BOSTON UNIVERSITY AMAZON ROBOTICS DESIGN REPORT

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A Multi-Robot System for Cooperative Object Transport

1. Concept Overview

Here, we discuss our design and construction of a multi-robot system (MRS) that may carry arbitrary loads to increase the efficiency of warehouse automation. We provide research and background information to justify our design, a system overview and breakdown, as well as project logistics.

Given the research in multi-robot systems (MRS), our team investigated regularly shaped floor robots (like small Kivas) and their application in carrying arbitrary loads. Our concept for such a system was a collection of identical collaborative robots, each similar in size to a Roomba. Combined, they would constitute a MRS that could be tasked to transport previously unknown objects of various sizes, loads, and geometries through a warehouse environment. Our minimal viable MRS may be loaded with an object, and directed to an end position. Given perception and load sensing capabilities, the MRS may additionally adjust itself dynamically to best control its cargo, avoid collisions, and ensure safe transport.

2. Motivation

With the increasing volume of orders and demand for faster fulfillment, warehouse automation has become an integral component of the global supply chain. Despite the technology's rapid development, there remains significant challenges to overcome. Whether enduring fluctuating demand, handling unstructured and structured processes, or interacting with human workers, robotic automation must move towards a scalable, task agnostic, and self-supervising future to realize greater efficiency. Although early adopters have seen success deploying robotic automation in structured environments, further development is needed in perception and human-robot interaction for robotics to handle unstructured processes.

Handling Unstructured Processes

Traditional warehouse automation has primarily focused on structured, repetitive tasks, such as moving a box with strict dimensions from point A to B. This narrow focus allows these systems to be more efficient than human workers at a given task, releasing humans to focus on more unstructured and complex tasks. However, this kind of structured automation can create extraneous processes and bottleneck efficiencies. Given the endless variation of object characteristics and destinations that may occur in a warehouse, there are often steps in the supply chain to transform processes from unstructured to structured in order to accommodate these traditional automation techniques. Examples include repackaging, palletizing, or laying out roadmaps for vehicles to follow. We believe creating a system that can better handle unstructured process has the potential to significantly broaden the application of automation and reduce resources devoted to restructuring processes.

Human Cooperation

Warehouse automation is often partitioned from human workers to optimize automation efficiency and and increase worker safety. However, the benefits of partitioned automation are only a manifestation of automation's current limits; a local minimum rather than an absolute. Separation of workers and automation and ultimately limits efficiency and flexibility. Therefore, creating a collaborative system that works alongside human workers reduces system constraints and increase performance.

Scale in Integration

Traditional warehouse automation often operates at a fixed speed regardless of demand. Whether a warehouse is experiencing excessive or scarce demand, these automated systems often have little room to scale dynamically to accommodate the spectrum of scenarios. Similarly, when a system is tasked to handle a process from step A to B, the rigidity of these systems prevent the system from integrating with further processes such as steps A, B, C, etc. Creating a system which can scale in demand and process integration is desirable, and has potential to alleviate these limitations. Such a dynamic system may better adapt to a warehouses' dynamic needs.

Benchmarking

Within the domain of object transportation, there are previous solutions we may benchmark our system against. Forklifts are a fundamental tool of the warehouse supply chain. When operated carefully, these machines are able to effectively transport a large range of loads through a warehouse environment. However, without collision avoidance and expert human handling, forklifts pose an immense safety hazard. They also require their load be palletized, which adds a packing and unpacking step the the pipeline. The required cost, human operation, and load rigidity all limit this solution's efficiency. Dollies, hand carts, and rollers offer alternative low cost and relatively adaptable solution within this domain. However, these tools have limited maneuverability and are both labor and skill intensive to operate safely and efficiently. These constraints ultimately limit the pool of qualified human workers and reduce efficiency.

The Kiva robots which Amazon uses today present a significant development in warehouse automation. They're capable of efficiently transporting compact shelving units to human workers for stow and retrieval. However, they are limited to carrying these shelves in their structured, grid environment. A robotic solution that can carry arbitrary loads in an environment shared by humans presents potential to help automate unstructured processes in a scalable way.

3. Background Research

An array of research has considered the benefits of self-assembling robots. The core concept around these robots is creating modular units that can join together dynamically in order to address unique tasks. Several research groups have explored this modality and proved its utility. Tuci conducted pioneering work illustrating the benefits of modular, self-assembling "s-bots" that were able to transport objects, though they note difficulty in decision making with their multi-robot system[1]. Gross continued work with s-bots, and developed improved methods for autonomous self-assembly that scaled well for many s-bots[2].

[1] Tuci 2006
[2] Gross 2006

Related research has also been conducted with similar robots like Sambot[3], which is notably more cube-like and able to take on a wider range of structural forms.

