.773049645	$160.00
RMD-X4 1:6	MyActuator	BLDC Servo + Gearbox	1.200	1.200	600		300	4	$250.00
36PG-3650BL-14 12V	E-S Motor	BLDC + Gearbox	0.392	0.392	290	36	450	0.871459695	$ 42.50
36PG-3650BL-14 24V	E-S Motor	BLDC + Gearbox	0.784	0.784	570	36	450	1.74291939	$ 42.50
AKE80-8 KV80	CubeMars	BLDC Servo	12.000	30.000	570	80	570	52.63157895	$339.90
DCM4112	Phidgets	BLDC Servo	0.490	0.490	4000	57	4000	0.12254902	$ 83.44

Linkage Deflection Model and Validation





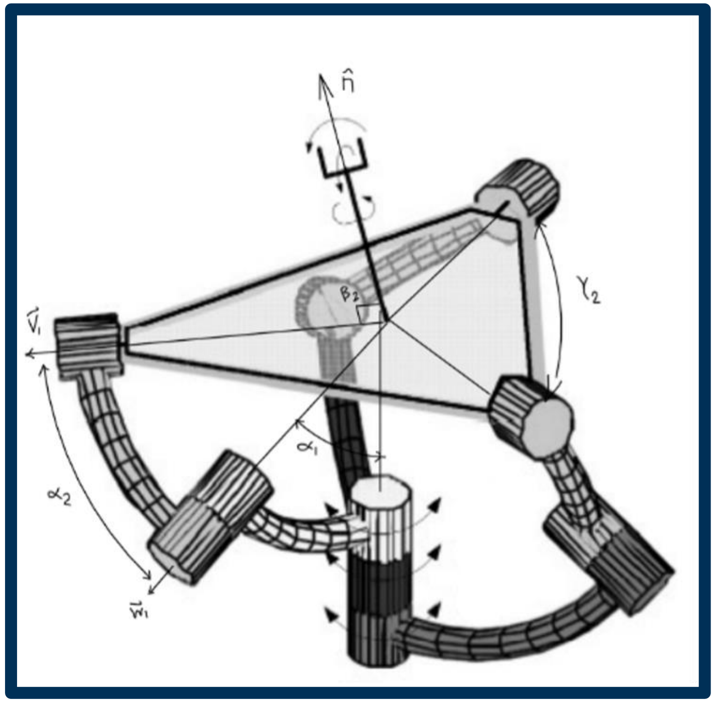


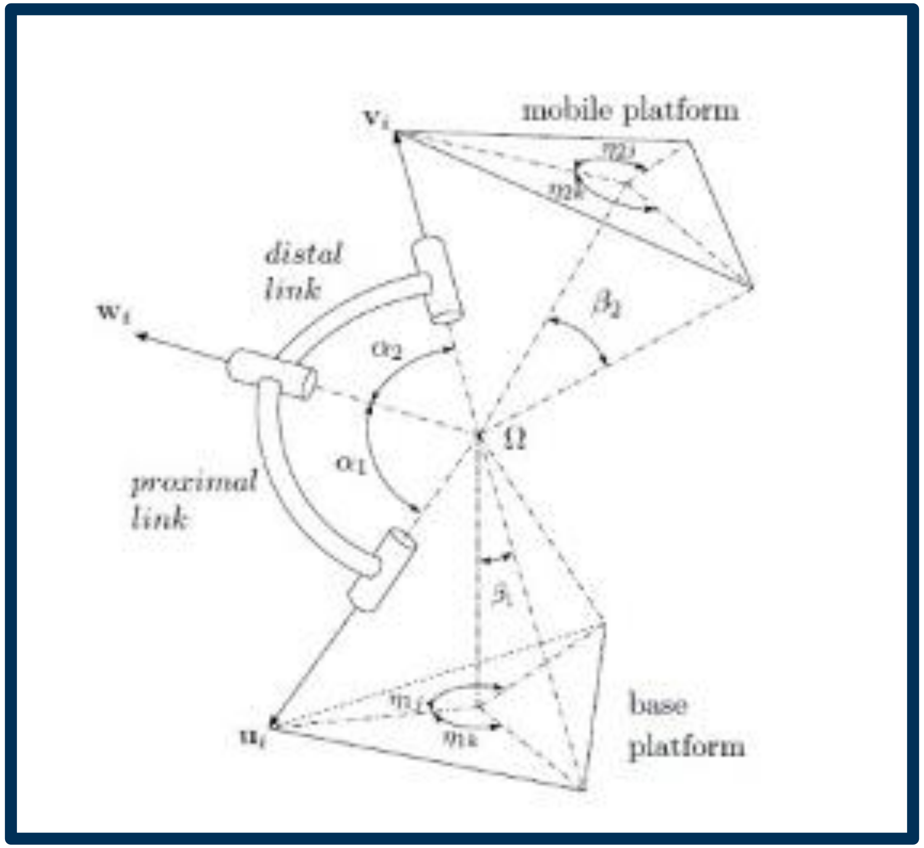


Kinematic Formulation

- Global Conditioning Index
  - Dexterity of System
  - Range of Motion

- Formulation Validation
  - Results less than 1% difference between various research papers

