B.O.O.S.T: Battery-Optimized Onsite Swapping Technology

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Background

Multi-robot systems demonstrate great potential for a wide range of applications, from disaster relief, to interplanetary exploration, to improving industrial warehouse efficiency. **The operational time of existing mobile robotic systems, however, is the limited by finite battery life.** Existing solutions have limitations:

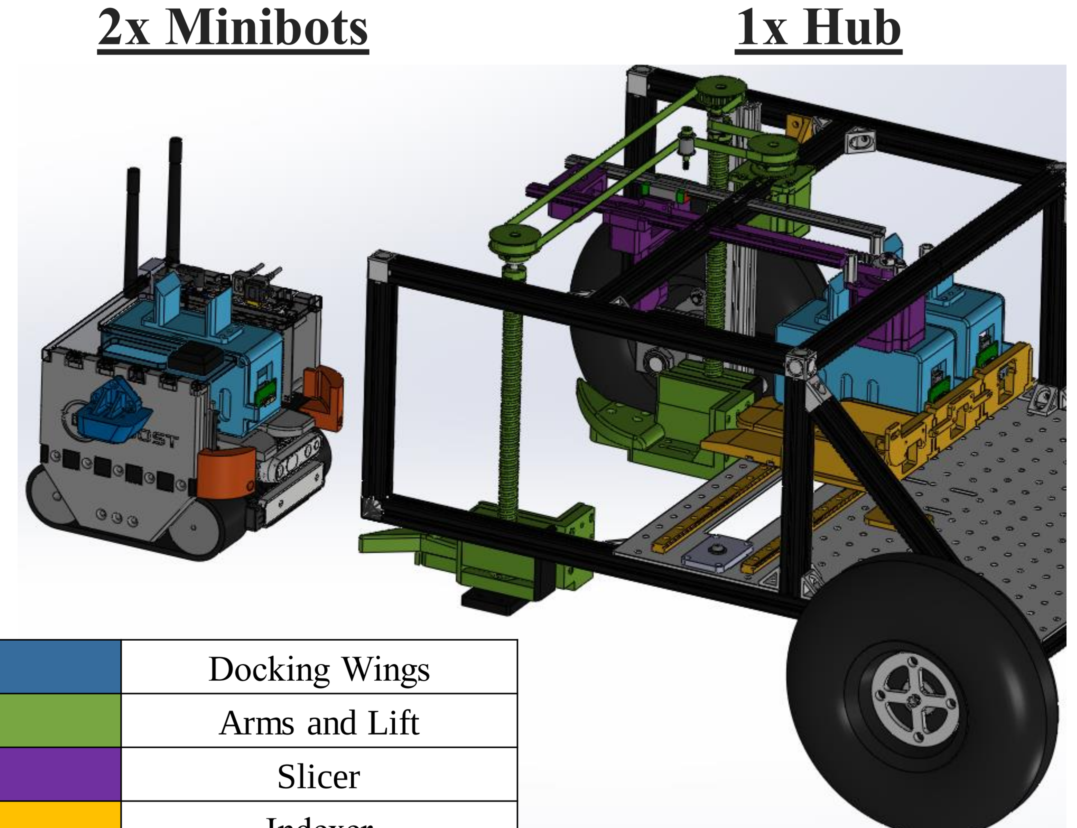
Solution	Limitation
On-Board Power Generation	Poor Scaling
Tethered Power	Limits Operational Range
Charging	Long Robot Downtime
Human Intervention	Undermines Autonomy

Problem Statement

To design a **multi-robot architecture that overcomes the limitations of finite battery life** and is capable of operation over **uneven terrain.**

Design Overview

2x Minibots **1x Hub**



	Docking Wings
	Arms and Lift
	Slicer
	Indexer
	Battery Module
	Minibot Bumpers

Battery Swap Procedure

1. **Hub** charges **battery modules** with its own supply.
2. **Minibot** explores until it is low on battery.
3. Minibot drives into hub dock. **Docking arm** and **bumpers** assist initial alignment.
4. **Docking arms** lift minibot into position for battery swap.
5. **Slicer** moves **battery module** between minibot and hub.
6. **Indexer** moves battery cache to receive or send off.

