B.O.O.S.T

Spring 2023 ME Executive Summary

Design Team

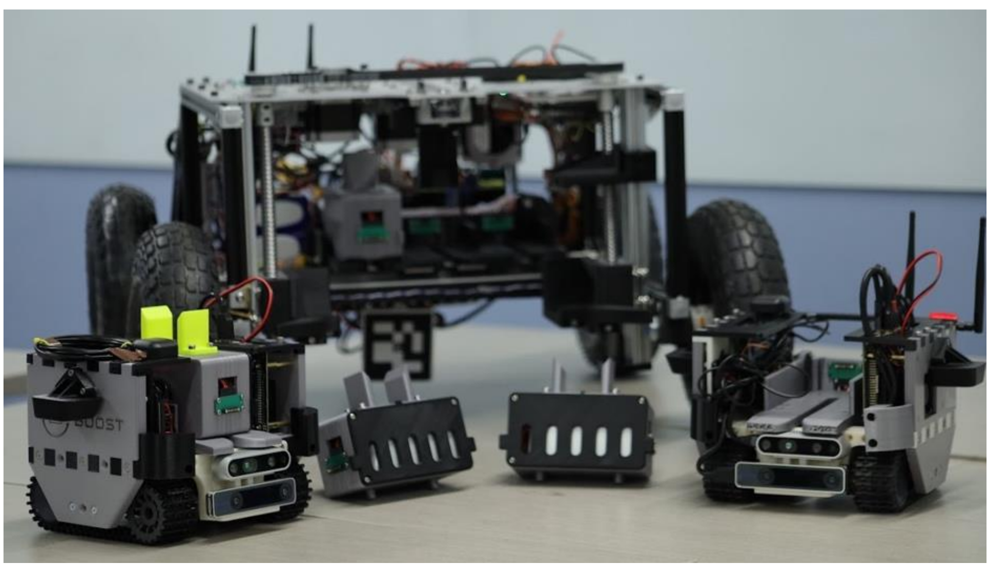
Naomi Cooke, Ethan Holand, Ethan F. Muhlon, Alex Storrer, Chloe Wilson

Design Advisor

Medhi Abedi

Abstract

Fleets of field robots can work together to efficiently complete tasks, with wide applications spanning agriculture, disaster relief, or planetary exploration. However, field robots today are limited by finite battery life, requiring long downtime to replenish. B.O.O.S.T: Battery-Optimized Onsite Swapping Technology, proposes a novel solution to recharge a multi-robot fleet on unknown terrain. In this architecture, a ”hub” robot recharges a cache of "battery modules" while "minibots" explore the surrounding environment. When the minibots’ batteries run low, they return to the hub and initiate a docking sequence. B.O.O.S.T’s simulation-optimized mechanical alignment mechanisms allow for efficient and reliable docking. During this process, wings (on either side of the minibot) and arms (on the hub) are engaged for precise final alignment. Once docked, battery exchange is performed utilizing three intertwined subsystems: lifting, slicing, and indexing. Lifting primes the battery to be removed the minibot. The slicer pushes the depleted battery module into an empty charging slot on the indexer. The indexer selects a charged battery module, which is inserted to the minibot by reversing the slicer. Once the new battery module engages with the minibot, the hub deploys the minibot to continue its mission. The team approached the goals of docking and swapping by rapidly iterating through geometries using a combination of simulated and physical testing. Through testing, the team has validated a fully functional system, and aims to continue the work to publication and continue discussions with NASA JPL.



For more information, please contact m.abedi@northeastern.edu.

Need

From environmental surveying to agricultural cultivation, a distributed ground-based robotic system can efficiently monitor large regions. However, existing mobile robots intended for long-term use are limited by their finite power supply. Current solutions to replenish robot power each pose limitations. First, human intervention to replace onboard power supplies undermines the robots' autonomy. Next, adding individual power generation to a fleet of robots greatly increases the overall size, weight, and cost of individual systems, compounding as more systems are added to the network. Finally, tethering a robot to a power supply risks entanglement and limits its range. Therefore, this project aims to offer a new solution to overcome current challenges of continuous robot field operation.

