Marsupial Robotics: Background Review: MEIE 4701: Capstone 1

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Abstract

Fleets of multiple robots have the potential to save lives in disaster scenarios, explore more ground in the search for life on Mars, or simultaneously re-plant a field, but they have limited run-time due to a finite battery life. In this paper, a "mother" robot is proposed to sustain a small fleet of "children" robots by mechanically docking. Research was conducted on this class of multi-agent robotic system, known as marsupial robots, and the capabilities required for these interactions. Marsupial robotics is a young field with limited research and no market presence due to the complexity required for multiple robotic systems to physically interact in unknown environments. Marsupial robots require a means of "docking," or physically interfacing with one another. Once docked, the mother robot can support the children robots through multiple interactions such as charging, data exchange, and item handling. Charging can occur via three methods: wired, wireless and battery swapping. Additionally, docked robots could physically exchange materials to free up onboard storage. Many current docking systems require adjustments to compensate for positional error and are designed for controlled indoor environments. In outdoor field environments, the likelihood of this positional error is multiplied. The challenges of docking in uneven outdoor environments provide an opportunity to develop a mobile charging solution to improve all applications of multi-robot systems.

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1 Introduction

1.1 Problem Statement

From environmental surveying to agricultural cultivation, a distributed robotic system opens opportunities for increased efficiency and coverage of a wide area. The finite power supply of existing robots intended for exploration or long-term use limits the range of area they can cover. Adding individual power generation to a fleet of robots has several limitations, as it greatly increases the overall size, weight, and cost of individual systems, compounding as more systems are added to the network. The primary problem this project aims to resolve is that robots cannot operate in the field for long periods of time due to limited power supply.

The architecture of marsupial robotics helps to address some of these limitations. Marsupial robots involve a larger mother robot that assists one or more child robots. Child robots may dock to the mother robot for charging, data exchange, or to be lifted and carried through the environment like their namesake mammals. By having a mother robot to provide support to the children robots, it is possible to survey a larger area with ground-based robots capable of carrying heavier payloads. As a unique field of robotics, no existing models of marsupial robotic systems were found that were capable of simultaneous charging, data exchange, and item handling in outdoor environments.

1.2 Proposed Solution

The purpose of this project is to design a proof-of-concept marsupial robotic architecture to demonstrate recharging in semi-rough environments. It will involve a mother robot which provides a charging station for up to four smaller child robots. To address the power limitations of current robotic systems, the first iteration of the mother and child architecture will develop a robust docking mechanism which enables the children to charge from the mother's power supply. If this primary problem statement is addressed within the time frame of capstone, additional capabilities will be added to the system to address other limitations in the field of robotics. In descending order of priority, the capabilities of the proposed mother and children architecture could demonstrate:

1. Robust docking over semi-rough terrain
    (a) Power exchange between mother and child robots
    (b) Data exchange between mother and child robots

2. Payload exchange between mother and child robots
3. Transportation of child robots on mother robot

A robotic architecture capable of performing these functions would demonstrate the practical applications of a marsupial system where the mother provides mobile charging to the children. Children will be able to dock into the mother robot to recharge from its power supply, increasing the longevity of field operations. Having multiple children allows a wider area to be covered for environmental survey. When deployed, children will be able to gather information about the environment with a sensor suite. When docked, children bots could exchange this data to the mother robot for transmission to the user. While outside the scope of the first iteration, methods of physical environment interaction such as picking up an object could be incorporated into the children for future iterations of this architecture. External physical objects of interest could be identified to mark on a map for future reference or for retrieval. Children which can interact physically with the environment and exchange payload to the mother would be able to prove the feasibility of this architecture for applications such as taking samples from the environment and storing them for future scientific analysis.

There are many applications for a robotic architecture with these capabilities. Environmental surveillance and mapping, from extraterrestrial to subterranean exploration, could extend across larger areas without sacrificing the ability to take samples from the environment for analysis. Implementing this architecture as a curator for sustainable agriculture could help efficiently care for crops while gathering valuable data on field health. Search and rescue operations could be augmented by an autonomous system capable of efficiently searching where aerial vehicles cannot. Any situation which can benefit from a ground-based robotic system capable of surveying wide areas for long periods of time would be a potential application for this architecture. As this robotic architecture is in a relatively unexplored field, the scope of this project is to develop a proof-of-concept system which can demonstrate autonomous docking, charging, data transfer, and localized navigation. At this time, a specific application was not chosen, as the goal is instead to demonstrate a universal architecture as a baseline for future development. Mechanical alignment would assist close range sensory guidance to develop reliable docking alignment. Once this primary scope is addressed, verified with testing, and within acceptable bounds of error, additional capabilities will be added to the design. Details of the physical interaction with the environment, what sensor suite the children may carry, and the size of the payload to be exchanged between the mother and children, would all be selected with the time and resource limitations of capstone in mind. As versatile as this proposed architecture would be, it does have some limitations. Many of these limitations exist due to the condensed timeframe and budget of capstone and are not inherent to the premise of the architecture. Future iterations of this system could overcome such limitations with more

time and resources. The larger mother robot will require a large battery as a power supply, as a solar panel would not be enough to charge the children robots and would be too complex for the scope of this project. It will need to charge at a base camp using an external power outlet, where it will be immobile for the duration. Moreover, the robots will not be completely autonomous due to limitations in data transmission and wireless communication. The mother robot will be controlled by an external base camp that communicates wirelessly. The children's physical interaction with the environment will be limited by child robot size and the design of the manipulator mechanism. Moreover, none of the robots will be equipped to traverse extreme terrain, such as a forest floor or rocky field.

1.3 Scope of Research Review

The goal of this review was to study existing mechanisms and architectures in the field of robotics to help guide future design decisions. Existing marsupial systems utilizing the mother and child architecture were reviewed to understand the fundamentals of this architecture, its limitations, and points for improvement. Existing models of autonomous or semi-autonomous robotic docking were examined, as well as what charging mechanisms for docking ports are proven to work well in industry. Finally, research was conducted into mechanisms for handling physical objects, including methods for exchanging an item between two robots.

This review has several limitations. For fields of study with industrial examples, such as docking and charging, only the examples that seemed comparable to the proposed system size and needs were considered. Standards in the field of robotics were considered alongside research into novel mechanisms for each research subsection. Since the examples most relevant to the goals of the proposed system were selected, this ultimately was only a small pool of the total number of examples available and reviewed. Furthermore, marsupial robotics is a very novel field with only a handful of relevant and accessible publications. Overall, the research was limited to sources in English that were readily available through Google Scholar and published journals accessible through NU credentials.

2 Background Review

Background research was conducted to build baseline knowledge necessary before approaching specific solutions to the problem statement. Research was divided into analysis of marsupial robots, docking systems, battery charging, and item handoff. The sections are related in succession: marsupial robotics is a class of robotic systems in which larger robots sustain smaller systems, via some method of docking to align both robots for interaction. That interaction can be in the form of battery charging or item handoff.

Charging is part of the primary goals for the proposed solution, whereas item handoff serves as a secondary goal to be pursued only if time and resources allow. For each subject, background research was conducted on standards, literature, and patents, where applicable.

2.1 Marsupial Robotics

2.1.1 Principles and Concepts

Just as humans can achieve greater tasks in teams, so can robots. The field of multi-agent robotics focuses on the interaction and collaboration of two or more robots. These robots can be homogenous, meaning that they have identical capabilities, or heterogenous, in which the robots are designed for different roles. One variation of multi-agent heterogeneous systems is marsupial robots. The name and function are inspired by nature; from kangaroos to opossums, marsupials are the order of mammals which carry, nurture, and guide their young (Figure 1, left). Similarly, a marsupial team involves a larger robot which sustains and deploys smaller systems (Figure 1, right). This is differentiated by other heterogenous systems, as there is a pre-designed hierarchy in which one or more smaller robots are physically reliant on the larger robotic system to maintain continual operation.