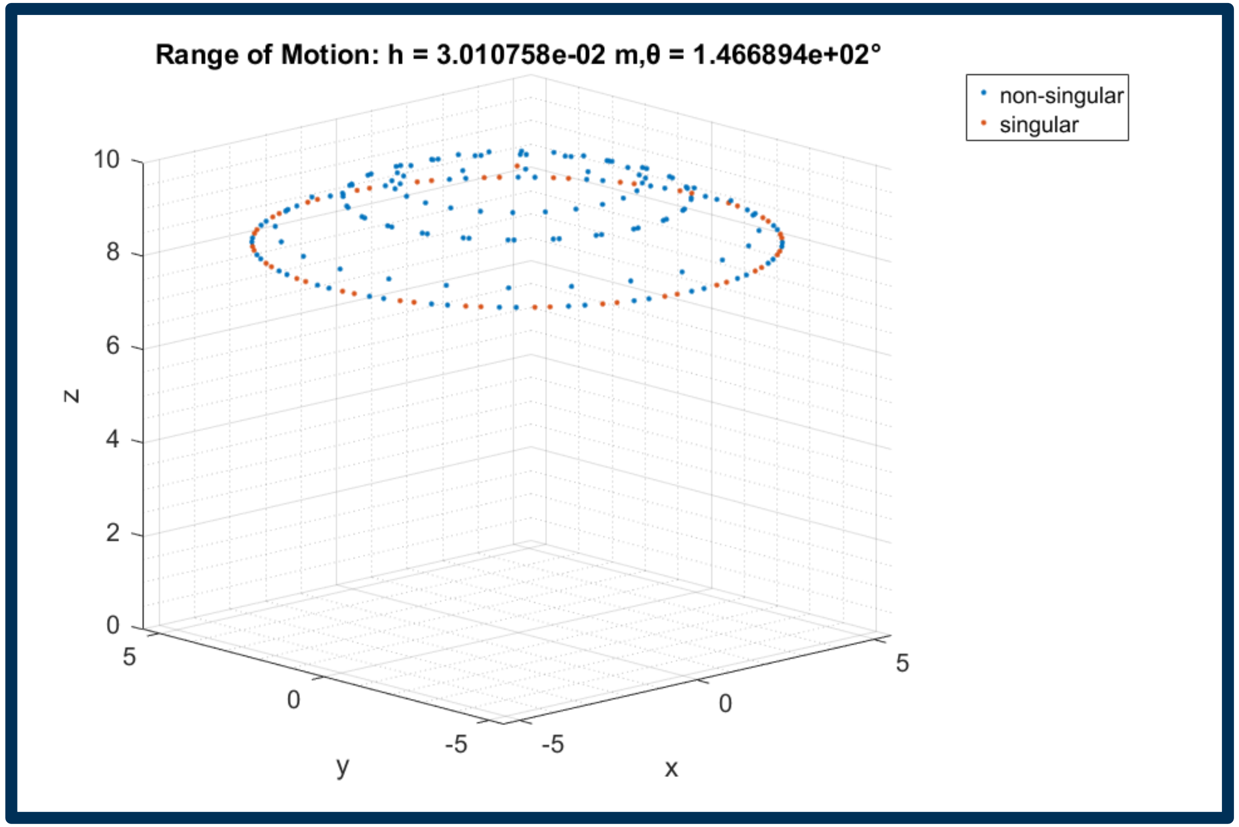




Kinematic Formulation

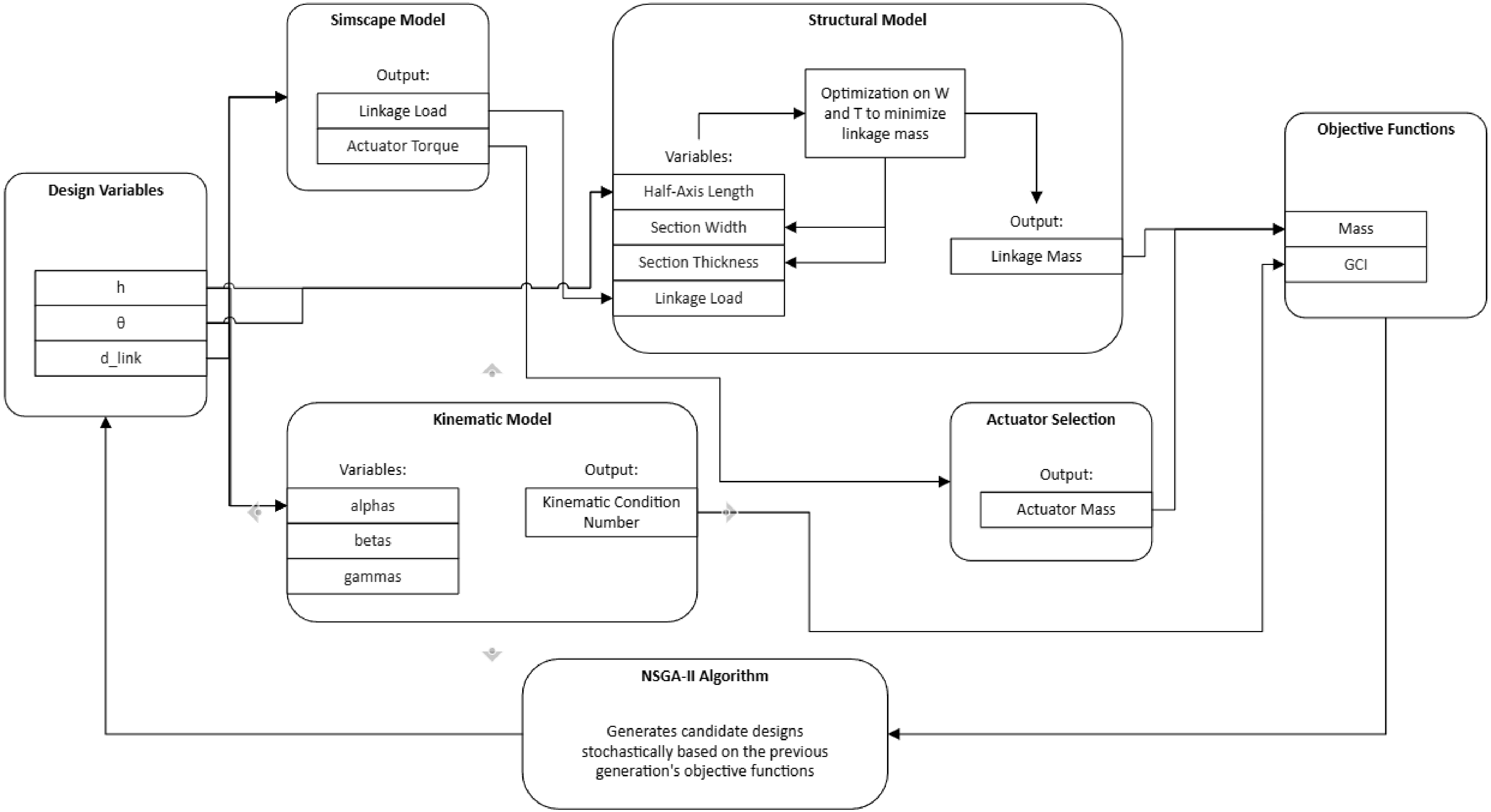
<u>Optimal Workspace</u>

- What determines the controllability of our SPM?
- Difference between singular and non-singular points