There is similar depth of research focused on cooperative object transportation specifically. Tuci, Alkilabi, and Akanyeti's, "Cooperative Object Transport in Multi-Robot Systems: A Review of the State-of-the-Art"[4] provides a comprehensive view of work within the domain of our proposed conceptual design. This review highlights the many past modalities, challenges, and possible directions of future work. These studies once again demonstrate that cooperative MRS inspired by biological systems offer a flexible, dexterous, and robust approach to automation.

"Ants have evolved extremely effective competencies to cooperatively retrieve items that can be hundreds or even thousands times the weight an individual can carry (Czaczkes et al., 2011). Owing to cooperative transport, ants can perform faster prey retrieval reducing both the exposition of foragers to predators, and the risk of food being caught and eaten by other aggressive species (Hölldobler et al., 1978; Yamamoto et al., 2009). The speedy retrieval of prey also reduces the time workers are involved in transport tasks, freeing them for other colony relevant tasks (Feener and Moss, 1990; Tanner, 2008). Cooperative transport also reduces the energy cost of transport by allowing carriers to keep up with the dense flow of traffic and by reducing the possibility of traffic jams (Czaczkes and Ratnieks, 2013). Biologists suggest that these complex group level responses are underpinned by simple behavioural rules (Franks, 1986; McCreery et al., 2016). We think that important lessons can still be learned from observing the complex cooperative transport behaviour shown by various ant species. It is then the task of roboticists to transform these observations into fruitful design principles and effective methodological choices to develop robust, flexible and scalable MRSs that cooperatively transport objects."[5]

Work has also been done in multi-agent decision making. Parker developed a biologically inspired algorithm to enable distributed systems of robots to make the best decision given a set of solutions[6]. Another biologically inspired algorithm developed by Parker and Zhang[7] allowed robots to collaborate through changes to their workspace instead of direct communication. Biology has inspired several other papers which discuss group behavior of multi-agent robotics[8]. At a systems level, path planning will be an important aspect of this project. Significant research has been conducted in multi-agent path planning that we would like to evaluate for our MRS[9,10,11].

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[3] Wei 2011, Zhang 2018
[4] Tuci, Alkilabi, and Akanyeti 2018
[5] Tuci, Alkilabi, and Akanyeti 2018
[6] Parker 2009
[7] Parker and Zhang 2009
[8] Berman 2007, Lerman 2004
[9] Wang 2016
[10] Leonard 2001
[11] Panagou 2013

At a higher level, research has been conducted on human robot interaction (HRI) with swarm robots[12]. We believe that with the use of human detection and tracking we can create a MRS that's able to work alongside humans.

4. System Considerations

Our minimum viable prototype (MVP) is a system of three identical robots that must be able to transport a load of arbitrary shape and size. A homogenous system provides greater ease of replacement and control. The system must safely navigate with the load throughout a warehouse environment. In order to work collaboratively, human-robot interaction is an integral component. As discussed in our motivation, coordination and cooperation between robots and humans will help increase the performance of the system. Therefore, the system must be intuitive to operate.

Given these objectives, we have outlined three modalities that our system must exhibit to reach the minimum product.

Load Transport

Load transportation is the core capability of our MRS. For the prototype, the MRS must be capable of carrying 15kg per robot on level ground. Extending this capability to accommodate bumps, inclines, and elevator gaps is a desirable feature. Each robot must have a rubberized, free rotating, and compliant loading platform to allow an external actor, such as a human worker, to place objects onto the system. The MRS must then transport the load via teleoperation and/or compliant guidance. Compliant guidance would allow a human worker to lightly guide the object by physically pushing it, allowing the MRS to contribute the bulk of the pushing force. It is desirable for the MRS to characterize the loaded object using centroid analysis for more optimal control. Beyond teleoperation and guidance, we may further consider autonomous navigation to a desired destination.

Working with Humans

Allowing humans to fluidly interact with the MRS is fundamental to its operation. The MRS must communicate its intent, state, and action while allowing humans to intuitively guide or adjust its behavior without fear of collisions or malfunctions. Therefore, the system must be capable of matching human walking speed (1-1.5 m/s) and moving omnidirectionally. It is desirable that the system recognize humans and be aware of their position. Guiding the robot via effortless touch or teleoperation as stated above is and clearly communicating with humans is necessary feature to achieve successful, fluid operation.

Formations

Given independently driven constituents, the MRS must maintain a formation from loading throughout transport. At the simplest case, these formations will be preconfigured and dictated by human workers. An advanced feature could explore self-assembly in which the MRS uses its point cloud sensor to observe

[12] Kolling 2016

a given object and autonomously determine an optimal configuration. Once loaded, a given rigid object will constrain the system. Error propagation may occur and cause robot to slip, therefore it is crucial the MRS can detect translational strain and compensate appropriately.