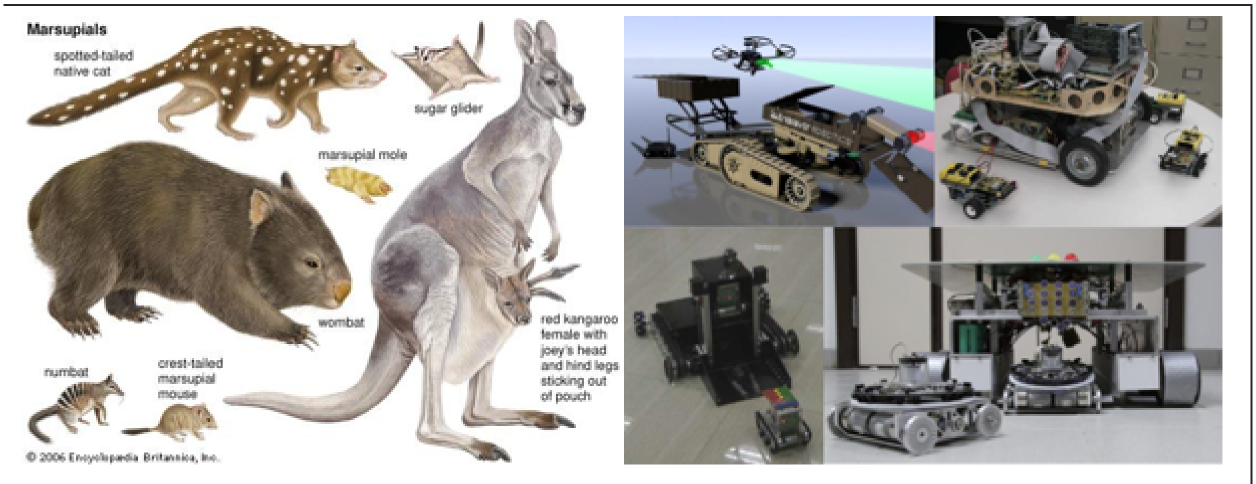

Figure 1: (Left) The marsupial order of mammals. (Right) [1] Marsupial-inspired multi-robot systems [2] [3] [4] [5]

In literature, the robot units of a marsupial system are referred to by a variety of names. The larger robot is sometimes referred to as the "mothership" or the "mother" to a "child" or "daughter." Alternatively, some works refer to the larger robot as a "carrier," "container," or "dispenser" for an onboard "passenger." For the remainder of this paper's analysis, the terms "mother" and "child" will be used.

2.1.2 Literature

Although development on marsupial systems began in the mid-90s, the term was first popularized in 1999 by Dr. Robin Murphy. Murphy et. al defined a team of marsupial robots as "a collection of mobile robots, where one or more robots are at least temporarily physically dependent on another for directives, transport, power, communication, etc." [6]. To perform search-and-rescue missions, Murphy's team developed "Silver Bullet," a toy Jeep modified with onboard sensing, processing, and communication. Silver Bullet featured an actuated rear hatch to deploy "Bujold," a small, tracked robot.

Figure 2: Silver Bullet and Bujold, the first popularized marsupial robotic system [6]

Silver Bullet and Bujold were successful in demonstrating the potential of heterogeneous multi-robot systems (Figure 2). The pair of robots were able to navigate to the general vicinity using the mother robot and deploy the smaller robot to weave through complicated and narrow terrain. In a variety of tests, the team of robots performed the tasks more quickly and efficiently than a singular system. However, this solution was limited, as the robots maintained power and communication via a 100-foot tether, limiting the travel range of the robot and risking possibilities of entanglement. Furthermore, the system architecture was only designed to support one child robot.

Following this research, for the AAAI 2002 Urban Search and Rescue Competition, Georgia Tech developed one of the first marsupial systems highlighting the advantages of multiple child robots. The system consisted of one ARTV-mini, a wheeled mobile robot, and four Sony Aibo Legged robots, as shown in Figure 3 [7]. The alternate mobility scheme of the child robots was proposed to allow greater navigational flexibility across both systems. The robots featured onboard batteries and wireless communication chips, and therefore did not need to be tethered. However, the dock to house the children was a flat aluminum plate that the Aibo robots had to precisely align and “sit” onto. This interface lacked self-alignment, stability, and recharging capabilities.

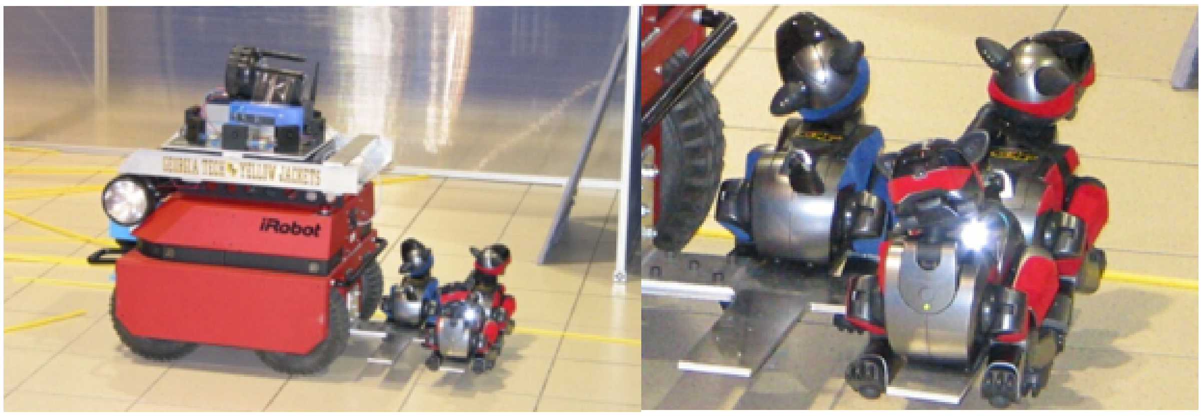

Figure 3: The Georgia Tech ARTV-mini and Sony Aibo marsupial system, demonstrating carrying capacity of multiple legged child robots. [7]

The SaddlePack system, proposed in 2007, is one of the first and only marsupial robots that can carry and deploy multiple children whilst providing charging capabilities upon retrieval. The system achieved a 90% rate of successfully detecting and docking [8]. However, based on available information, it was only designed and tested in controlled, flat environments. The SaddlePack system is shown in Figure 4 below.

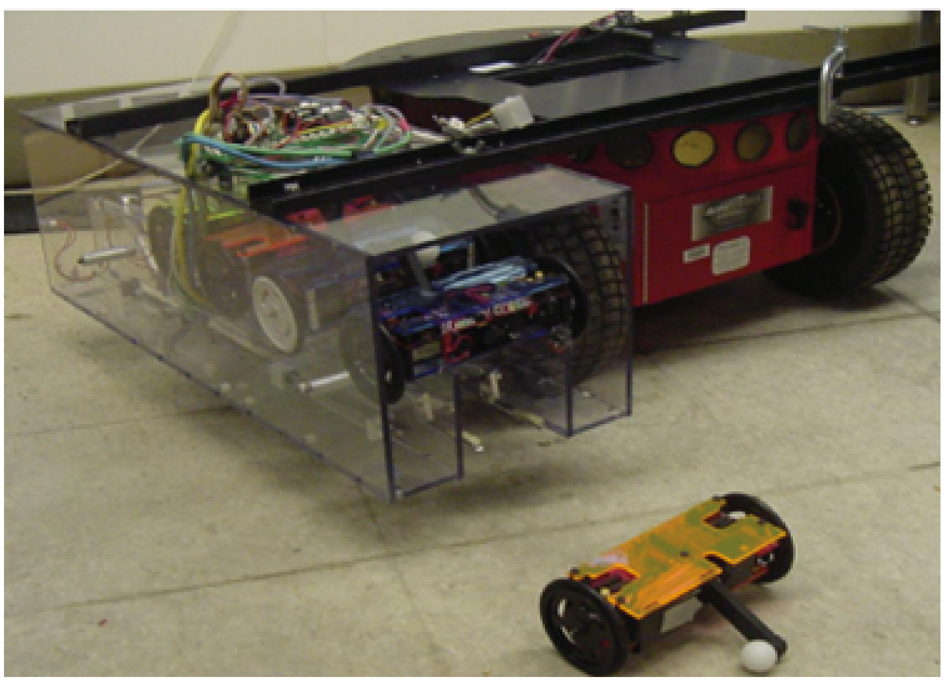

Figure 4: The SaddlePack marsupial robot, one of the first and only documented marsupial systems to include charging [9]

An analysis of these previous works, as well as several additional sources in later years, are synthesized in Table 1 below.

Table 1: **Existing Marsupial System Capabilities**

Name (Mother) (Child)	Year	# of child robots	Mobility (Mother) (Child)	Docking Mechanism	Charging Capabilities	Source
Silver Bullet Bujold	1999	1	Wheels Treads	Folding ramp	12V battery on mother robot tethered to child via 100-ft cable	[10]
ATRV-Mini Sony Aibo	2002	4	Wheels Legs	Legged clamp	None	[7]
SaddlePack	2007	6	Wheels Wheels	ACME screw and slider shuttle	Variable-force scissor pressing child to electrical contacts	[11]
TraxBot & eSwarBots	2013	5	Treads Wheels	Conveyor belt ramp	None	[12]
MACS RACS	2014	1	Tread/wheels Tread	Lifting platform	None	[9]

In the present day, marsupial robots remain a relatively unexplored field, with just 28 papers referencing the keyword in the IEEEXplore digital library as of June 2022. It is possible there are other multi-robot systems with similar capabilities that are not labeled with this name, which were therefore not discovered during the search.