Optimization Architecture

Analysis Methods & Results



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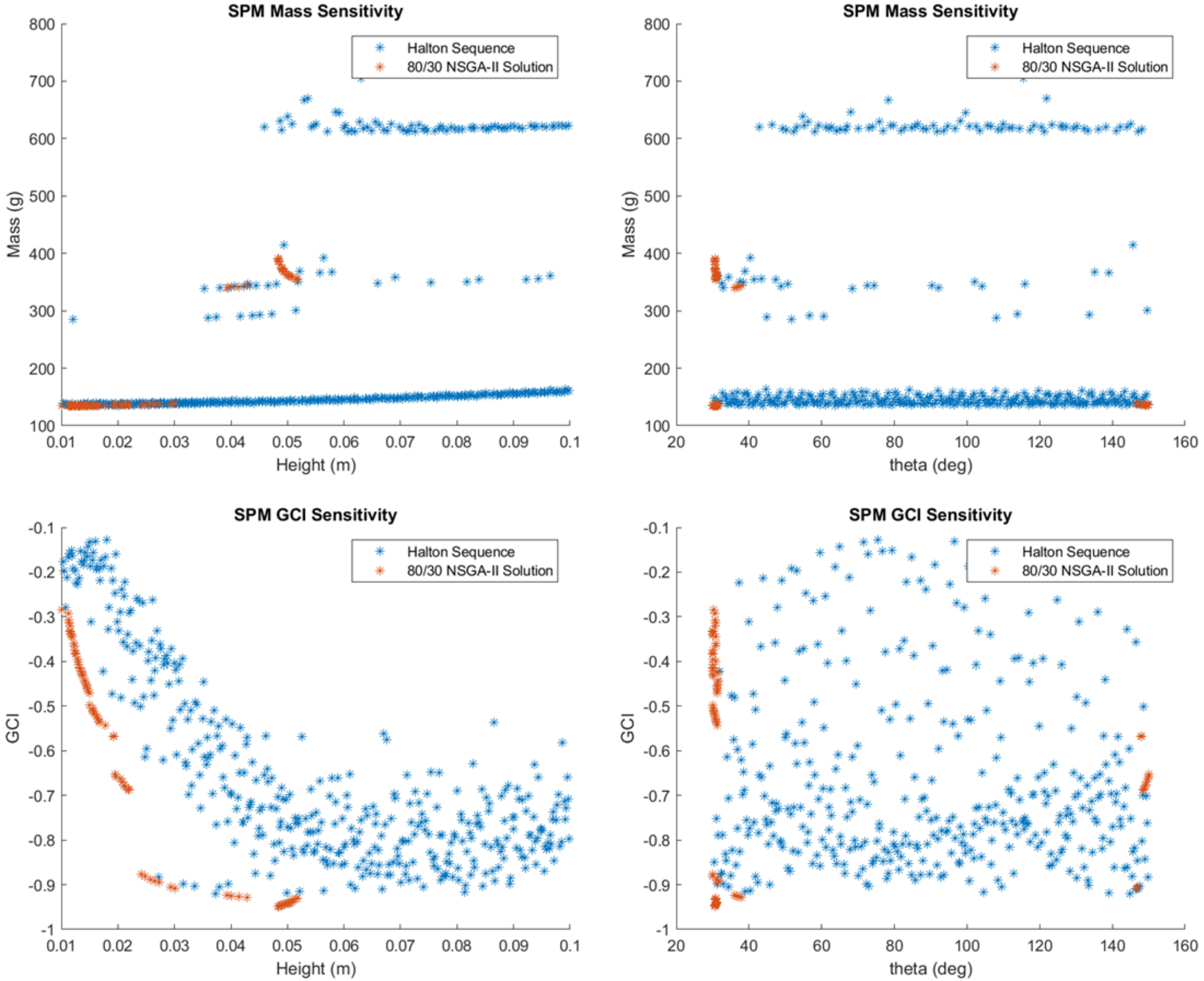