Mandatory	Desirable	Advanced
Compliance	Load Characterization - Centroid Analysis	SLAM and Path finding
HRI	Collision Avoidance	Advanced HRI
Teleoperation	Incline and Bump Navigation	Dynamic Self Assembly
-------------------	Preconfigured formations	Track and follow

Table 1: Prioritized system features

Based on the necessary functions, we created a table that outlines the mandatory, desirable, and advanced goals of our robotic system. Required features are the minimum characteristics the final product must exhibit. This includes the compliant mechanism, HRI, and teleoperation or guidance to move. The desirable goals were categorized as such because, while beneficial, they are not necessary to achieve our basic operations. The advanced goals are ones we intend to pursue after the mandatory and desirable goals are met.

6. Use Cases

Given these modalities and capabilities, our MRS can be used to load and transport arbitrary, irregularly sized objects. A specific example would be unloading a couch from a truck to a warehouse. The robotic system would act as a “smart dolly”; functionally identical to a dolly in its use of transporting a heavy object, but with the added features of being more safe, maneuverable and effortless to push. Humans would unload the couch from a truck and place it on the system of robots. The robots would be in a preconfigured formation that the human had assembled or selected. After loading the couch onto the system, the human can guide the robots through the warehouse. With a small push on the couch, the robots would sense an applied force and travel in the necessary direction with respect to the environment. The human would comfortably walk alongside the robot and lightly guide it to its final destination, where another mechanism may be used to remove the couch from the MRS and into its new location.

7. System Breakdown and Specifications

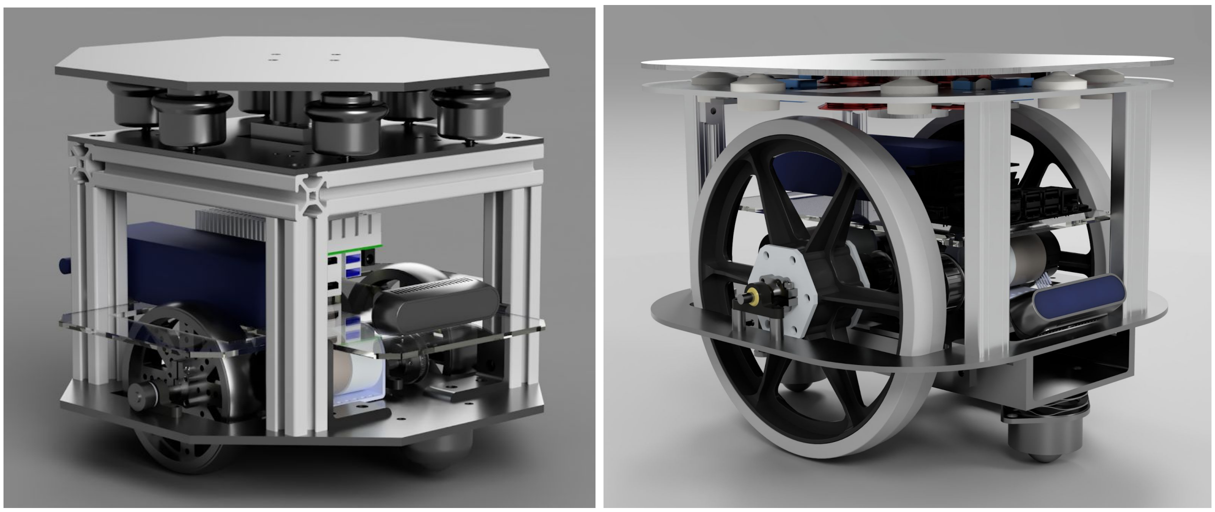


Figure 1: *Iteration 1 (left) and Iteration 2 (right)*

Specifications	**Unloaded**	**Max load, level ground**
Max load per robot in motion	—	15 kg
Max static load per robot	—	30 kg
Max speed	1.5 m/s	1 m/s
Max accel	1 m/s^2	0.4 m/s^2
Req. torque (2 motors)	0.39 Nm	0.63 Nm
Req. speed	141 RPM	94 RPM
Est. Battery Life	2 hours	1.25 hours

Table 2: *Specifications of a single 2nd iteration robot in the MRS.*

To get an idea of a single robot's capabilities, rough specifications are given in Table 2. Derived specifications for the motors and battery were computed for 10 cm radius wheels and a 25 Watt-hr battery. We assume a 65% overall efficiency and an unloaded robot weight of 5 kg. For the loaded, level ground case, 1 m/s was targeted as this is approximately average human walking speed. For the unloaded case, 1.5 m/s is on the higher end of estimates of average human walking speed, still within a safe range for a warehouse.

Compliance Mechanism

The application of a compliant loading mechanism for use in a MRS, as far as our research has shown, has not been explored before. Therefore, the compliance mechanism differentiates the system from previous work. Given it's a core function of how object transport works in our system, it is the most critical and high risk component of the MRS. This mechanism must resolve force input into its vector components to both sense human input, correct system divergence, and characterize the load's centroid. Furthermore, this mechanism must support the specified load and rotate freely in order to simulate holonomic (omnidirectional) movement and prevent over constraining the system.