2.1.3 Patents

Only one patent, US20170190048A1, has been issued for a marsupial robot system as of June 2022 [13]. Filed by ANTHROTRONIX Inc in 2015 and published in 2017, the patent has since been abandoned. This patent primarily focused on the concept of marsupial robots for distributed mapping of an environment, and how the data communication can be structured to encompass multiple "tiers" of robots. The primary benefit proposed by this infrastructure is an "increase in processing time and power" due to parallel task performance. It features a highly abstracted diagram, seen in Figure 5, and does not detail the mechanical means of achieving docking.

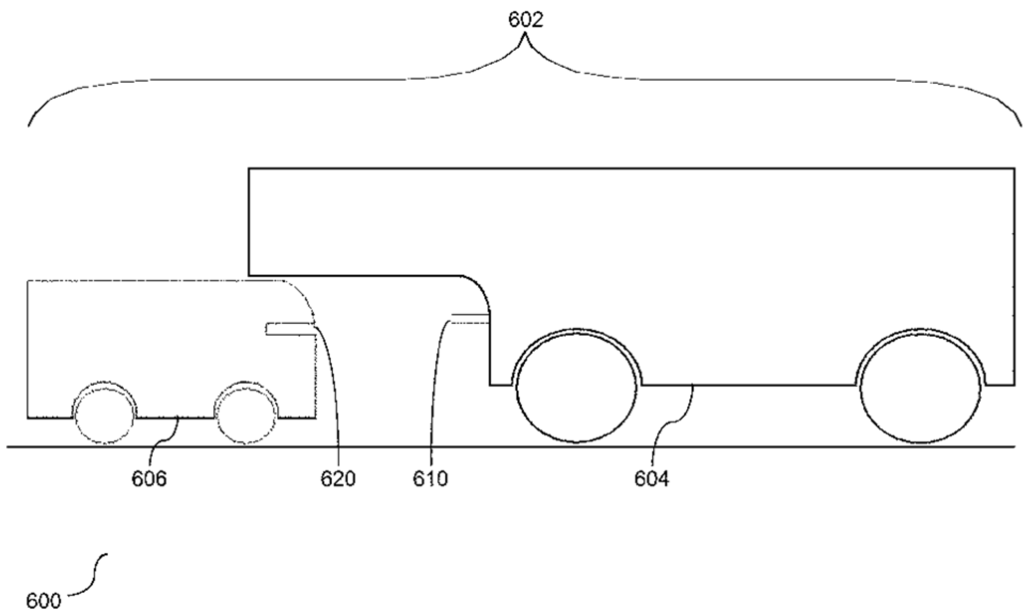

Figure 5: Patent US20170190048A1 – "Marsupial Robotic System" docking mechanism

2.1.4 Products

Marsupial robots are an emerging field still relegated to research laboratories, primarily Dr. Robin Murphy's Center for Robot-Assisted Search and Rescue at Texas A&M and Dr. Trung Dung Ngo's More-Than-One-Robotics Laboratory at the University of Prince Edward Island, Canada. Beyond these research-based laboratories, no known products exist on the market. The patent mentioned previously may indicate that there was some movement to commercialize a system, but it has since been abandoned.

2.1.5 Analysis

Marsupial robots may have limited laboratory research and no market presence thus far due to the inherent complexity required for multiple robotic systems to physically interact in unknown environments. Many marsupial robots focus on carrying the children onboard; however, Murphy notes that while this is a common implementation of the marsupial concept, it is not intrinsically necessary.

Previous marsupial robots have primarily been implemented in search-and-rescue disaster relief applications [14], [11], [15], [16]. Furthermore, other systems have been implemented for exploratory purposes, such as the DARPA Subterranean (SubT) challenge [17] and NASA's Axel Rover [18] . Predominantly, many systems have been designed without a specific application in mind, as the core architecture is still not refined.

Nearly all marsupial systems either lack charging capabilities or utilize a tether, limiting the lifespan or mobility of their systems, respectively. The only systems identified with charging capabilities were designed for flat laboratory environments. Based on this analysis, the team has found that the core technologies required to achieve a marsupial system (docking, charging, localization, and communication) are not yet mature enough to handle rigorous conditions. An enhanced docking interface to align two robots under a variety of environmental terrains may be highly beneficial in bringing these robots from the laboratory to the outside sphere.

2.2 Docking

The top priority of the proposed robotic architecture is to have a robust and reliable docking system which allows the children to mechanically mate with the mother robot over semi-rough terrain. As described, the defining feature of marsupial robotics is that one robot can sustain another or aid in the completion of its tasks, so the development of a docking mechanism for mother and child interaction is of utmost importance. Research was carried out exploring existing robotic docking systems, evaluating various docking controls and use cases .

2.2.1 Principles and Concepts

Robotic docking is a term to describe a procedure in which two electromechanical components are fixed with respect to one another. Such mechanisms are usually designed making use of a latching or interlocking component which physically prevents an object from moving in a certain way by making use of mechanical interference [19] [20]. Many everyday devices such as blenders, washing machines, and automobile ignition systems use mechanical interlocks to operate since, with careful design, they can be reliable for safety sensitive applications, require little maintenance, and can operate passively constrain a mechanical system. Figure 6 shows a typical deadbolt mechanism, an example of a common mechanical interlock [21].

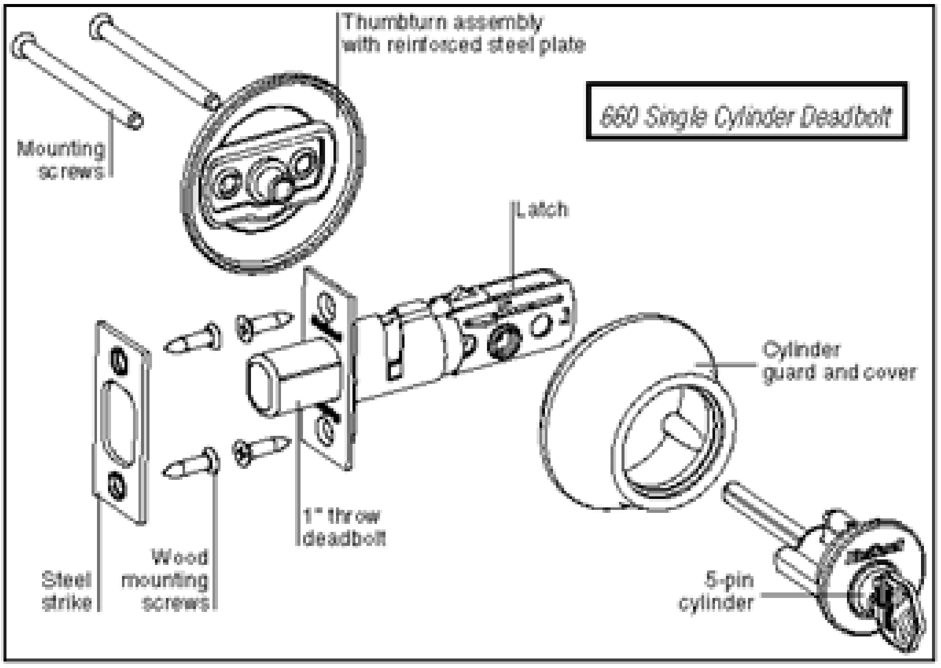

Figure 6: Diagram of a deadbolt mechanism. Lock shuttles deadbolt forward and backwards constraining a door from opening

While a docking mechanism can be quite simple, a robotic system needs to be designed to overcome positional errors that accumulate during nominal robot operation. Positional errors refer to the differences between the true position of a robot and where the robot thinks it is [22]. These build up due to mechanical issues with a robot, such as deformation of joints and mechanical backlash [23]. The goal of the research was to gain insight into existing robotic docking mechanisms as well as to gain a better understanding of different methods used to overcome positional errors for more reliable docking.

2.2.2 Literature

The problem of overcoming positional errors has been addressed by many research groups, either trying to mitigate errors using mechanical controls or software controls, and in some cases a combination of both. This section has been broken into two distinct fields of research: sensor-based controls and mechanically based controls.