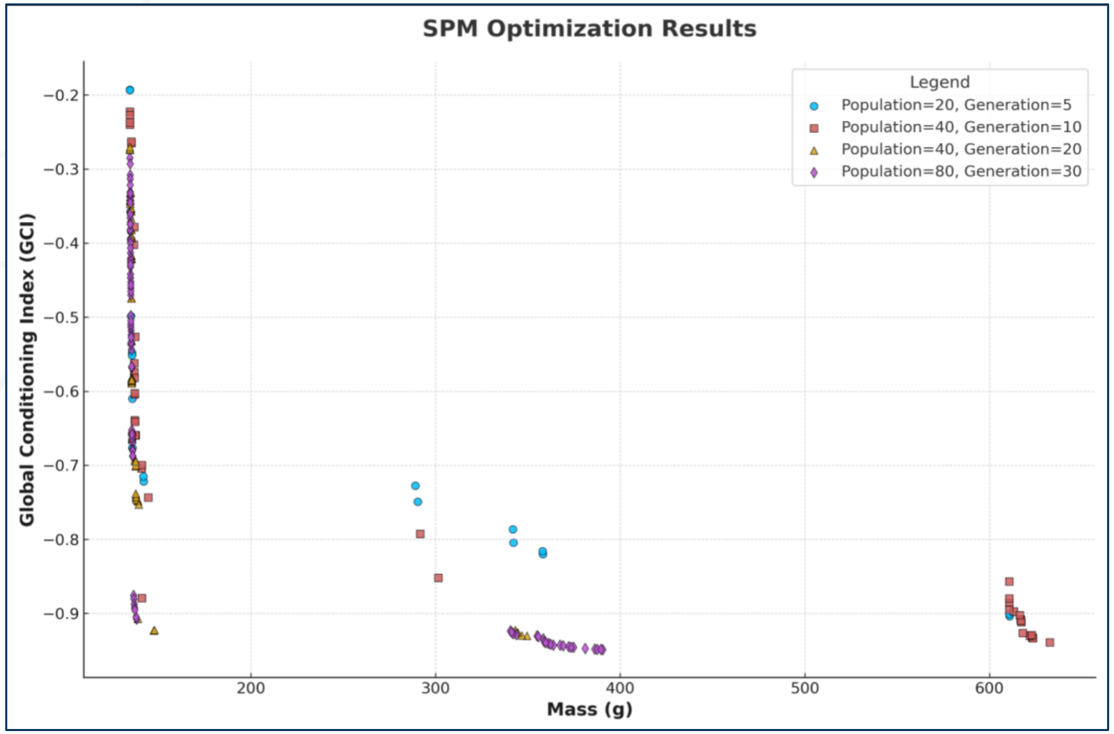
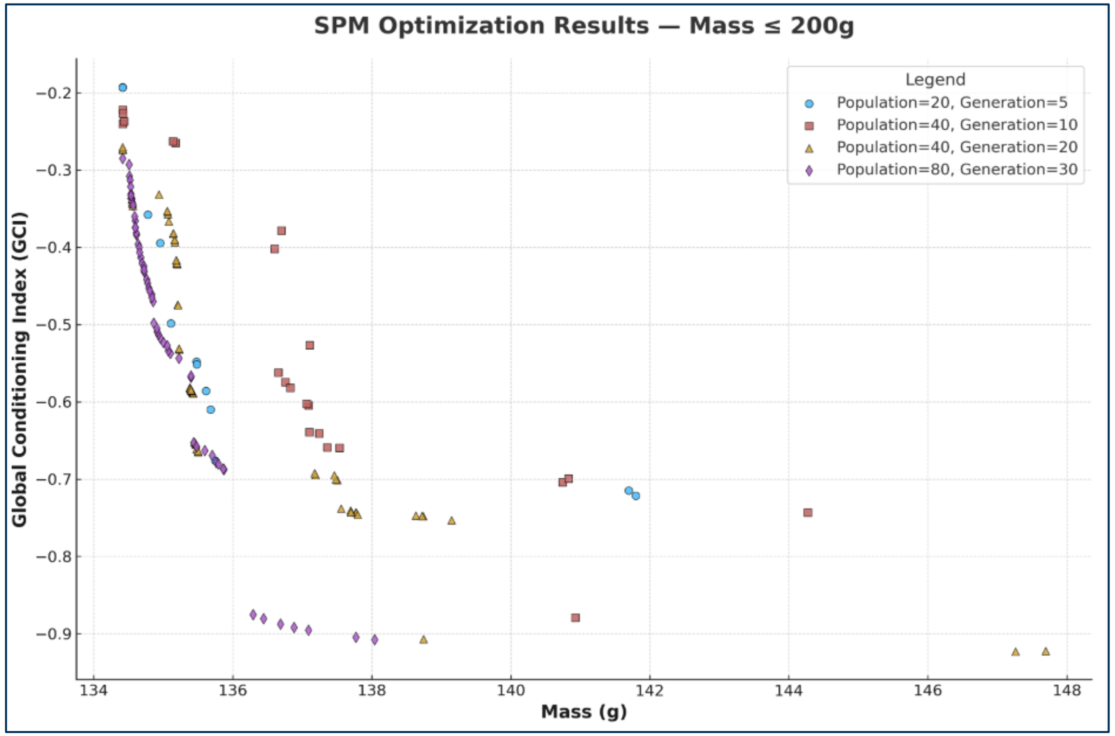
Final Results and Conclusion