When an object is placed onto the MRS, it constrains the translation of each robot in system with respect to one another, mitigating formation deviations that may occur throughout transport. A compliant, freely rotating loading platform provides mechanical flexibility to ensure the system is not over constrained. Due to the propagation of odometry error, robots and their loaded objects are inclined to slip. Torque sensors in the drivetrain serve to reduce this odometry error. The compliance mechanism additionally allows the MRS to resolve object forces providing an additional means of error correction. Another function of the compliant mechanism is identifying an object's centroid. Such a capability could allow the MRS to optimize its formation and kinematics for each unique load. Further, our compliant mechanism allows the system to respond to human input. The mechanism senses when the object is pushed, and reacts in a compliant manner. Therefore, to guide the system, a human worker may lightly push the object to its desired destination.

A range of initial modalities were considered. A multi-axis force sensor placed in a central supporting column beneath the support plate had the potential to resolve applied forces and moments in up to 6 axes with minimal oscillations and design complexity. However, commercially available multi-axis force sensors proved cost prohibitive. Similarly, manufacturing our own sensor with a series of strain gauges and wheatstone bridges was abandoned due to its required development time and cost. Joystick like solutions were abandoned since offset loading would tilt the plate and produce a false input. Furthermore, modalities such as spring and wire potentiometer in combination with a mechanism such as a two axis linear stage or parallel manipulator could cheaply resolve displacement to force yet would exhibit increased oscillatory behavior and design complexity.

The first iteration design implemented a series of four 10kg load cells arrange in a square mounted rigidly to a central block. The central block housed a linear bearing for the loading platform's central column to pass through. The central linear rod column was mounted to the loading platform with a flange. The loading platform then rested on a series of ball transfer units to support the vertical load. This design in theory, would allow free rotation while resolving the force in the x-y axis. A cut out around the central chuck could limit displacement and prevent overloading the load cell. Testing this first iteration compliance design confirmed its rotation and vertical load viability yet revealed that the series of rigidly mounted load cells were overconstrained. Thus, when a force was applied to the system, each load cell was equally strained producing an equal response and ultimately an unresolvable signal. Furthermore, due the central column's length, central block's height, in addition to gaps between the ball transfers and loading platform, this design exhibited a significant moment arm which strained the load cells when an offset load was applied behaving more as a joystick than a 2 axis force sensor.

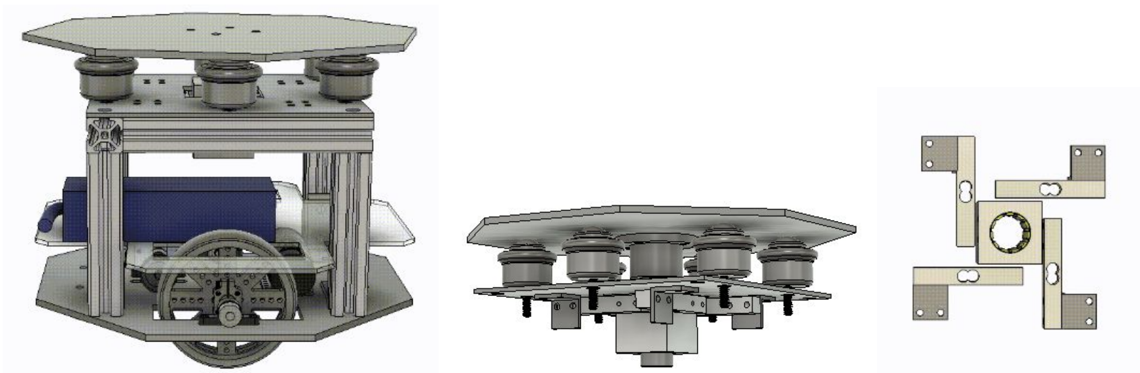


Figure 2: *Compliance iteration 1 design*

The second and final iteration leveraged knowledge gained from previous tests. Pleased with load cell cost and performance (sensitivity, hysteresis, etc…), these sensors were again implemented in a square orientation. This design then utilized eight rollers sharing 4 axes. A spring placed between each load cell and roller provided a compression force to the central column while allowing each roller to displace when compressed. The rollers gripped the central column and allowed free rotation while the spring translated all force to each load cell. The central column utilized a short aluminum pipe welded to the loading platform to reduce the moment arm and provide a port to potentially view loaded objects. This design utilized recessed ball transfer units to again support the vertical load while reducing the loading platform height and moment arm. Using a cut out around the central column again prevented overloading the load cells. Upon testing this mechanism, each load cell produced an isolated response allowing one to resolve an applied force into its vector components. Furthermore, the response produced from offset loading proved negligible. Ultimately this design achieved its required functions. Reducing roller sliding and rotation friction is one possible future development.