2.2.3 Sensor Based Controls

Researchers at the National Chung Cheng University in Taiwan developed some of the first robotic docking systems with their autonomous security robot which tackled the problem of positional errors by tracking the intensity of light sources fixed on a stationary dock [24]. Ultimately the application of such a robot was limited due to the strong influence of surrounding light, however this paved the way for future software-based controls based on sensor feedback.

Another group, from Carnegie Mellon University, made use of a CCD camera and 3D landmarks with their robot "Sage" to ensure collision avoidance in the Carnegie Museum of Natural History and to facilitate docking and charging [25]. This system proved to be effective for long distance operation with 3D markers, but when docking at a close distance the accuracy was limited by the resolution of onboard sensors

Figure 7: 3D marker for Carnegie Sage robot

Researchers at Beijing University of Technology also took a purely data-driven route to overcome positional deficiencies making use of lidar sensors for positional feedback [26] . LIDAR is a method to measure distances based on the time it takes for a laser to be emitted and returned to a sensor. Their robot used LIDAR to scan a room to create a virtual point cloud, or a virtual representation of the environment around the robot. This was fed into a dock identification algorithm along with onboard odometer data to control the motors and tell the robot where to go. This lidar data feedback loop happened frequently enough to achieve positional errors of less than 2 cm in any direction and less than 3° off the expected docking position.

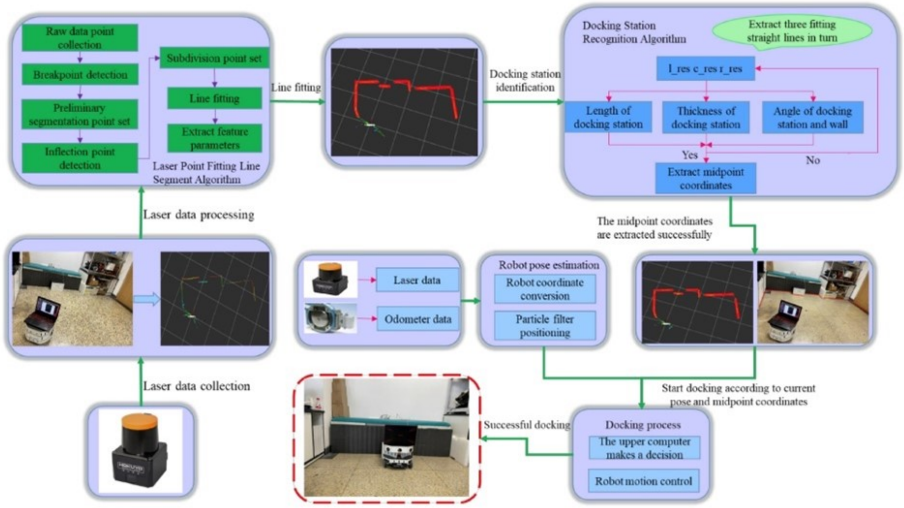

Figure 8: Overview of LIDAR autonomous docking scheme

2.2.4 Hardware Based Controls

While electronic controls can mitigate positional accuracy, there is always inherent uncertainty with any sensor, so it is important to design a physical docking interaction which allows for some amount of positional error.

A group from the Intelligent Robot Laboratory at the University of Tsukuba developed a robust mechanism for the swapping of service tools for mobile robots. This group focused on the mechanism design to mechanically couple the robot to different cleaning tools with a common mating interface [27] . Their mechanism was resistant to positional errors making use of a cam and arm system. The cam would be rotated until it contacted the "lock bar" and the arm utilized lead ins to capture and constrain the components in multiple directions. Additionally, they achieved a very robust interface utilizing worm gears which cannot be back driven.

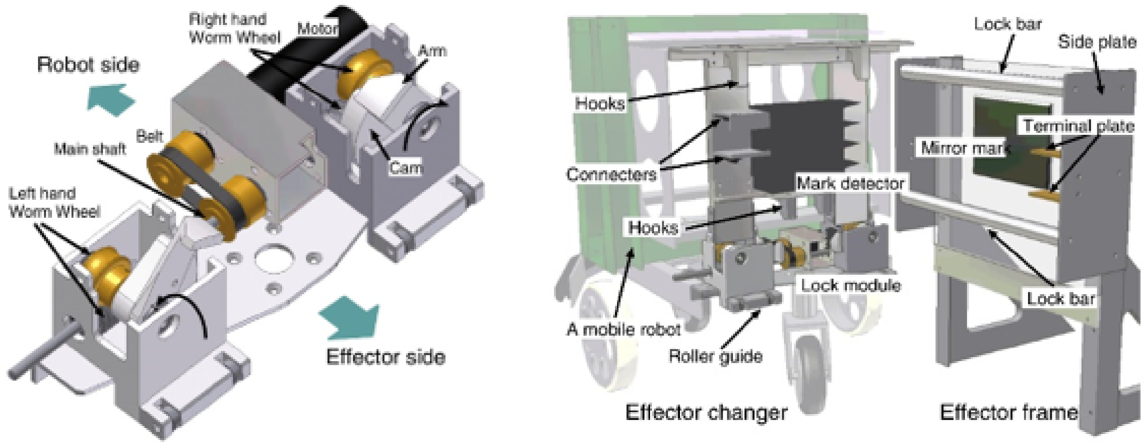

Figure 9: Diagrams of Docking Mechanism

Wu, Teng, and Tsai developed a service robot which would automatically dock to exchange a battery to ensure little to no downtime of the robot. Their system utilized a magnetic guide strip for rough alignment of the robot, but their dock was designed adapt to positional errors; their dock was fixed to an oscillating bar, so when the robot encountered it, the entire dock pivoted to align with the robot. The dock then actuated simple grabbing arms to engage with the robot to complete a battery exchange [28].

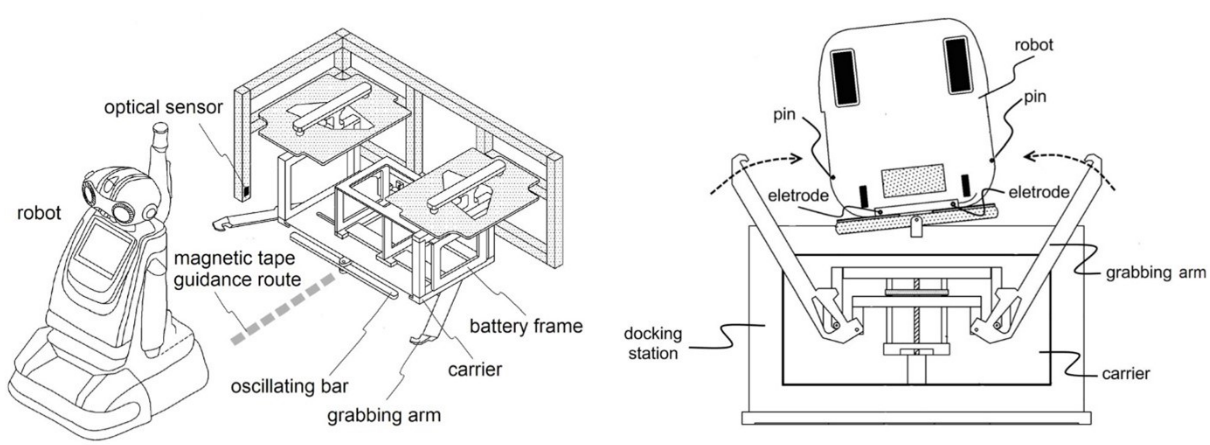

Figure 10: Oscillating robot dock to overcome positional tolerances

2.2.5 Products and Patents

One of the biggest applications of mechanical docking is in the field of service robotics. The Shark RV1000S robot vacuum and the iRobot Roomba are two household examples of robot docking [29]. These robot vacuums typically (with exceptions of high-end robot

docks) utilize their dock mainly for recharging, and accordingly, are not particularly sensitive to positional errors nor do they require a robust docking scheme. These robots simply drive up to a contact pad and charge. With multiple competing products on the market for docking robots, patents exist related to the technology. European patent EP2273336B1 from 2004 and United States patent US8352114B2 from 2011 offer very similar ideas for docking of mobile robots for recharging and are shown in Figure 11 below [30] [31]. Each patent discusses the method of navigating to the dock, but each utilizes passive contact pads leaving full freedom to innovate with the docking mechanism itself
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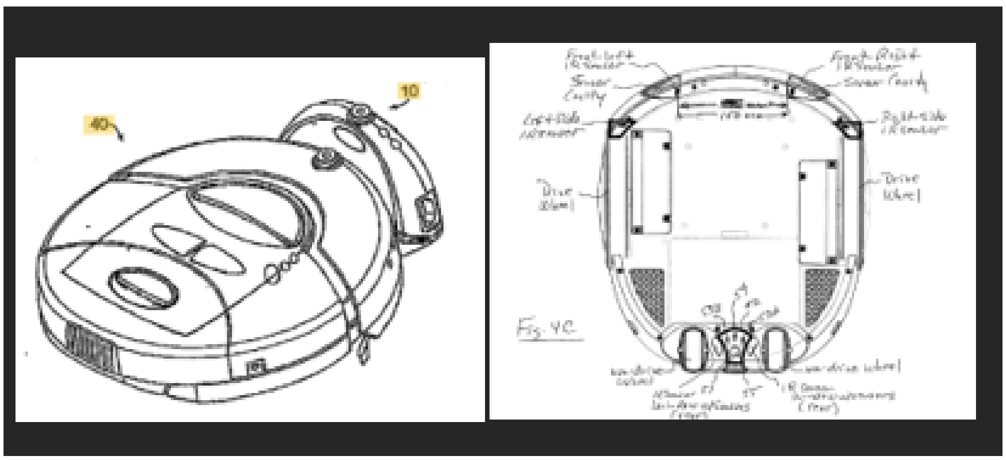