Background and Significant Prior Work

The field of multi-agent robotics focuses on the interaction and collaboration of two or more robots. These robots can be homogeneous, with identical capabilities, or heterogeneous, wherein each robot has a unique function. One variation of multi-agent heterogeneous systems is marsupial robots, where one robot is temporarily physically dependent upon another for a continued operation [1]. The name and function are inspired by nature; from kangaroos to opossums, marsupials are the order of mammals that carry, nurture, and guide their young. Marsupial robotic systems have been developed since the mid-90s for search-and-rescue missions and roving tasks, with various docking mechanisms and directives from search and rescue to environmental exploration [2-12]. Few patents and products use a marsupial architecture, and many existing models lack a solution to finite power supply other than using a tethered cable, which limits mobility range.

In order for these marsupial robotic systems to interact, the child robots must physically dock with the mother robot. Robotic docking is a term to describe a procedure in which two electromechanical components are fixed with respect to one another [13-14]. For mobile robotic systems, docking must be rigorous enough to overcome positional errors using mechanical interfaces and software controls [15-16]. Various research groups have used CCD cameras, photosensors, or LIDAR in order to navigate a robot towards a 3D marker [17-19]. These methods can combine with mechanisms that use magnets or interlocking mating faces to secure the robot to a final position [20-24]. However, most existing docking methods are designed for use on flat terrain.

The goal of docking is to position the minibot in a known relative position to enable a battery to be exchanged with the hub. Methods for battery swapping have been explored in home robotics. The battery is kept in a case optimized for swapping, reducing risk of electrical contact being lost. A mechanical system grips the battery case and moves it axially to a receiving case where it can charge. The same mechanical components then take a fresh battery and position it into a receptacle on the robot [25]. This methodology has been explored in several studies, though all swap the battery between a stationary station and a mobile robot, rather than two mobile robots.

Design Solution

The mission starts with the minibots, exploring the environment and autonomously carrying out tasks, while the hub follows along ready to sustain the swarm by charging a cache of battery modules. When the power wanes for a minibot, it returns to the hub and begins the docking sequence as outlined in Figure 1.

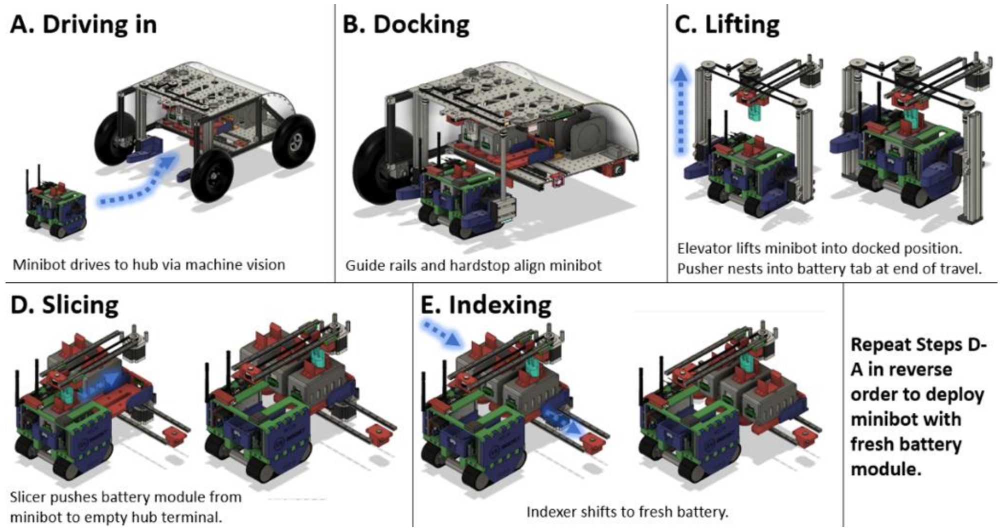


Figure 1: Minibot Docking and Battery Exchange Procedure.