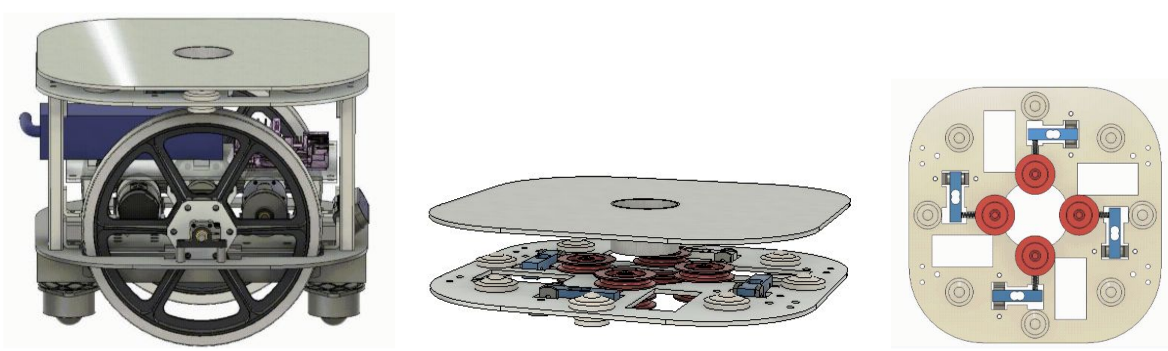


Figure 3: *Compliance Iteration 2 design*

Drivetrain

The drivetrain is a fundamental system of the MRS which must be designed to handle the outlined specifications. The drivetrain will serve two functions: robot motion and load distribution. A differential drive system will be employed to allow for a zero-point turning radius and ease of control.

The unloaded case places a constraint on motor speed, while the loaded case places a constraint on motor torque. Given that the loaded, incline case doubles the required motor torque, our MRS prototype will neglect inclines and leave this as an advanced goal. Brushed and brushless motors were considered for use in the drivetrain. For the purposes of a prototype within the scope of this project, a brushed DC motor was selected, with specifications as shown in Table 3.

Motor Type	**Encoder Type**	**Model**	**Stall Torque (Nm)**	**No-Load RPM**	**Stall Current**
12V Brushed DC Gearmotor	Hall Quadrature	Pololu (70:1)	1.41	150	5A

Table 3: *Motor selection for a single robot in the MRS.*

The load itself and bumps on the driving surface (within specification) also constrain the drivetrain. Therefore, the drivetrain must remove the load from the motor axle to prevent damage and absorb shock to mitigate robot and cargo displacement. Coaxial bearing supports, belt drive, and right-angle gearing were considered to address this. Suspension was considered in the form of springs connected to casters, or integrated into the design of the chassis and frame. To maintain three degrees of freedom (2 translation, 1 rotation) while supporting a load, the loading pad needed to freely rotate independent from the drivetrain. Initial considerations included ball bearings or a lazy susan turntable.

The first iteration design utilized a differential belt drive design with the selected motor to allow for omnidirectional motion, stay within space constraints, and take radial force off of the motor shaft. The two-wheel two-ball-transfer design implemented 5 cm radius wheels, 3 mm width MXL belts and corresponding pulleys, steel ball transfers, and 6 mm bore triboplastic self-aligning pillow block bearings as shown in Figure 4. The pulley gear ratio was 1.5:1, to allow for a higher top speed in the event that the human walking speed estimate proved to be inaccurate.

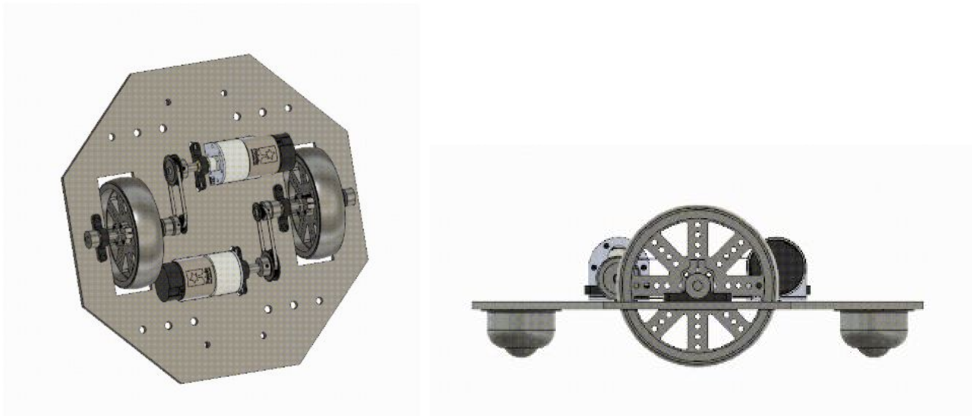


Figure 4: *Drivetrain Iteration 1 design*

Stress in the selected belts proved to be too great for consistent performance, causing the tension members to break and the belt to deform during testing. Accuracy of the pulley center-to-center distance estimates was limited by inconsistent mounting heights of components, reducing tensioning accuracy. Additionally, pillow block placement left pulleys at the end of cantilever moment arms, causing bending at shaft collars. Suspension had been omitted from this design, which resulted in inconsistent wheel and ball transfer contact with the ground.