Constraints:

- Dock and swap battery on **unknown terrain**
  - Docking must account **for mechanical misalignment in 6 DOF** for both hub and minibot
- Battery swap must be **quick and reliable**
- Emphasis on **scalability**

Entry Lead-In Optimization

Purpose:

Verify and optimize geometry of **docking receivers** and **minibot bumpers** to maximize successful entry **regardless of entry vector**

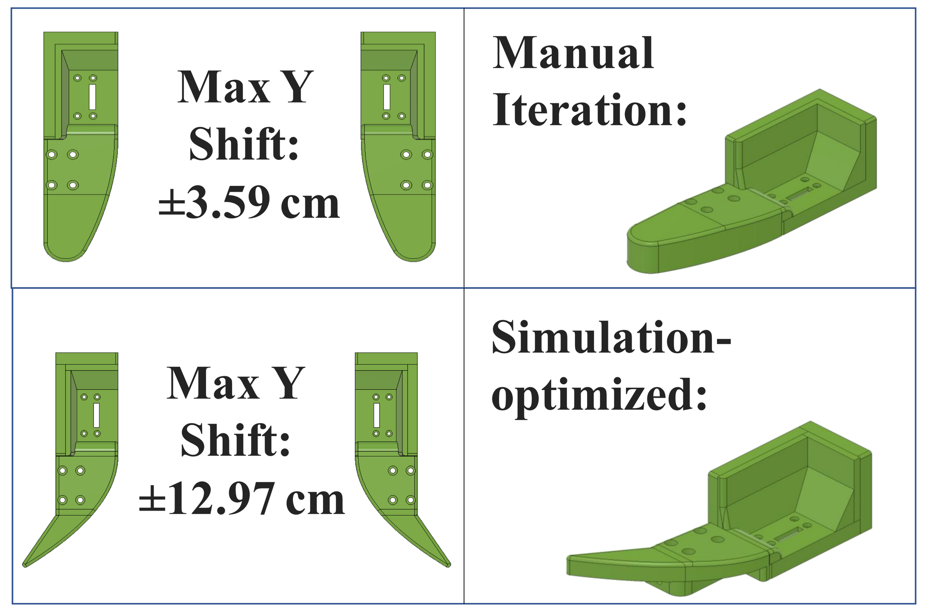
Analysis:

Simulated minibot entry for **hundreds of randomized starting positions** to find performance rate using Monte Carlo design

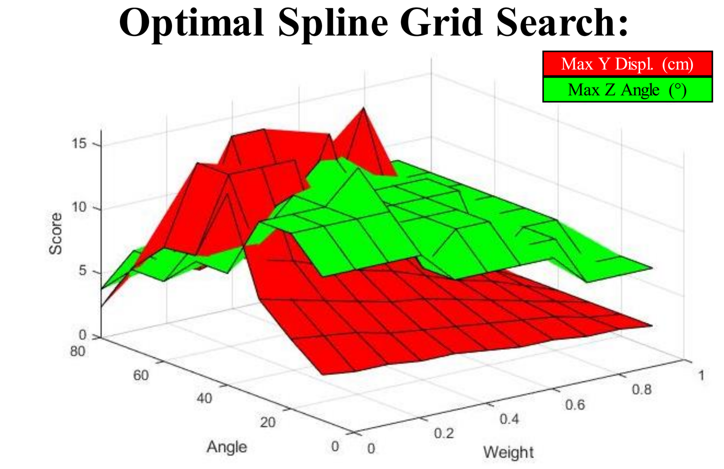
MATLAB

Impact:

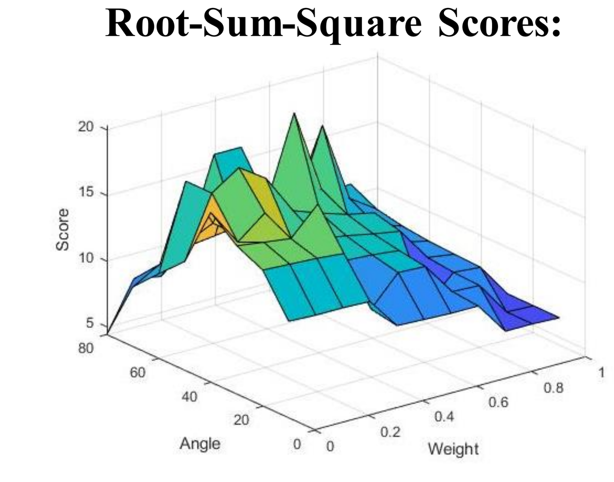
Implemented **bumpers** on minibot and **verified performance of optimized lead-ins** on arms.

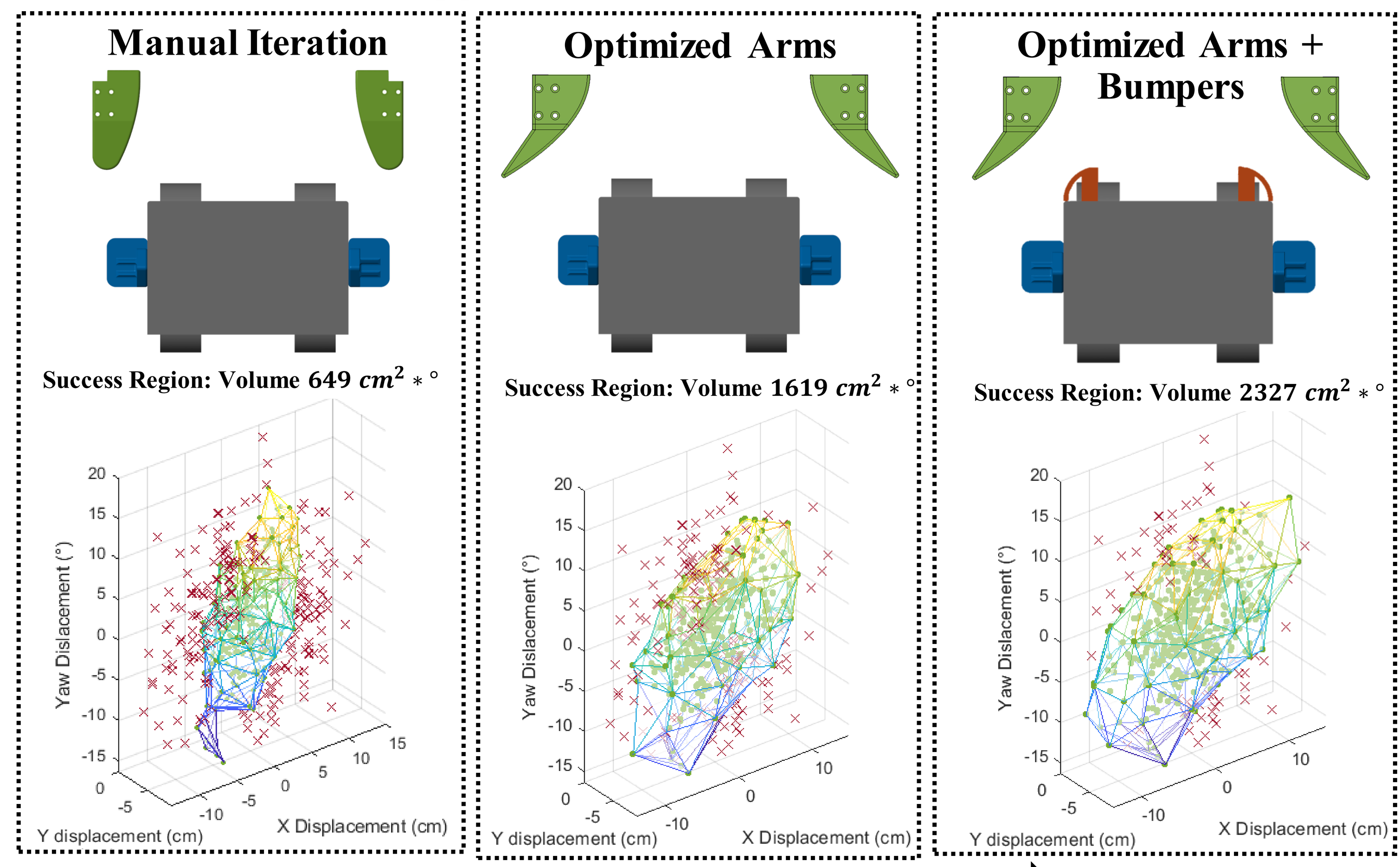


Optimal Spline Grid Search:



Root-Sum-Square Scores:

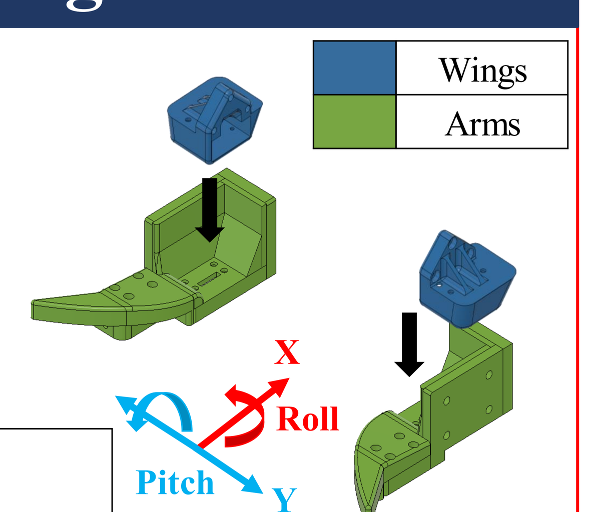


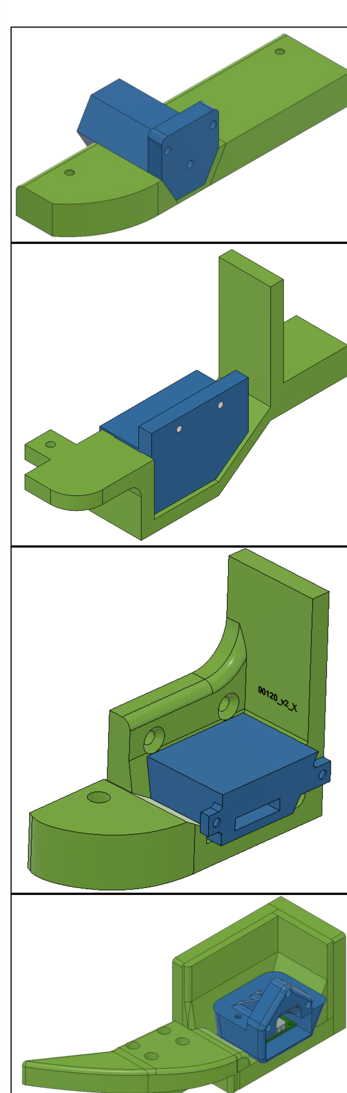


258.6% Volume Compensation Increase

Lifting Misalignment

Purpose:
Optimize wing and arm mating geometry to account for **± 5° and ± 5 mm misalignment in 6 DOF**





Series 1:
- Easy overshoot x
- Unconstrained in y
- Small area of engagement

Series 2:
- **Hard stop** fixes overshoot in x
- Profile resolves **roll**

Series 3:
- **Side wall** constraints y and correct **pitch**
- Over-constrained edges cause jamming

Series 4:
- **Optimized** using simulation performance

Simulated a **Fractional Factorial** Experimental Design

Efficiently investigates the effects of combined misalignment without testing thousands of combinations.

Studied sim results to optimize designs

Final wing and arm design **passes all ± 5° and ± 5 mm combined misalignments** explored in simulation!