The docking sequence has two phases: **entry**, which centers the robot, and **lift**, which provides final alignment and primes the battery module for removal. During entry, a minibot drives toward the hub and is roughly aligned by the minibot's bumpers and the hub's deflectors. To remove pose uncertainty inherent to uneven terrain, a lifting subsystem raises the minibot off the ground, using gravity and nesting geometry for final alignment.

Once docked, the battery exchange sequence occurs. At the apex of lifting, a tab protruding from the battery module engages with the overhead slicer, which pushes the battery module into the open slot on the indexer. The indexer, shuffles to a fully charged battery module where the slicer engages and pushes the fully charged battery module into the minibot. Finally, the lift lowers and the normal force of the ground undocks the minibot, allowing the minibot to continue exploring the region.

Each battery is packaged in a custom 3D-printed case for battery safety, power management, and ease of exchange (Figure 2a, left). The battery was chosen based on the criteria of allowing a minibot to be powered for two hours on a full charge with a profile to easily fit within the minibot. Mechanically, the battery module includes a tab on the top for the slicer to engage with to swap batteries between the hub and minibot. As well as vents to avoid overheating, hard stops/velcro to secure the battery's placement in the module, and hard stops on the battery module and module receivers to prevent the user from accidentally placing the module in the system incorrectly. Electrically, the battery module includes a battery management system (bms) that evenly charges each cell of the battery, a fuse, and a relay with continuity acting as the switch. The battery modules and receivers implement a pin and slot design (Figure 2b, right), which uses the principles of exact constraints to allow the battery module to slide in and out of the hub and minibot even with large amounts of misalignment.

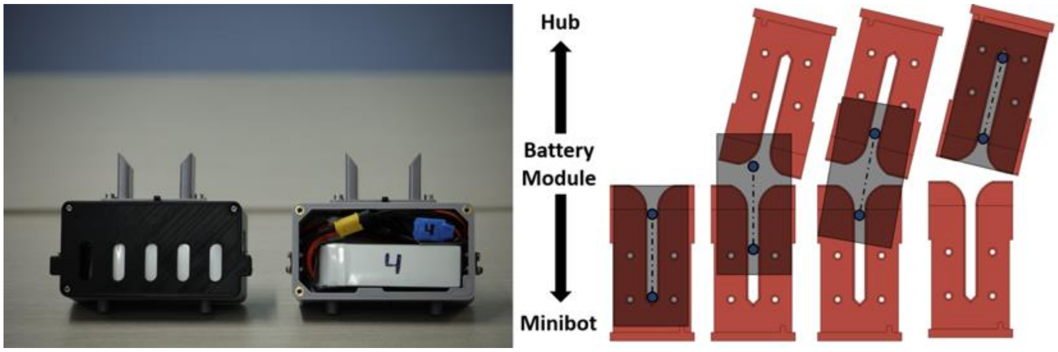


Figure 2a (left): Custom Battery Module housings.
Figure 2b (right): Two pins on the underside of the battery module (shaded gray) guide the module from hub to minibot without jamming.

The minibot's main task is surveying its variable terrain environment and being able to dock into the hub for battery module swapping. Mechanically, the minibot has a tank tread drive system allowing for all-terrain drive. The minibot has been tightly packaged to contain all the necessary electronics, with a central cavity for a battery receiver (Figure 3).