The second iteration design remained a differential belt drive with two wheels and two ball transfers, and used the same motor and bearing selection as Iteration 1. This design implemented 10 cm radius wheels, 10 mm width T5 belts and corresponding pulleys, steel ball transfers in nylon housing for weight reduction, stacked wave disc springs, and aluminum spacers to mount components.

Figure 5: *Drivetrain Iteration 2 design*

The belts for this iteration were selected to be able to withstand required belt tension and pulley wrap stresses. Uniform spacers allowed for consistent component mounting and pulley center-to-center distances, increasing tensioning accuracy. Belt pre-tension was estimated by plucking the belts after mounting, and measuring their frequency of vibration. Additional pillow block bearings were placed to eliminate cantilever axle moment arms. Suspension was added in the form of springs to the ball transfer units, allowing for consistent wheel and transfer contact with the ground. Future development might include different selections of casters for greater versatility, and more powerful motors to enable the robot to transport heavier loads.

Body and Chassis

The fundamental purpose of the body and chassis is to support the load and house the hardware and electronics. During the design stage, different metal materials were looked at for structural stability as well as low weight. Aluminum 6061 was chosen for the base plate of the chassis, the compliance support plate, and the loading platform for its strength and weight. With the ball transfer units on the compliance mechanism taking all the load from the object, we needed to ensure the compliance would not bend nor buckle under the compression of the load. For iteration one, one inch t-slotted aluminum framing was used to create a box-like structure, as seen in Figure 6:

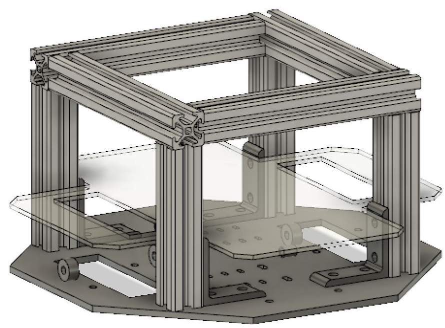


Figure 6: *Iteration 1 frame and chassis design*

Recognizing that there was not enough space to house the drivetrain and the electronics, a second level chassis was added to hold the battery and necessary hardware. The second level chassis was made out of acrylic to keep the weight down while still holding the necessary hardware.

Moving from iteration 1 to iteration 2, the body and chassis had many adjustments that ultimately helped reduce the weight and free up space. A Finite Element Analysis (FEA) was conducted on the compliance support plate to test the strength of the framing and plates themselves:

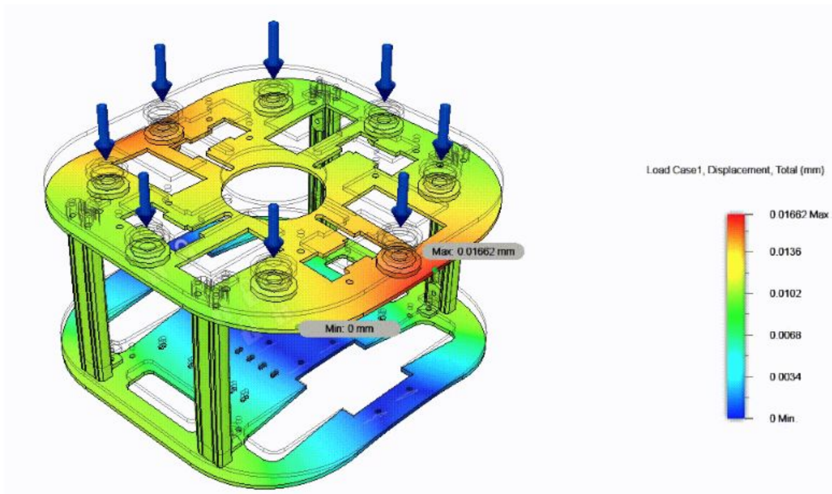


Figure 7: *Finite Element Analysis on chassis and framing*

As seen in the figure above, the maximum displacement the plate experience was 0.01662 mm of deflection with a maximum load of 30 pounds distributed across the ball transfer units. With these results, the loading platform and base plate thickness were reduced, the size of t-slot framing was reduced, and the box shaped frame design was removed. The iteration two design is shown below in Figure 8:

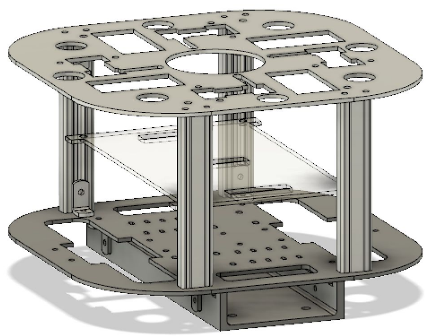


Figure 8*: Iteration 2 design for body and chassis*

With larger wheels and more space necessary for the drive train, room needed to be cleared up on the baseplate. The robot moved from an octagonal design to a curved square to add more space in the corners. With larger wheels, the robot had a lot of room underneath it, so a U-channel was added to house the electronics, therefore freeing up space on the second level chassis to reduce the size of the acrylic plate. Cutouts were also added to the support plate to reduce the weight in this aspect.