Figure 11: (Left) Docking mobile robot presented in EB2273336B1 [30]. (Right) Docking mobile robot presented in US8352114B2 [31]

Other patents exist such as US6969030B1 and US10953999B2 which are more concerned about physical docking methods, but each is related to a very specific application (space docking and aerial docking) [32] [33]. These patents can be used as an additional source of design inspiration, but they are not directly applicable to our small-scale robotic system.

2.2.6 Summary

Robotic docking is a very complex problem which becomes more complex with a mobile docking hub, however based on the review of literature, there are many avenues that can be taken to overcome relevant design challenges. Positional error is one of the most critical aspects in the docking mechanism design; the system needs to be resistant to positional errors making use of software and sensor-based controls, yet the mechanical aspect needs to be compliant enough to overcome any remaining misalignments. Determining the degree of positional accuracy achievable with sensor-based controls will have a significant impact on how compliant the mechanical controls must be. Additionally, docking robots have mainly been implemented indoors for service applications and thus are not required to have significant constraints on the reliability and strength of their connections. There is an opportunity to innovate in the field of mobile docking robotics by expanding their use cases to outside the home with development of more robust mechanical constraints and positional error controls.

2.3 Recharging

The primary function of the docking mechanism is to charge the child robots. Charging involves transferring energy from a power supply through a connector to a battery. Research was carried out exploring existing charging systems.

2.3.1 Principles and Concepts

There are three main technologies for how electrical devices are charged. The most common method is wired or plug-in charging as seen with charging phones, laptops, or an electric vehicle. The second type consists of battery swapping, such as replacing batteries in a TV remote. The least common type is inductive charging or wireless charging, used for charging cellphones and small devices. In wired charging a power supply is plugged into a device and facilities an electron flow which charges the device. In wireless charging the receiving device has a receiver induction coil made of copper and the charging station has a copper transmitter cable. When the two are placed next to each other, a current flows through the transmitter coil to generate an electromagnetic field which the receiver converts to electricity [34] . Wireless charging tends to not be as efficient as wired charging and requires more time to charge the same device than its counterpart. Battery swap tends to be the most expensive option as it depends on the battery's cost.

Figure 12: (Left) Wired Charging. (Middle) Wireless Charging. (Right) Battery Swapping

2.3.2 Literature

One of the primitive solutions to charging robots is to use a charging cord tether that connects a robot to a power supply. This limits the range of motion of a robot to a circle with a diameter as long as the charging cord. Moreover, the cord could become tangled as the robot moves, generating navigational obstacles. These limitations prompted researchers from Vrije Universiteit Brussel Belgium in 1997 to build and test autonomous recharging of mobile robots.

Figure 13 shows the charging station for this study, which included "a regulated power supply connected to a rectangular metal plate on the floor and a round metal plate mounted horizontally above" [35] . Each robot had three active infrared sensors, two white-light sensors, and two modulated light sensors to assist with navigation and alignment with the charging plates. They additionally were able to measure the internal voltage and current of their system for charging. The robots were equipped with antennas to contact the metal plates of the charging station and charge the robots and is classified as wireless charging This study emphasized the value of sensing and measuring the current and voltage during the charging process as well as proved the viability of charging via contact between conductors.

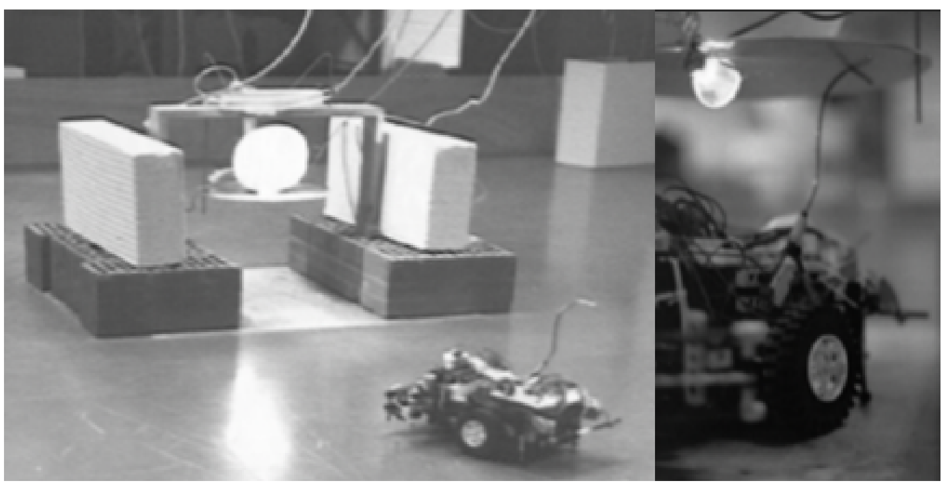

Figure 13: (Left) Charging Station. (Right) Robot Contacting Charging Station [35]

One scholarly article evaluates the differences between battery swapping, plug-in, and wireless charging. The performance estimation models concluded that "throughput time performance can be significantly affected by the battery recovery policy, that inductive charging performs best, and that battery swapping outperforms plug-in charging, charging by as large as 4.88%, in terms of retrieval transaction throughput time" [36] . The study focuses on robotic mobile fulfillment systems (RMFS) and use the divide and conquer approach that marsupial robotics use but instead are used primarily for warehouse applications.

2.3.3 Patents

One patent for a plug-in charging technology is United States patent US8718856B2 granted in 2014 created by Kevin Walter Leary at PowerHydrant LLC [37] . The technology is a stationary robot that aligns with a robot arm and docking interface to charge an electric vehicle.

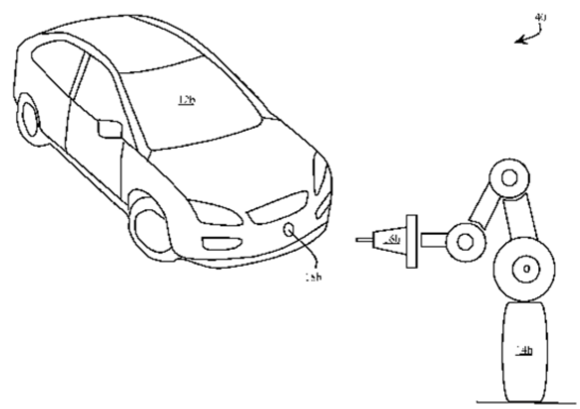

FIG. 2

Figure 14: Plug-in Charging[37]

One patent for a battery swapping technology is United States patent US20170259675A1 granted in 2019 is a stationary system that replaces car batteries created by Tesla Inc [38] . This includes a vehicle lift and a secondary battery lift that aligns with the vehicle's old battery and replaces it with a new one, shown in Figure 15.

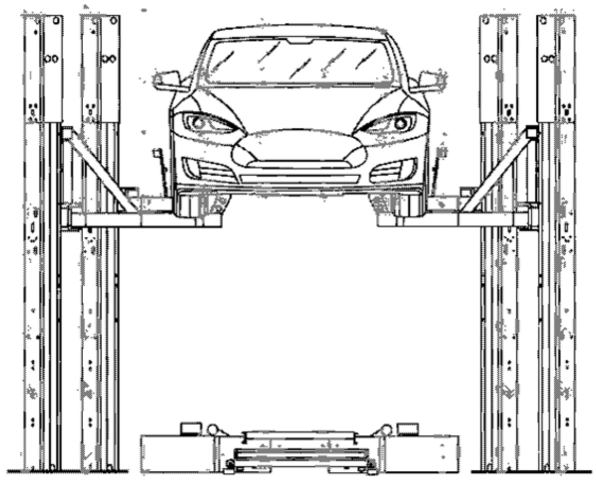

FIG. 21

Figure 15: Battery Swap [38]

One patent for inductive charging technology is Germany patent DE102020201187A1 filed in 2020 and currently pending is a stationary robot that aligns its end effector/inductive charging surface with the underside of a vehicle battery created by Volkswagen AG [39] .