SPM NSGA-II Solutions and Halton Design Space Exploration



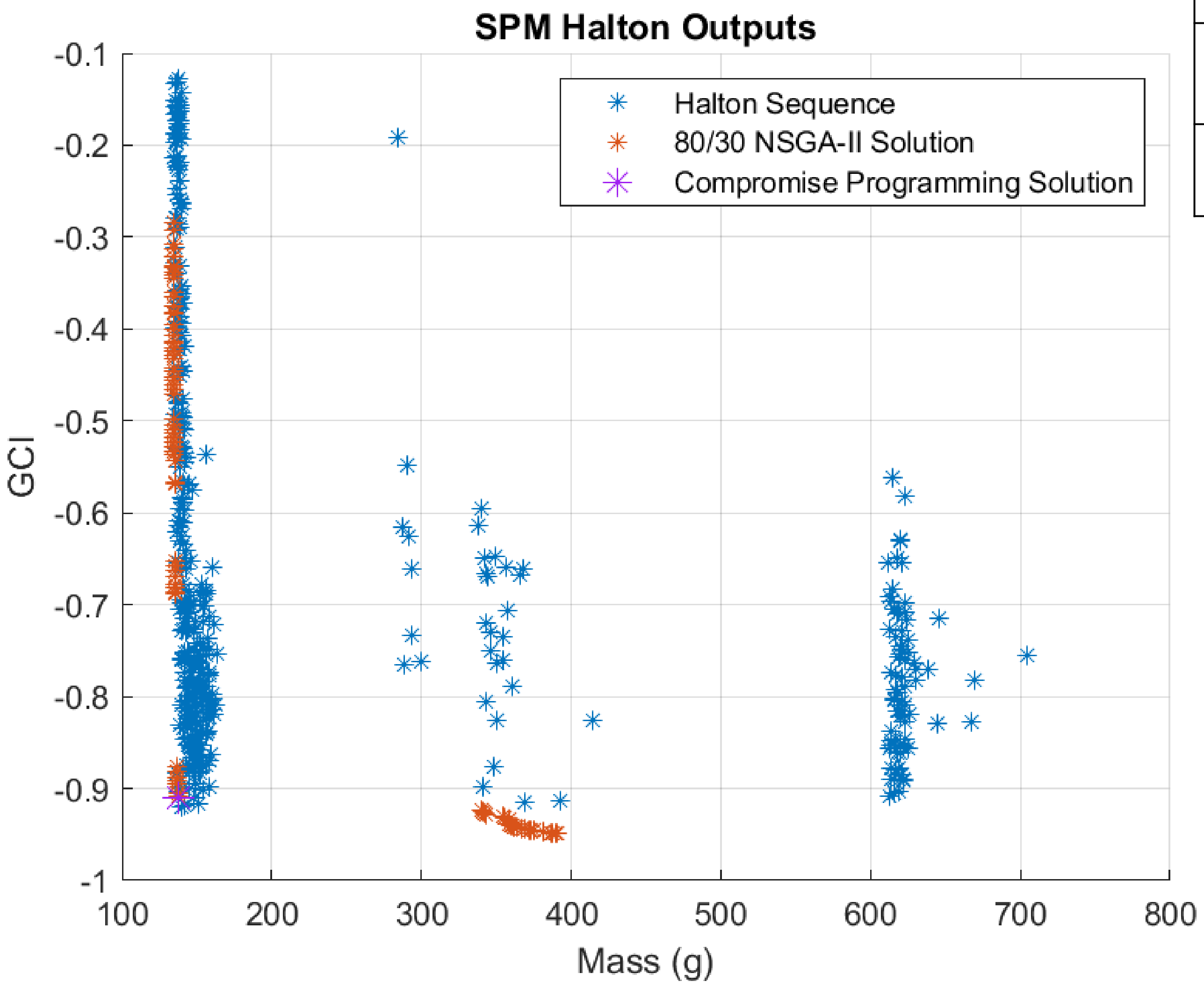
Combined Solutions from NSGA-II trials





Optimal Solution				
GCI	Mass (g)	Height (mm)	Theta (deg)	Base Diameter (mm)
0.91	138	30	146.68	96

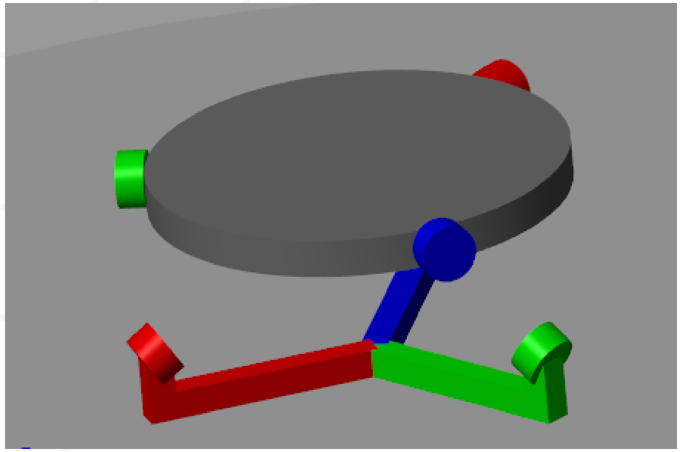
Optimal Solution



Optimal Solution				
GCI	**Mass (g)**	**Height (mm)**	**Theta (deg)**	**Base Diameter (mm)**
0.91	**138**	**30**	**146.68**	**96**

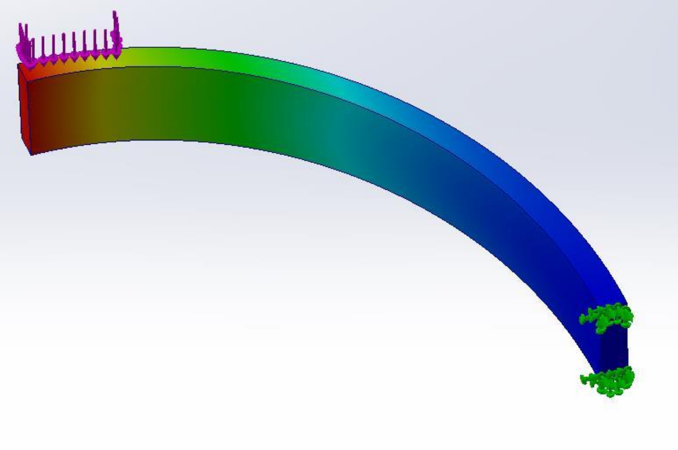
- **Actuator Discontinuities**: Pareto front breaks stem from discrete actuator choices; mass jumps occur when switching to higher-torque motors, guiding selection near transition points.
- **Dexterity–Mass Tradeoff**: Higher GCI requires stiffer, heavier linkages to handle torque, linking dexterity gains to structural mass increases.
- **Modeling Insights**: Despite simplified deflection and collision assumptions, adding base diameter as a variable and actuator discreteness yielded mass-efficient, high-GCI designs validated in Simulink.