Overall, the weight and price of materials was reduced from iteration one to iteration two. Moving forward into future design, a fairing would be desired to shield the inside mechanisms and create a visually pleasing robot. Vacuum forming and injection molding have been researched as methods to do this. While vacuum forming provides a quicker and cheaper process, more complex features of the fairing would need to be injection molded. For prototyping, 3D printing, particularly in state-of-the-art materials like carbon fiber reinforced plastics[13], could be used in conjunction with molding processes for adding complex features.

Perception and Computation

Perception is a key consideration in order to create a robot that's safely able to move and navigate in an environment alongside human workers.

Each robot is outfitted with an Intel Realsense D435 depth sensor which provides a stream of RGB and depth data for a wide field of view (~100°) in front of the robot. Each robot additionally has a NVIDIA Jetson Nano, which allows for GPU acceleration on some of our algortihms.

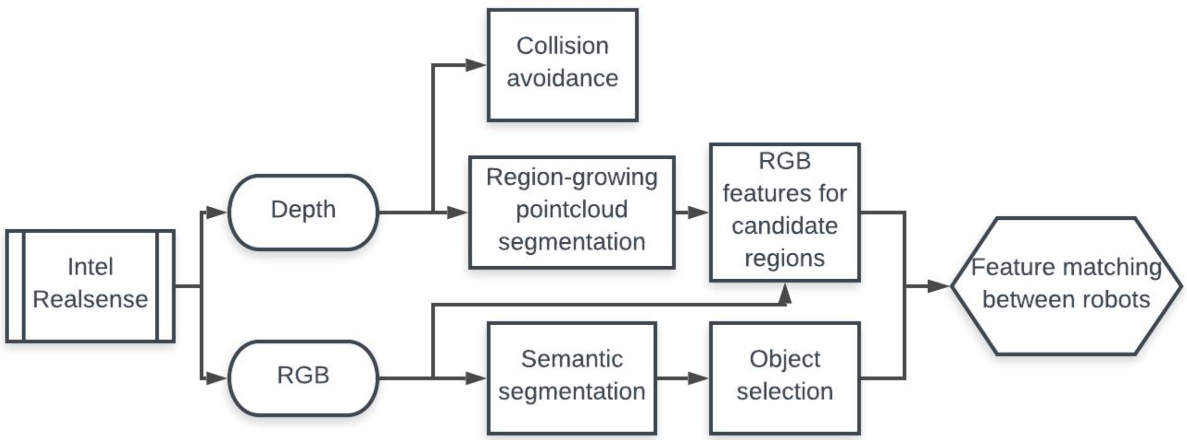


Figure 9: *The vision pipeline for the robot for collision avoidance and advanced perception.*

There are two chief goals for perception: collision avoidance and object perception. Collision avoidance is the more simple goal, and is accomplished by simply considering the depth (or distance) at which objects in the robot's field of view are at. Collision avoidance performed locally for one robot will propagate throughout the system, given each other robot's passive compliance.

Object perception is the more advanced goal, and constitutes most of the pipeline. The goal is for the system to be capable of semi-autonomously perceiving a load held up by human workers, and then navigating under the load in order to carry it. The pipeline considers depth and RGB data independently, and then fuses it at the end. Depth data is segmented based on a region-growing algorithm, so individual surfaces may be extracted from the overall depth map. RGB features are then computed for each surface, after they are filtered by a heuristic (i.e. angle relative to ground, flatness). RGB data is semantically segmented, and potential objects of interest are chosen based on a semantic understanding of the scene. Currently, the algorithm looks for the region of the image near detected human, assuming this will be the object humans are carrying. Finally, the pipeline completes when candidate surfaces are corresponded with a region of interest from the RGB pipeline, and feature matching is computed across the system of robots. For the surface which passes a threshold of feature matching, if one exists, robots then localize

[13] https://markforged.com/materials/#composites

themselves based upon a computation of their position in space with respect to the depth data on each feature which has been matched, effectively using the object as a local region for the system to localize around.