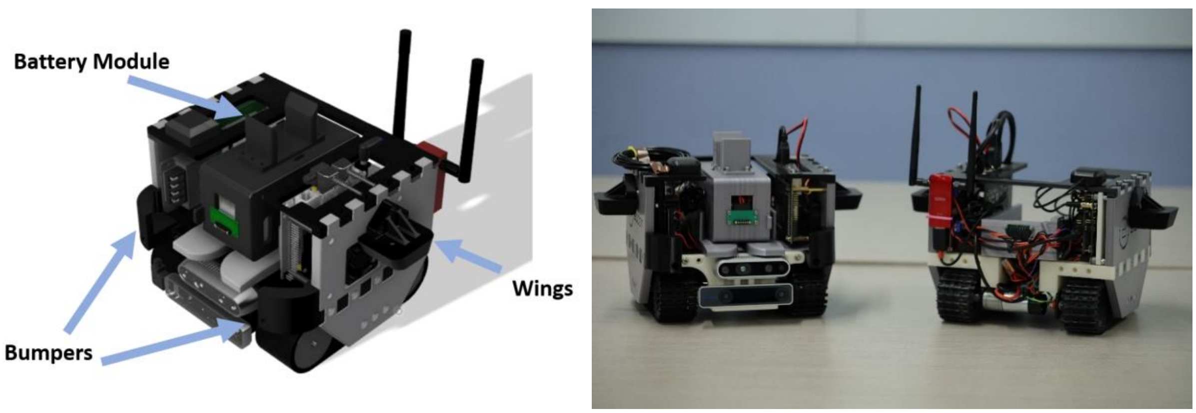


Figure 3a (left): Minibot diagram. Figure 3b (right): Completed Minibot.

Two ”wings” protrude from the side of each minibot and are used as mating surfaces during the docking lifting phase. One wing has a custom docking PCB in the wing that mates with the ”arms” of the hub lifting subsystem to provide temporary power during battery swapping. This is paired with a custom power swap PCB which allows the minibot to be powered by both the battery module and the hub during docking. The custom minibot PCB and the Nucleo talk with the motor driver, GPS, and IMU. While the Jetson Nano communicates with all other electronics and enables navigation and computer vision. Lastly, the two stereo cameras for computer vision allowing the minibot to explore the environment and autonomously dock in the hub.

The hub houses three batteries, one for charging the battery modules, one for the hub drive system, and one for the remaining electronics on the hub. The electronics for charging the battery module include a 5v regulator and an 8-channel relay with continuity acting as the switch. These components connect to three buck-boost converters and a fuse for each battery module charging slot in the indexer.

The hub drive system is a front-wheel drive with each wheel equipped with a CIM motor, motor controller, and a circuit breaker. Each motor controller connects to the receiver allowing the drive system to be controlled remotely.

The remaining electronics on the hub include a CNC driver which communicates with the stepper motors for the docking, slicing, and indexing mechanisms. The Jetson Nano communications with all the electronics on the hub and delegates to other microcontrollers. The custom minibot pcb monitors the each battery module's voltage. While the Hub's GPS and IMU are used as a reference point with the minibot's IMU and GPS to know the relative locations of one another to aid in autonomous docking.

The lifting/docking mechanism (Figure 4) on the hub consists of two linear rail carriages actuated by a motorized ball screw. Using a single NEMA 23 coupled with a belt and pulley system both arms are driven synchronously. Mounted on the linear rail carriages are two custom 3D-printed lifting arms that mate with the wings of the minibot to allow the minibot to remain rigid when fully docked and the hub to power the minibot via the wings during the battery module swapping sequence.