Motor and Structural Analysis

Stepper Motor Selection by Required Torque

Required Torques:

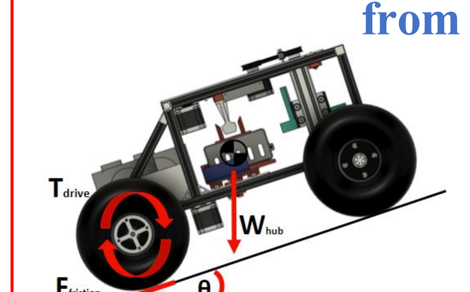
Lifting:	0.0179 N·m
Slicer:	0.0445 N·m
Indexer:	0.1226 N·m

$$T_R = \frac{F \cdot d_m}{2} \cdot \left(\frac{L + \pi \cdot \mu \cdot d_m}{\pi \cdot d_m - \mu \cdot L}\right)$$

Selected Nema 23
Holding Torque: 1.26 N·m

Driving Motor Selections

Most conservative drive case: **accelerate from rest up 10° incline.**

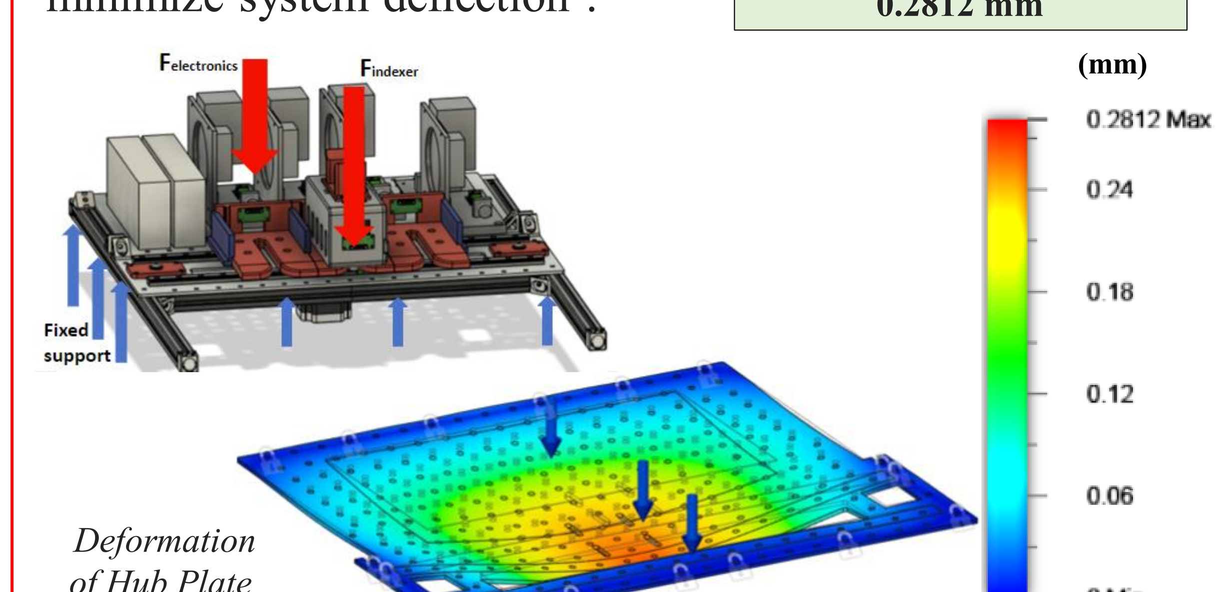


	Minibot	Hub
Drivetrain Torque (N·m)	0.91	28.0
Gearing Ratio (N·m)	1	7
Torque Margin	0.636	1.578

Hub Plates analyzed for **bending** with conservative loads to minimize system deflection .