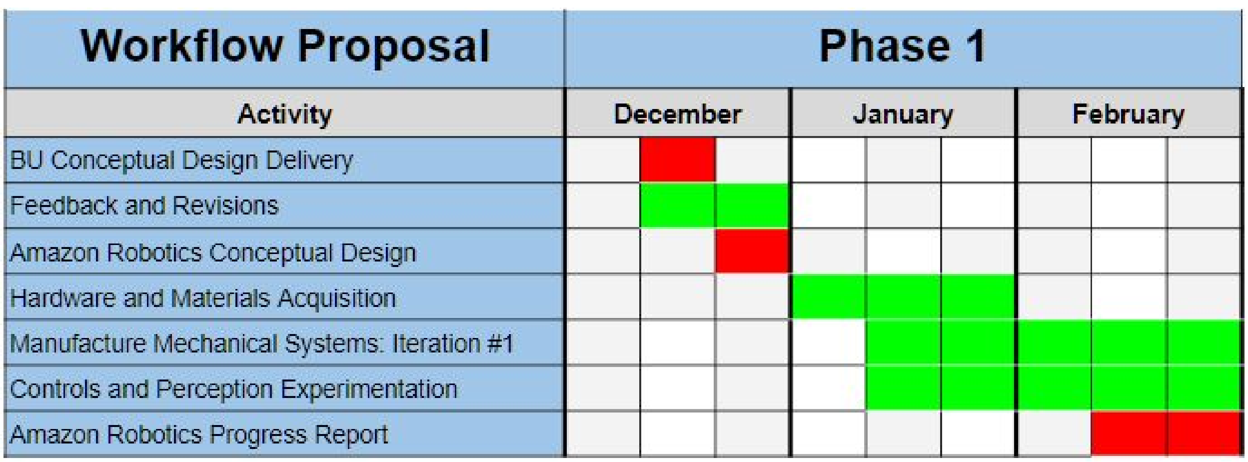
5. Estimated Material Costs

Compliance $60 ● $30 Force sensors ● $30 Mechanism Drivetrain $370 ● $180 Motors ● $190 Hardware	Chassis $150 ● $150 Materials Electronics $80 ● $50 Battery ● $15 Power distribution ● $15 ADC	Perception $300 ● $100 NVIDIA Jetson Nano ● $200 Intel Realsense D435i

Table 4: *Approximated bill of materials for each module of the robot.*

The total cost for one 2nd iteration robot was approximately $950. A full fledged depth perception system for each robot may be unnecessary, but would be ideal for identifying load geometry. This cost could be further reduced at scale.

6. Project Timeline



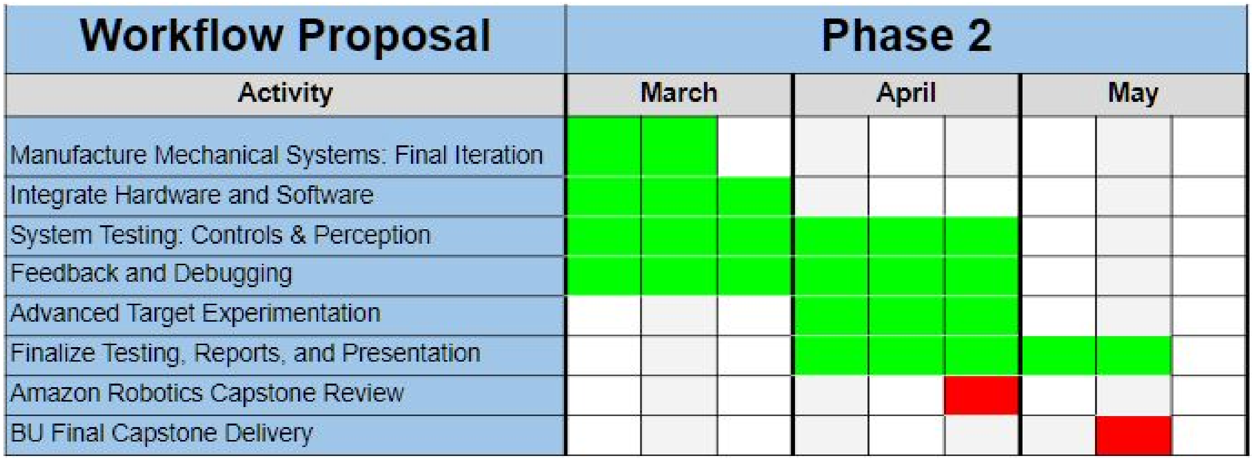


Table 5: *Timeline of total capstone project. BU deadlines given in red.*

The workflow shown above depicts the complete timeline and key delivery dates throughout the capstone. Phase 1 was focused on prototyping and experimentation. After proper specification and conceptual design feedback, materials were purchased. Next, controls and perception experimentation were conducted while the initial iteration of the drivetrain, compliance mechanism, and body and chassis were manufactured. Phase 2 focused on redesigning a 2nd iteration, finalizing manufacturing, system integration, and perception and controls. After rigorous testing, feedback and revisions, the final project was delivered to Boston University May 3rd. Client delivery and development will continue into the summer.

Modules	Leader
Perception, Collision Avoidance & Path Planning	Lucas Watson
Compliance Mechanism & Loading Platform	Andrew Brillaud
Drivetrain	Max Davidowitz
Body & Chassis	Gianna Iafrate
Controls	All

Table 6: *Table of system modules and the module leader.*

Based on the breakdown of the system, the assignments were given on the basis of modules comprising our MRS. While each team member contributed to designs for each part, every module had a clear leader to organize the designs, ideas, and implementation. Because controls played a part in every aspect of the system, all members contributed.

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