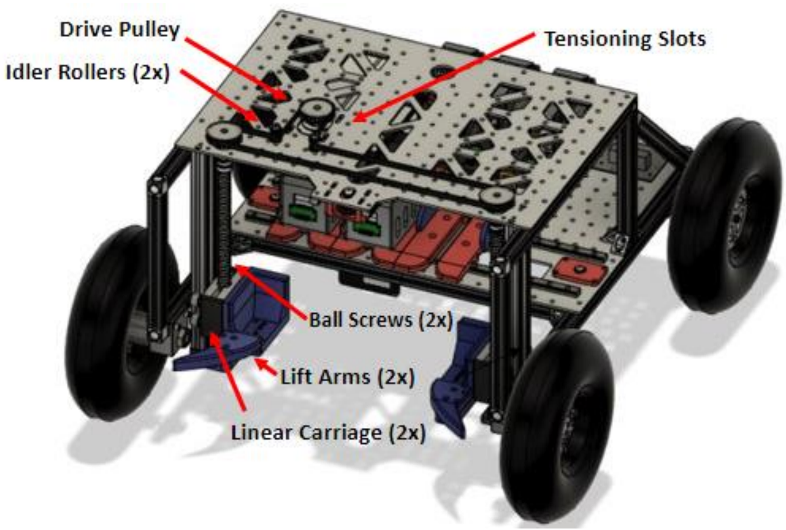


Figure 4: Hub lifting system Overivew. Lifting arms raise along two ball screws driven in sync by a belt.

Both the battery slicer (Figure 5a, Left) and the indexer (Figure 5b, Right) consist of a tensioned pulley, driven by a stepper motor. Each mechanism has a limit switch mounted at the beginning of each track to allow the linear carriage to zero itself and know its relative position.

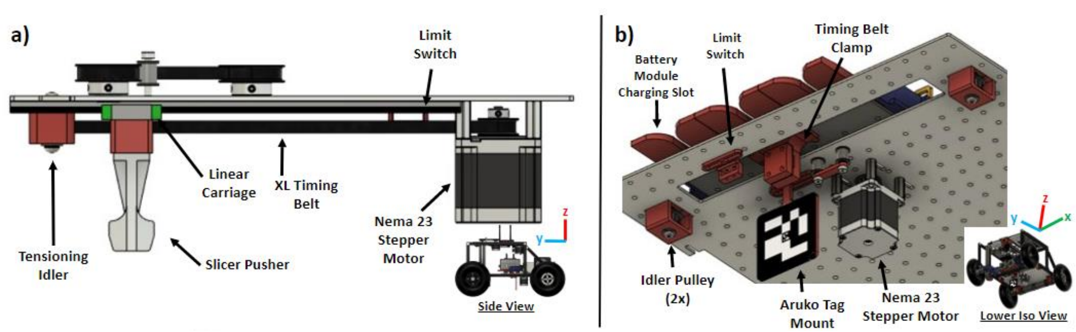


Figure 5: (a) Side View of Slicer Mechanism. (b) Bottom View of Indexer Mechanism.

Design Process

At the onset of the project, the team focused on determining a method to make swarm robotics more applicable to field deployment. A concept of a large "hub" robot with many docking ports was determined, and the hub robot would lend the capabilities of transporting, recharging, and refilling minibots as they conducted a field operation. The minibots would be equipped with a metal detector to provide a useful field surveying function.

As development progressed, the team encountered scaling challenges with the initial solution. Due to the cascading costs of expanding the hub with additional docking ports for each minibot, the team evaluated whether it was possible to service all robots with just one docking port. Previously, the limitation preventing this was the charge time of at least one hour per minibot. As the minibots had less than two hours of runtime, this prevented the system from operating with more than two or three minibots. To eliminate this challenge, the team pivoted to a battery swap mechanism. With this, minibot downtime was reduced from an hour of charging to ninety seconds of swapping. In addition, the cost of the system reduced considerably; rather than scaling the hub to be larger and stronger for each minibot, a battery swapping architecture can service any number of minibots with a single docking point and a three-actuator swapping mechanism.

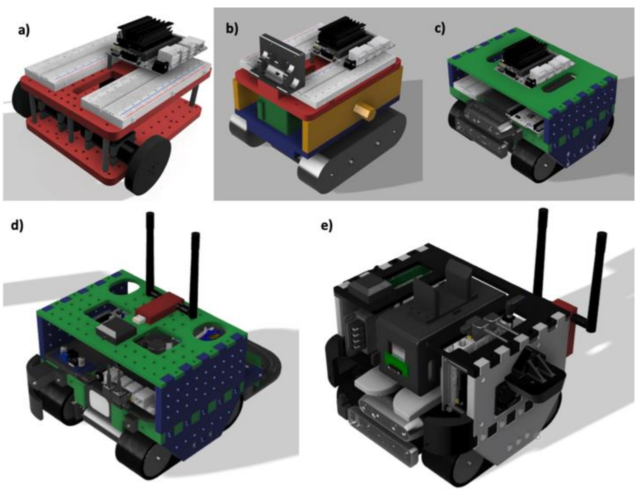


Figure 6: Minibot Iterations From left to right (a) Iteration 1 (b) Iteration 2 (c) Iteration 3 (d) Iterartion 4 (e) Iteration 5 (final). Optimized to house electronics and mounting procedure.