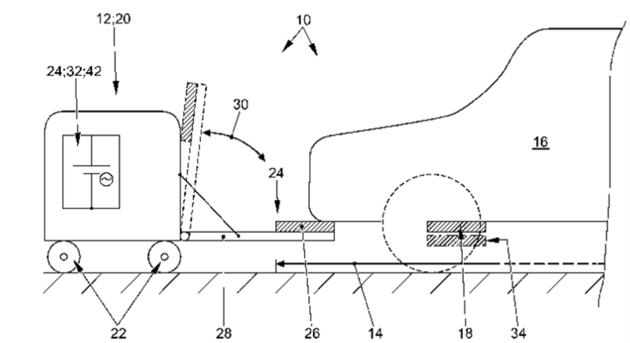

FIG. 1

Figure 16: Wireless Charging [39]

2.3.4 Products

When it comes to robotic charging, a common application is in the field of mobile service robotics. The Shark RV1000S robot vacuum and the iRobot Roomba are two examples of robot charging mechanisms that couple with docking [39] . These robots utilize their dock for recharging in the form of inductive charging by driving up to a contact pad and charging. These robots can also charge separately from the dock by having the owner plug them in to a power supply via plug-in charging like charging a phone. Figure

17 shows in green the contact points on both the docking station and the bottom of the Roomba. One of the limitations of these products is that they are designed for and operate in controlled environments on flat surfaces and indoors. The docking system can also only charge one Roomba at a time with no easy scalability because each household only needs one Roomba.

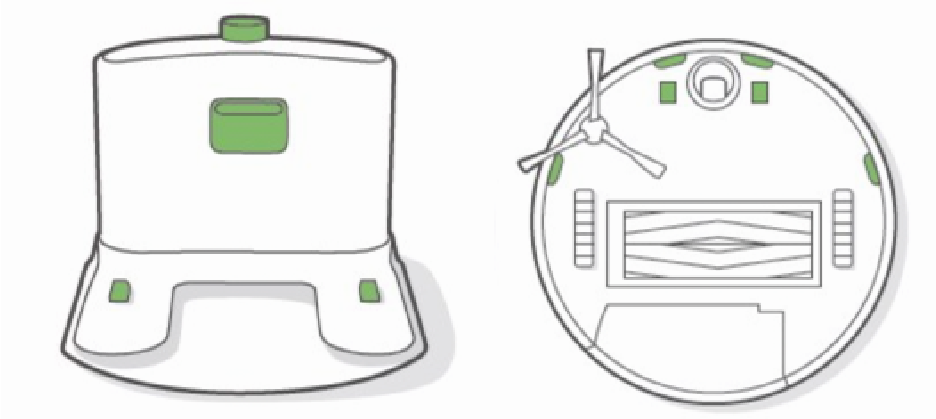

Figure 17: (Left) Docking Station. (Right) Roomba Contact Points

2.3.5 Summary

Robotic charging is an important problem to address since it is the biggest limitation for mobile robotics due to how long robots can last on a single charge. Based on literature and patent reviews there are several different directions that can be taken to implement a charging system. Most instances incorporate the charging and docking system together while others utilize an additional device to charge the robots. The three types of charging were battery swapping, plug-in and wireless charging with wireless charging being the most common in the field of robotics due to its versatility. Although wireless charging is the least efficient, it is commonly used for robots due to key advantages over the other methods. Plug-in methods introduce a charging cable that limits robot mobility. Battery swapping is more costly and complex, as it requires an additional mechanical system to execute the battery exchange. Wireless charging can function well with minimal alignment accuracy, whereas both plug-in and battery swap methods must be precisely aligned to function. As this project aims to enable charging for mobile children robots designed for long-range environmental survey, wireless or contact charging seems to be the most suitable charging option.

2.4 Item Interaction

One secondary goal for the mother and child architecture is that the children may eventually be able to interact physically with the environment in some way and exchange material goods to and from the mother when docked. To guide the design process for this interaction, research was done into what methods already exist for a robot to interact physically with its environment.

2.4.1 Standards

The first area of research was existing standards in the field of robotics. Robots interact with the environment using a mechatronic device called a manipulator [40]. A manipulator, also commonly called a robotic arm, consists of links and joints. The number of joints increases the degree of freedom of movement, increasing the range of motion for the manipulator. Joints allow restricted relative movement that may be planar or rotational [40]. At the end of the manipulator is a device called the end effector, which enables the robot to interact physically with the environment. End effectors are designed to allow the robot to carry out a specific task, and may include mechanical, magnetic, or pneumatic grippers, sensors, or tools for industrial applications [41]. In Figure 18 below showing an example of a robotic manipulator, link 6 acts as the end effector.

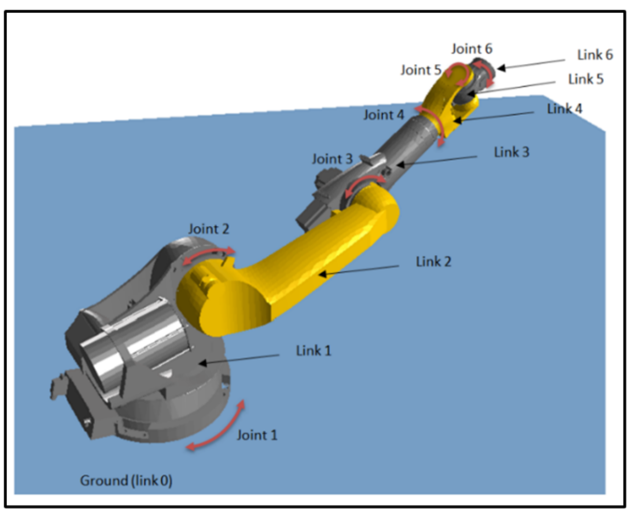

Figure 18: Example of Robotic Manipulator with Labelled Joints and Links

To move freely in 3D space, manipulators must have at least 6 degrees of freedom [42]. The goal of a manipulator is to carefully control the position of the end effector in space to carry out a specific task. To determine the position of the end effector in space, vector kinematics is utilized. Overall, research into the standards revealed that the primary method for robots to interact physically with the environment is using a manipulator, or robot arm, equipped with an end effector which caters to a specific application.

2.4.2 Principles and Concepts

To better understand how robotic manipulators are implemented, research was conducted into the principles behind vector kinematics and degrees of freedom. The degree of freedom of movement for a manipulator can be described by Equation 1:

$$n_{dof} = \lambda\,(1 - n) - \sum_{i=1}^{k} (\lambda - f_i) \tag{1}$$

Where n is the number of links, λ is 3 for planar mechanisms and 6 for spatial mechanisms, k is the number of joints, and f_i is the number of degrees of freedom for the i_{th} joint.

The position of the end effector in 3D space can be described by an array with the position projected onto the x, y, and z axes. The orientation of the end effector or any object in space can be modelled using the rotation matrix. This matrix describes the orientation of an object using the dot product of its frame of reference axes against those of a second, known frame of reference. Figure 19 describes the rotation matrix for an object in Frame B by comparing it to Frame A [40].

$$R_{AB} = \begin{bmatrix} \widehat{x}_B \cdot \widehat{x}_A & \widehat{y}_B \cdot \widehat{x}_A & \widehat{z}_B \cdot \widehat{x}_A \\ \widehat{x}_B \cdot \widehat{y}_A & \widehat{y}_B \cdot \widehat{y}_A & \widehat{z}_B \cdot \widehat{y}_A \\ \widehat{x}_B \cdot \widehat{z}_A & \widehat{y}_B \cdot \widehat{z}_A & \widehat{z}_B \cdot \widehat{z}_A \end{bmatrix} = \begin{bmatrix} \widehat{x}_{AB} & \widehat{y}_{AB} & \widehat{z}_{AB} \end{bmatrix}$$

Figure 19: Rotation Matrix to Describe Orientation of Object in 3D Space

Figure 20 below shows how the rotation matrix manifests in cartesian space.