FEA
F.S. Yield Safety = 10.6

Maximum Deflection:
0.2812 mm



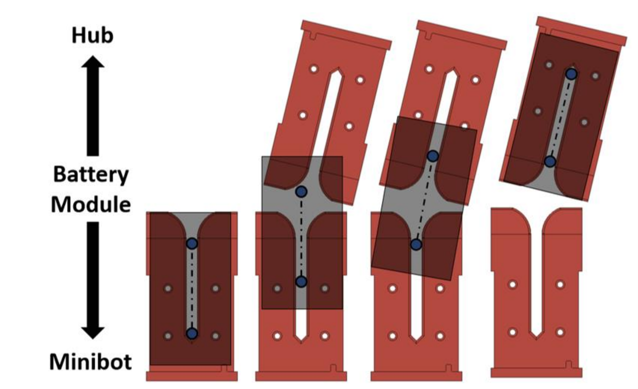
Deformation of Hub Plate

Design Validation

Battery Swap Reliability Tests:

Conducted **50 consecutive, autonomous battery swaps** on flat terrain

100% Success Rate



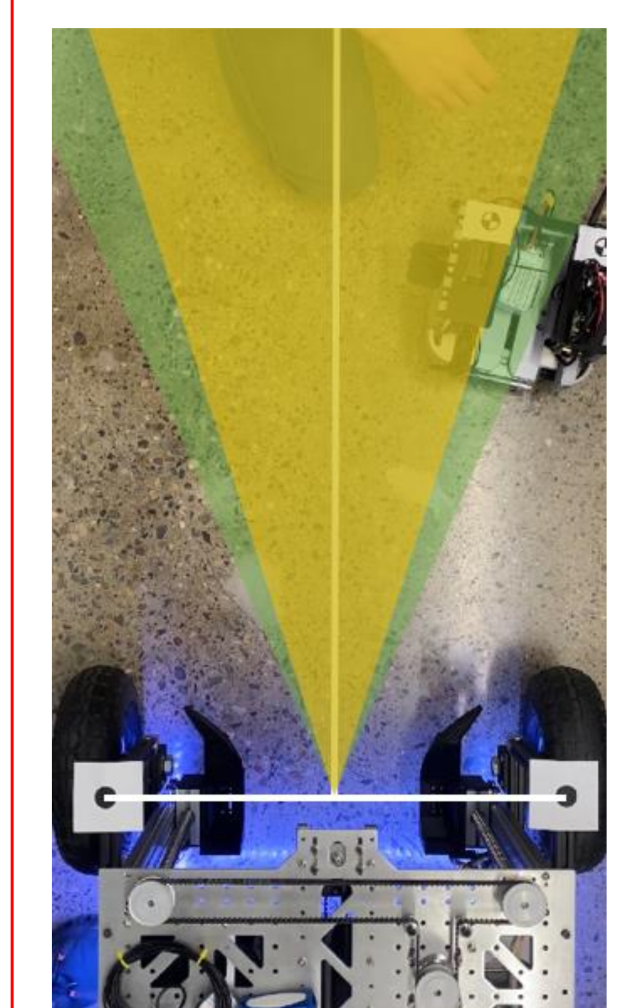
Real-World Lifting Misalignment Verification:

Repeated **fractional factorial combined misalignment conditions** from simulation on real-world test rig with optimized design

PASS

Hub Pitch (deg)	Hub Roll (deg)	MB Pitch (deg)	MB Roll (deg)	MB y (mm)	MB x (mm)	Yaw (deg)	Sim	Real
0	0	5	5	0	5	0	PASS	PASS
5	0	0	5	0	0	5	PASS	PASS
0	0	0	0	5	5	5	PASS	PASS
5	0	5	0	5	0	0	PASS	PASS
0	5	5	0	0	0	5	PASS	PASS
5	5	0	0	0	5	0	PASS	PASS
0	5	0	5	5	0	0	PASS	PASS
5	5	5	5	5	5	5	PASS	PASS

Real-World Entry Verification:



- Minibot placed in **variety of initial positions** and drove straight into hub docking port
- Using Canny edge algorithms, minibot position tracked and analyzed in MATLAB

System Yaw Allowance:

With Software Navigation: ± 23.72°

Purely Mechanical: ± 17.72°

Future Work

1. Continue full-system characterization and **publish** results
2. Implement **fatigue simulation** to determine max cycles
3. Redesign interfaces to improve **sand and dust shielding**
4. Continue discussions with **NASA JPL** and other robotics companies for **future R&D**

Inclusivity in Design: Our project lowers the barrier to entry for scalable mobile robotics in applications such as assisted living

Acknowledgements

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