As the project developed, the team designed and built five iterations of the minibots, shown in Figure 6. Originally, minibot V1 (Figure 6a) was developed as a simple platform to test electronics. V2 (Figure 6b) was the first implementation of a tank drive to allow for all-terrain driving and the initial wing concept. V3 (Figure 6c) was a cleaned-up and optimized minibot which lowered the center of mass allowing for easier docking and lifting. V4 (Figure 6d) implemented additional electronics for the complexities of the software and electrical team as well as the payload/metal detectors. Finally, V5 (Figure 6e) is the current design which implements the new battery-swapping idea after the architectural pivot.

Docking has remained a fundamental aspect of the project throughout each iteration. Initially, the team opted for a physical approach of rapid iteration via 3D printing to determine the optimal mating interfaces. Figure 7 explores the iterations leading to the finalized design.

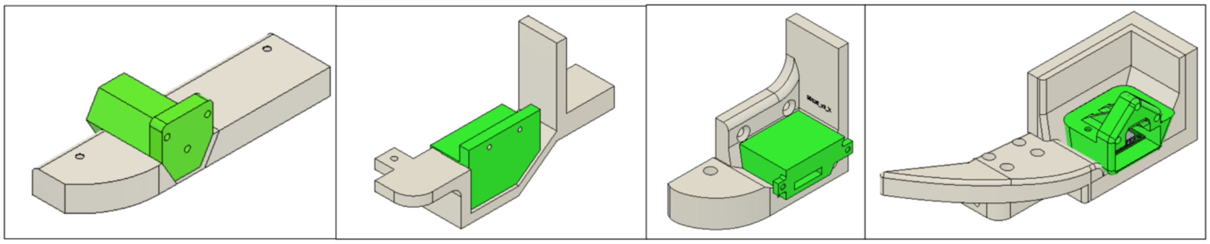


Figure 7: Wing and Arm Iterations. From left to right (a) Iteration 1.1 (b) Iteration 2.1 - added back hard stop to limit x (c) Iteration 3.1 - added wall to constrain y (d) Iteration 3.3 (final) - optimized entry shape and mating geometry to minimize jamming.

To aid with the evaluation of each design, a test rig was assembled, which was composed of a vertical linear actuator on an adjustable bed. Via this bed, angular or axial misalignment of the hub and/or minibot could be simulated, which was critical in characterizing the misalignment compensation of each design. Although this method was initially helpful, the slow turnover of 3D printing, laborious physical test campaign, and imprecise methods led the team to develop a physics simulation model in Matlab Simscape Multibody (Figure 8). The model began by quantifying the compensation bounds of a particular pair of mating geometries. The axial displacement limits were evaluated through a custom "axial iterative solver" algorithm, which uses a binary search method to rapidly find misalignment bounds within a time complexity of $O(log(n))$. Bound testing proved beneficial for quick approximations of geometric performance, but it failed to represent combined misalignment cases, which were more representative of real-world operation.