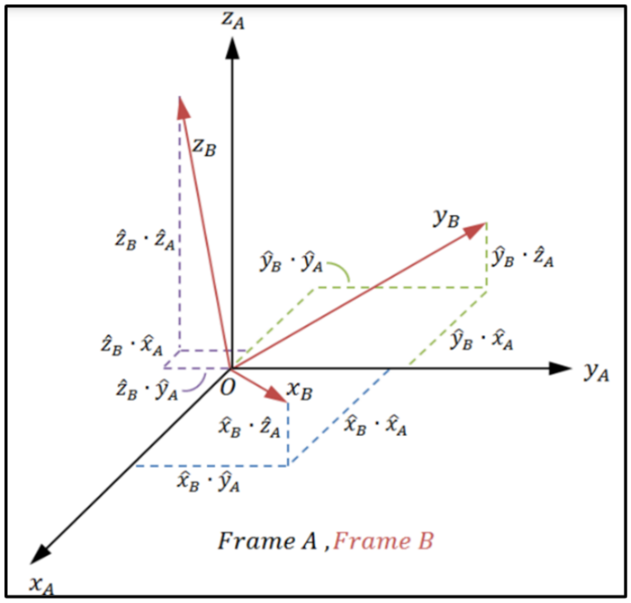

Figure 20: Rotation Matrix in 3D Space

Using the fundamentals of vector kinematics, inverse kinematics is often used to position the end effector. Inverse kinematics is a method for determining what position all the links and joints of the manipulator must be for the end effector to result in a desired, known position [43]. There may be multiple solutions, no solutions, or infinite solutions to inverse kinematic problems. Depending on the joints used in the manipulator, there will be movement restrictions and constraints that would be accounted for in an inverse kinematic approach [43]. Overall, the principles of vector kinematics drive inverse kinematics and allow the robotic manipulator to be controlled and the end effector positioned to accomplish specific tasks.

From this research, it was determined that the primary way to interact with the environment in a complex manner is to utilize a robotic manipulator. Inverse kinematics would be implemented in the software to control the manipulator. Manipulators enable an end effector to be positioned precisely in 3D space to accomplish specific tasks. A manipulator may offer more complexity and range than this project demands but understanding how these systems function and could be redesigned to fit the needs of the mother and child architecture provides a valuable foundation for future development.

2.4.3 Literature

While the mechanisms and control systems for robotic manipulators are fundamentally well-understood, ongoing research in the field of robotics delves deeper into how manipulators may interact with each other for item handoffs.

One challenge studied in literature is the ability to exchange items between two robots or between a human and a robot. A 2020 literature review explores the challenges and existing solutions for object handovers in robotics between a human and a robot [44]. The object exchange can be broken into two overarching phases that each pose their own series of challenges. First is the pre-handover phase, which requires communication, grasp planning, perception, handover location, and finally motion planning and control. Next is the physical handover phase. Here, key challenges are grip force modulation and adjustments for errors in handling. Throughout the interaction, the giver and receiver of the object exchange have unique responsibilities, as summarized by Figure 21.

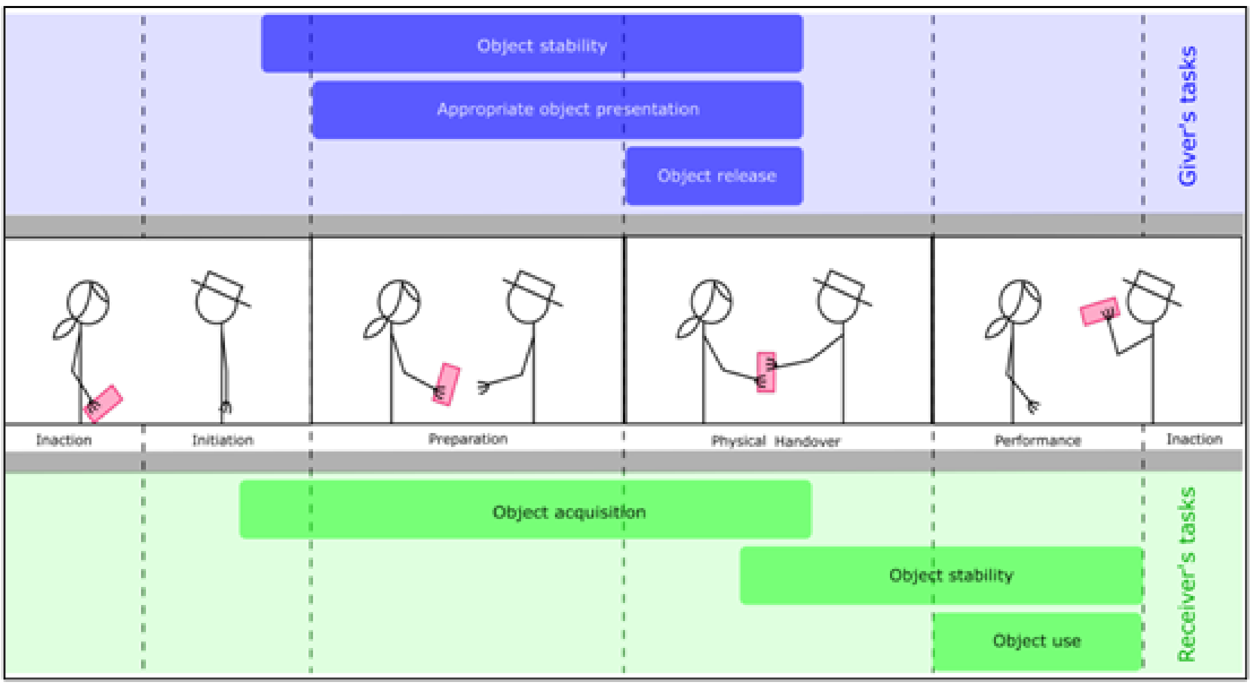

Figure 21: Breakdown of Responsibilities and Stages of an Object Exchange

Throughout the process of object handover, the robot must understand which stage of the exchange it is in and adjust accordingly to respond to the human receiver [44]. This study offers a valuable overview of the challenges of item exchange that must be addressed by a robotic manipulator.

A 2021 study by Costanzo *et al* proposed explored the algorithms that guide human-robot and robot-robot item exchanges and verified the feasibility of object handoff between two robotic manipulators via successful testing. Manipulators with 2-pronged mechanical grippers were tasked with handing off and receiving a simple rectangular object. The robots used a combination of visual and haptic sensors to identify the position of the object being held. Algorithms guided the robot motion and grip force to allow safe item exchange [45]. This study verified the ability of two manipulators to effectively exchange an object using visual and tactile information. The takeaway emphasized by the study was the importance of haptic sensors on the robots, as tactile information allows the robots to adjust grip force as the object is exchanged [45]. Figure 22 shows the manipulators exchanging the item in a successful test.

Figure 22: Two Manipulators Exchange a Rectangular Object

A 2018 study of human-to-robot handovers demonstrated the efficacy of an electromagnetic end effector for item handover [11]. While the contents of the study emphasized the psychological and physical reactions by the human giver during the interaction, this manipulator demonstrates the efficacy of an electromagnetic end effector for item exchanges.

Literature into item exchange using robotic manipulators reveals key benefits and possible limitations. The studied robotic manipulators have full range of mobility in 3D space, and therefore require complex algorithms to control the end effector position where the object handover takes place. Moreover, the literature emphasizes handoffs between gripper-type end effectors. Gripper-to-gripper handoffs involve a series of exchanges that require visual and tactile information for successful object exchange [44] [45]. For these reasons, a simpler approach to item exchange may be more suited to the mother and child architecture.

2.4.4 Products

To explore a wider range of existing methods for item handling in the field of robotics, existing products including and beyond robotic manipulators were explored.

As technology behind robotic manipulators has become cheaper and more accessible, there are a wide variety of robot arms that can be purchased for hobbyists or industrial applications. One robotic arm product that could be modified to fit the mother and child architecture is LewanSole xArm 1S Programming Desktop Robotic Arm [46]. This device has a two-fingered gripper, six degrees of freedom to enable full mobility in 3D space, is programmable through company software, and costs about $200. An image of the product is shown by Figure 23. It should be noted that there are many similar models of small, low-cost, programmable robotic arms that may be modified to handle objects for the children or mother robot.