Optimal Solution Breakdown

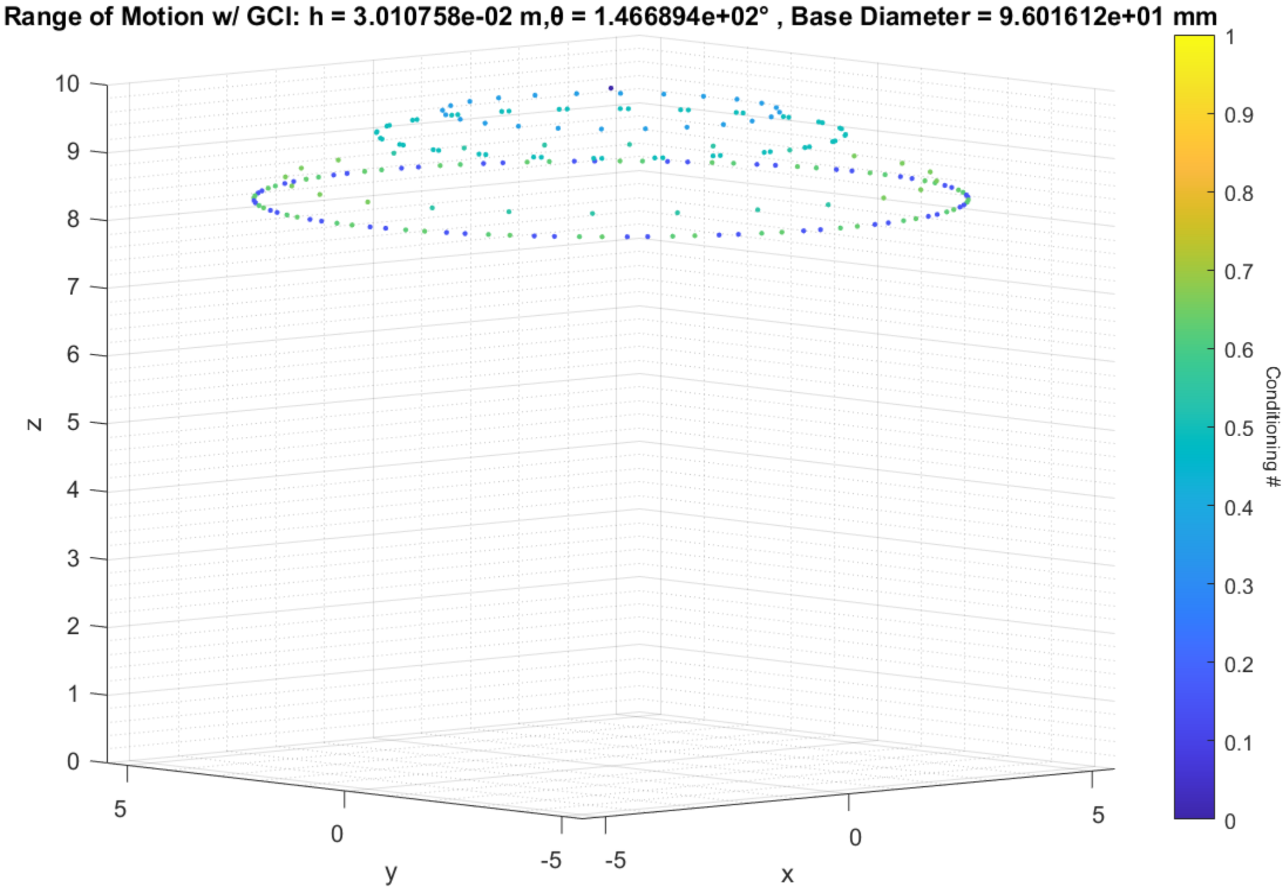


Optimized SPM Model Represented in Simulink

Chosen Actuator of CubeMars GL30 KV290



Optimized SPM Linkage with Dimensions:
a = 45 mm
b = 56.6 mm
Width = 3 mm
Thickness = 10 mm



Workspace of Optimized SPM

Conclusion

Lessons Learned

- Successfully scoped a complex design problem by simplifying where needed, allowing us to explore meaningful trends within project constraints.
- Gained hands-on experience with optimization tools like NSGA-II, building confidence in applying genetic algorithms to real engineering systems.
- Learned the importance of model fidelity—simple, fast approximations were key to balancing deflection, mass, and kinematic accuracy.
- Future work could include multi-pose load cases, refined linkage design, and physical prototyping to validate and extend our results.
- Exploring neural networks or surrogate models could accelerate evaluation time and enable deeper optimization, especially with discrete choices.

Future Prospects

- Consider a variety of load cases
- Manufacture of a physical prototype for comparison
- Training more complex models such as neural networks

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