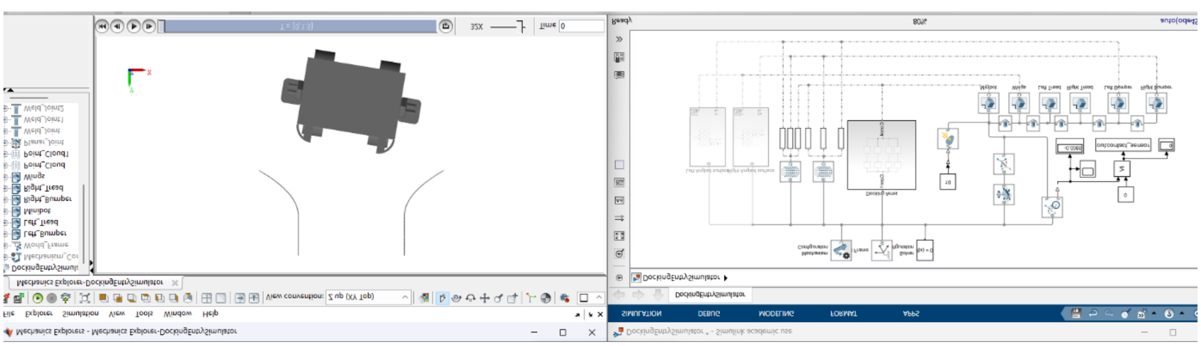


Figure 8: The rigid body physics simulation model developed in Simscape. Through this model, various docking geometries can be characterized and iterated upon rapidly without real-world delays.

After the benefits of simulation were realized, these concepts were taken to improve minibot entry misalignment compensation. The team built an additional Simscape physics environment to determine the validate hub and minibot bumper geometries. To accelerate the process of finding the optimal bumper geometry, a geometric solver was developed, which performed a grid search to find the highest-performing bezier curve.

Consulting with technical experts for consistent review was an essential element of the team's process. In addition to regular advisors, the team meet biweekly with Patrick DeGrosse Jr, a mechanical engineer who has worked at NASA JPL for over a decade and a half, including as the Mobility Lead of the Perseverance rover. DeGrosse Jr provided critical insight for the technical design and analysis of the project, meeting biweekly to provide feedback. Additionally, the team met with Professor Jaeger-Helton, who provided her expertise on testing, informing both the physical and simulated test campaigns and introducing the team to the fractional factorial testing method.

Results

To fully validate the docking and battery swap systems, the team has conducted an extensive suite of robustness testing. This testing can be divided into several main components: simulated and physical entry testing, simulated and physical lift testing, as well as physical battery swap repeatability testing. To evaluate the entry testing, randomized Monte Carlo simulations were implemented, in which the minibot is simulated in thousands of random starting orientations, generating a point cloud of successes and failures. To quantify the misalignment compensation of a particular design, the volume of the success region for a particular bumper geometry pair was computed. As seen in Figure 9, the highest performing bumpers expanded the range of permissible starting positions by 42.7%