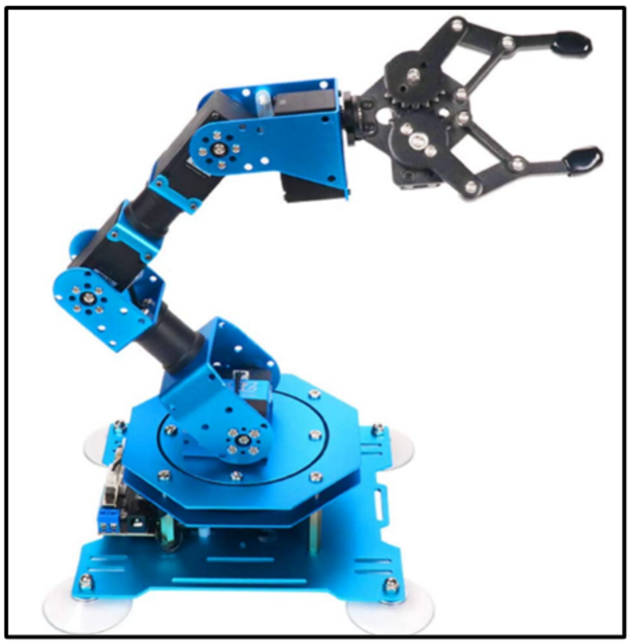

Figure 23: LewanSole xArm 1S Programming Desktop Robotic Arm

Other products for item handling were explored that do not follow the standard manipulator technology. The Shark RV1000S robot vacuum offers a solution for exchanging granular material objects between two interfaces [47] . When docked to the stationary charging port, a vacuum in the port sucks up granular material stored in the mobile robot. This method for exchanging granular material across an interface could prove valuable for applications involving sand, soil, or other granular materials. Figure 24 shows the mechanism behind this granular material exchange.

Figure 24: Shark Robot Vacuum Exchanging Granular Material with Vacuum Interface

An industrial example of material exchange and interaction are the Automated Material Handling Systems (AMHS), such as those developed by companies such as SYSTEMA or Rockwell Automation [48] [49] . These systems use simple mechanical motions to easily exchange materials between a mobile system to a stationary receptacle. Materials are picked up using basic mechanisms that may have mobility in only one axis. These systems often incorporate industrial standards such as box lifts, conveyor belts, and lifting devices [50]. Figure 25 displays several types of industrial material handling systems.

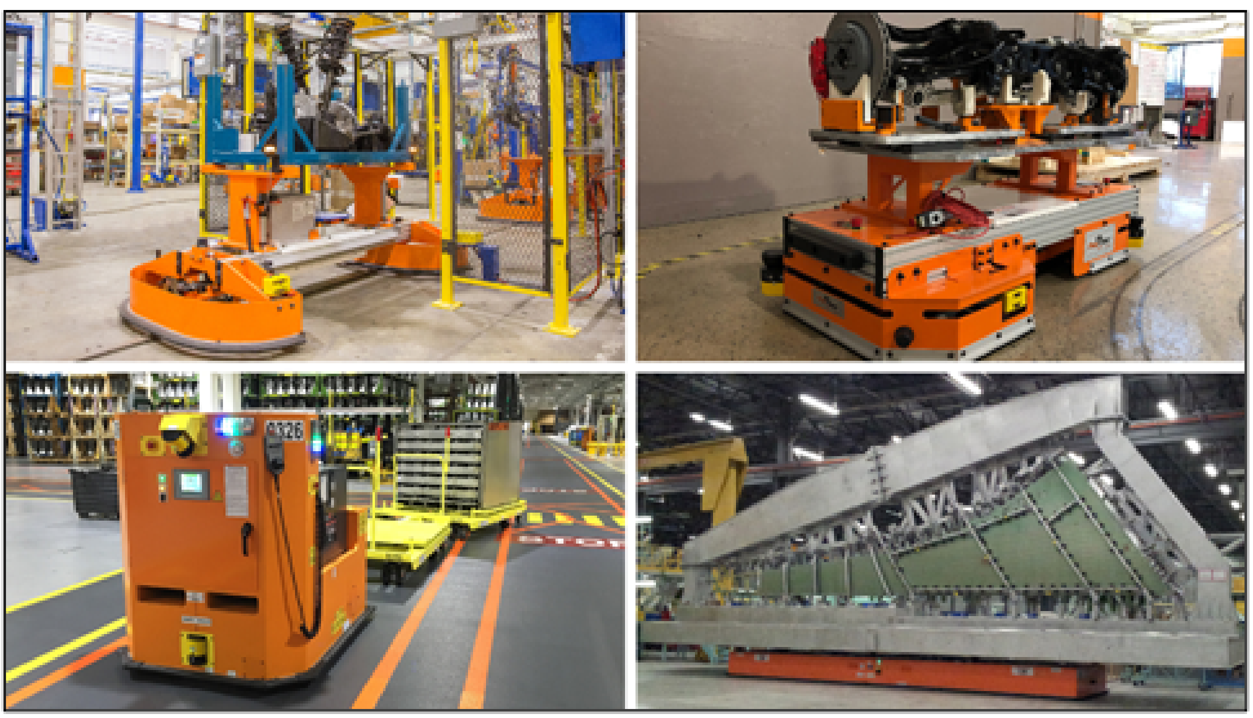

Figure 25: Some Industrial Automated Material Handling Systems

The driving principles and methods employed by industrial material handling systems could be downsized for application on the mother and child architecture to perform simple material movement and transfer.

2.4.5 Summary

While not a primary objective, a secondary goal for the mother and child architecture is to exchange a material object or interact physically with the environment. From this research, it was determined that the primary way to interact with the environment in a complex manner is to utilize a robotic manipulator. Inverse kinematics would be implemented in the software in order to control the manipulator. A wide variety of tasks could be accomplished using this system. However, a manipulator may offer more complexity and ability than this project demands. If granular materials are used, a vacuum method could be employed. Alternatively, industrial autonomous material handling systems provide various templates for simpler mechanisms that can move and exchange items that may be more prudent for the scope of this project. Overall, understanding how these systems function and could be redesigned to fit the needs of the mother and child architecture provides a valuable foundation for future development.

3 Discussion and Conclusions

The research done thus far for existing solutions in the field of marsupial robotics has uncovered many areas for potential areas for potential improvement. As such, it was critical to narrow the scope to a proof-of-concept of these individual mechanisms, rather than on a specific and limiting field application. This has come with its own set of challenges, such as choosing the specifications of each of these elements to begin basic designs, as well as pinpointing a specific goal or benchmark system to effectively solidify the project scope. Aspects such as the dimensions and weight of a prospective “sample” payload also lie at the heart of any subsequent design decisions for the mother and child robot. Given these restraints and the limitations of the time and budget afforded during the capstone program, the research outlined above was used to narrow in on one problem at a time within the field of marsupial robotics. For this project, that starts with proving the capacity for off-road, mechanically guided docking and charging to increase the operation life of children robots on a mission.

With this first goal in mind, the synthesized understanding of research done in the fields of docking and recharging (as addressed above) is some of the most valuable information necessary for iteration one of this project. In particular, it will be important to consider the challenges associated with current docking systems which do not account for uneven terrain. The patents mentioned above were helpful examples of existing mechanical solutions which were still capable of being improved upon, for example the European patent EP2273336B1 and US patent US8352114B2. However, since few current products are designed to handle uncontrolled environments, it was left unclear from the research how a variation in terrain could affect the repeatability of the docking mechanism. This is a gap in the team’s knowledge which will be filled with a combination of continued research in this field as well as the learning curve introduced by testing the team’s solution to this problem.

This research review focused upon research that would assist with mechanical design of the mother and children robots, with an emphasis upon docking and charging mechanisms. These areas of research were a necessary foundation to begin the design process for this project. However, future research and analysis must also be considered for the charging and electronic aspects of this solution. For example, there are environmental conditions such as dust or debris can impact the success of an electronic connection by impeding connectors or compromising current flow. It is also possible to form unwanted circuit connections via these impedances, which may lead to short-circuits and system failure. Unlike the problem of docking, there are extensive examples and attempts at researching this issue across fields where dust and unwanted material is present. However, an outstanding issue remains once again of the impact that the layout of the terrain itself will have on the repeatability of an electronic connection.

The research outlined above is only the beginning of the background information necessary to begin a design or prototype. However, it provides a foundation upon which to build the team's ideas and begin bridging these milestones. Some recommended steps moving forward from this point are to continue the brainstorming process using these points as a guide to determine their feasibility. For those solutions which come closest to solving the problem statement the team has outlined, it will be helpful to delve further into how they were developed or, if possible, observe them in use in-person to get a better understanding of those aspects which can be applied to this project. Lastly, in terms of the iterative process, the team has agreed on a roadmap where sub-systems of the solution would be developed to meet the bare minimum goals of its role on the robots, followed by an outline of design goal testing which will prove whether the system can hold up to repeated use.

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