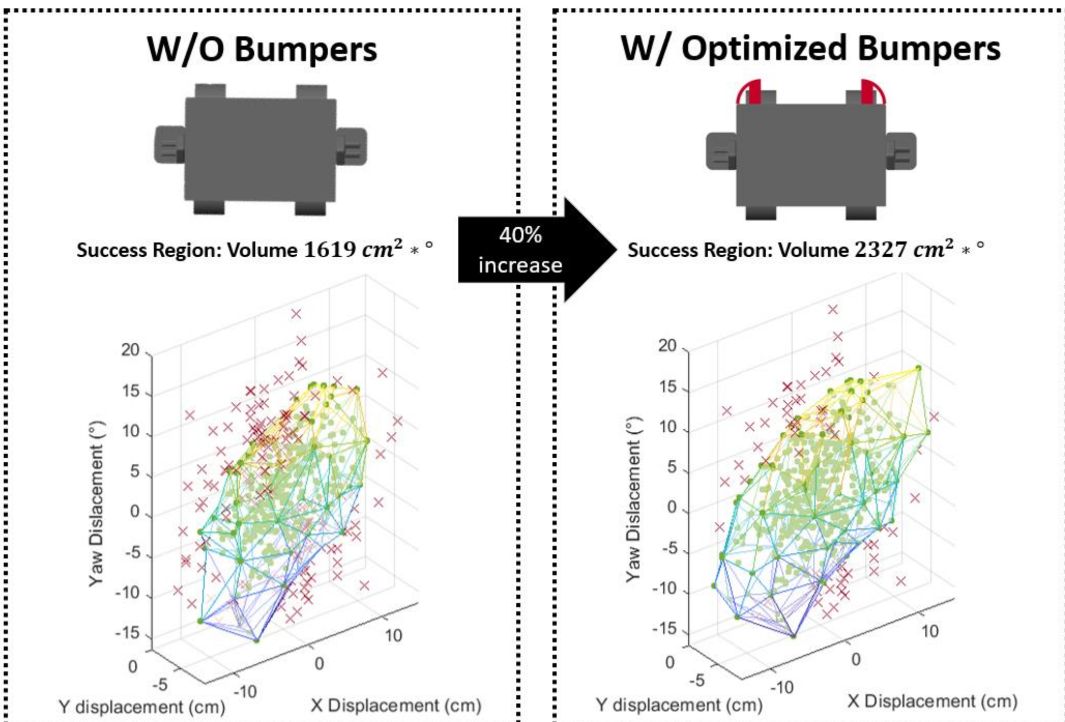


Figure 9: Permissible docking region comparison with and without optimized bumpers, evaluated via 500x Monte Carlo simulations.

The simulation-optimized entry geometry was then validated with a test campaign carried out on the physical system. The minibot was placed over a range of initial starting orientations, varying both lateral displacement and angular misalignment with respect to the hub, and driven straight forward represent a small subset of the simulated test data. Top-down video was recorded, and a Matlab script was developed using Canny edge detection algorithms to track the 2D position of the minibot throughout each docking attempt. Using this video analysis technique, the optimized bumpers were shown to account for 34.2 cm of lateral misalignment and ± 20.2 degrees of yaw misalignment.

Fractional factorial characterization was implemented for lifting alignment simulations and real-world testing. For the lifting simulations, wing and arm docking geometries were characterized with 5 degrees of angular misalignment and 5 mm of axial misalignment. A passing design was indicated by falling into the aligned xyz position in the simulation equivalent to PCB continuity on the test rig. The matrix was then replicated on a real-world test rig. The final wing and arm iteration successfully passed the experimental matrix combined misalignment conditions, matching the simulation performance to the test rig.

To test the reliability of the battery swapping system, the team conducted a series of tests in which a minibot repeatedly lifted, exchanged a battery, and lowered. As testing progressed, small mechanical errors were corrected, and the number of consecutive swaps was incremented. The final test of 50 consecutive battery swap cycles revealed a 100% success rate.

Summary and Impact

B.O.O.S.T. seeks to revolutionize the operation of robot swarm systems by overcoming the critical limitation of finite battery lives. With its innovative design, B.O.O.S.T. can expand mobile robotic applications to rough terrains, significantly reduce robot down-time by overcoming the issue of finite battery life, and serve as a proof of concept for an architecture that has broad field applications.

Moreover, by incorporating the ability to transfer other payloads from the minibots to the hub, B.O.O.S.T could find even further robotics applications. The group is enthusiastic about exploring the potential of the B.O.O.S.T. architecture with further development, particularly for large scale beach cleanup, search and rescue missions, and autonomous agriculture. B.O.O.S.T.'s scalable nature and robust drive system make it particularly attractive for outdoor applications. Although prior research has been conducted on the application of battery swapping technology for electric vehicles, there have been limited publications on battery swapping for mobile field robotics. The team aims to synthesize the project's findings in a research publication, emphasizing the novel approaches with the overall system architecture, docking analysis, and battery swapping mechanism.

Additionally, given its autonomous nature, B.O.O.S.T. has significant potential for extraterrestrial applications. Further development will focus on protecting the mechanism for operation in harsh environments. With the guidance of JPL Engineer Patrick DeGrosse Jr., the team hopes to explore the potential of B.O.O.S.T. for future Mars Missions.

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