Design of Multifunctional Paired Robots Engaged Across a Thin Plate
for Aircraft Manufacturing and Maintenance

by
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B.S., Mechanical Engineering, Worcester Polytechnic Institute, 2009

Submitted to the Department of Mechanical Engineering in partial fulfillment of the
requirements for the degree of

Master of Science in Mechanical Engineering

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September 2011

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ABSTRACT

The aircraft industry lacks an automated system for wing box manufacturing and maintenance. Currently workers assemble and inspect thousands of fasteners in the wing structure by hand. This manufacturing process consumes valuable time and resources. Mobile robots capable of navigating on the interior and exterior of the wing have the potential to perform the wing structure manufacturing tasks. This thesis describes the design, analysis, and implementation of paired robots engaged across a thin plate. Two robots, each capable of carrying an end effector, are engaged using strong magnets attracting each other and thereby supporting each body against gravity. The robots must move across the surface of the box, while avoiding interference with obstacles fixed to the surface. The multifunctional paired robots navigate the surface with three different operations. The paired robots are automatically loaded and unloaded from the confined box through a small entry hole using the “Flipping” operation. The “Drive and Slide” operation is used on horizontal surfaces. The robots “Step” over obstacles while securely holding each body against gravity. Parametric models of the robots are developed, and the conditions for the successful multifunctional operations are analyzed. The two primary failure modes are tipping of the robots on either side of the thin panel. An optimal trajectory that minimizes the peak tipping moments, while also minimizing how close the robots are to failure is designed to meet the many challenges of the stepping operation. The trajectory ensures that the failure modes are avoided during the disengagement of the strong permanent magnets in the stepping operation. The position trajectories are parameterized using cubic splines with the bounds being the start and end robot configurations. Prototype paired robots are constructed and experimentally tested. The prototype robots performed their multifunctional operation modes on a mock wing structure, validating the design and analysis.

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ACKNOWLEDGEMENTS

I thank my high school teacher Mr. Crowley for encouraging me to become a mechanical engineer. His physics classes and lab experiments inspired me. I considered my work in his classes the beginning of my engineering education.

I would like to thank my graduate studies advisor, Professor Asada. His energy and enthusiasm for engineering are incredible. He continually pushed me to do the best I was capable of. His guidance throughout the past two years has significantly improved my theoretical and analytical skills.

I thank the Boeing Company for their financial support of this project. The freedom they have given has made the project very interesting and enjoyable.

This thesis could not have been completed without help from many of the members of the d’Arbeloff Laboratory. I thank Patrick Barragán for all of the help over the past two years in many areas of the project. I thank Sang Ok Seok for his LabVIEW training, without such an excellent teacher I could not have implemented my design so quickly. I thank Anirban Mazumdar for his LabVIEW and general controls help. I thank James Torres for his help trouble shooting the robots, and analytical help designing trajectories. I need to also thank my undergraduate students for their contribution to the project: Grant Kadokura, and E.J. Hester.

I thank Rick Cullen for volunteering to help me prepare for a demo by constructing a test platform. He is a great fabricator.

I thank Manas Menon for mentoring me and helping me while I was transitioning in graduate school.

I must thank my girlfriend, Amy Kohler, for her support throughout the graduate program. She is the most caring and supportive person in my life.

My family made it possible for me accomplish to everything I have done. My parents taught me you can do whatever you want if you put your mind to it. My parents are my inspiration. I cannot thank them enough for everything they have done. I thank my Dad for supporting me, and sending me hundreds of meals during my college and graduate education. I thank my Mom for doing everything within her power to help me every chance she got.
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1. **INTRODUCTION**

1.1. **MOTIVATION**

The motivation for the work done in this thesis is to aid the development of a flexible aircraft manufacturing system. The current aircraft manufacturing practice utilizes many fixed based gantries, cranes and scaffolds. Construction of factories takes months of planning and many more for construction. The current manufacturing structure works well for constructing a large number of a single style of aircraft, but the global demand for aircrafts fluctuates greatly [11], and the current system is not easily scalable for times of growth or recession, nor adaptable for different styles of aircraft. Aircraft manufacturing could adapt to the changing market more rapidly by using mobile robots that can perform some of the manufacturing tasks. The mobile robots could be outfitted with various types of tooling for different types of aircraft and manufacturing operations. The new factory could easily adapt to demand fluctuations by scaling the number of robots deployed to match demand.

Another compelling reason to develop a new aircraft manufacturing system is to take workers out of hazardous and ergonomically challenging environments that are common in the current aircraft industry. Currently many manufacturing operations are repetitive and often in difficult to access spaces. Such conditions can cause repetitive stress injuries and therefore are detrimental to the worker’s health [22]. Robots that are capable of accessing difficult areas and working in environments dangerous to humans would benefit aircraft industry employees.

We envision a future factory that utilizes a larger number of mobile robots that will solve the issue of the current inflexibility in the aircraft manufacturing industry, as well as improving the productivity and environment for the workers. The future factory would base the aircraft
manufacturing process on mobile robots that are able to quickly be deployed when production
needs to be scaled up and scaled back when demand slows. Ideally the future factory would not
require complicated scaffolding and fixed based gantries that take months of planning and time
to construct. Instead, the factory could spring up in any space large enough to construct an
aircraft. The particular area of manufacturing that this thesis will address is the fastener
installation process within the aircraft wing box.

1.2. **Fastener Installation**

Fastener installation in aircraft wing box assembly is one of the critical manufacturing
processes performed largely by manual labor. Fasteners are pieces of hardware used to join two
or more components such as sheet metal or flanges. There are several hundred thousand fasteners
on common aircraft wings.

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1 Much of this section has been slightly modified from a similar section in [6].
Proper installation of these fasteners is a two-sided operation, a diagram of which is shown in Fig. 1. To maintain structural integrity, the process of installing the fastener must be performed while firmly clamping the parts as shown in A. On one side a hole is drilled, deburred (B), and the fastener inserted (C). The hardware is braced against the drill on the opposite side, and a nut or sleeve is attached to the inserted fastener (D). Finally the sleeve is crimped, or the nut tightened (E) and the excess material is removed (F). A less simplistic wing box is shown in Fig. 2. The two end effectors in Fig. 2b, one inside and the other outside the wing box, must therefore work together in aligning and engaging both sides of end effectors.
1.3. PRIOR WORK

Automation of this fastener installation is desired not only for increasing productivity but also for reducing injuries since it is an ergonomically challenging task. Several prior works attempted to use robotic devices for the wing box assembly. The snake-like robots developed at MIT [16],[17],[18],[19] as well as at CMU [23],[4] were designed to eliminate manual labor within a wing box, as it is difficult for workers to enter the wing box through a small access hole and lie flat inside the wing box. These snake robots are effective platforms for transporting an end effector into the confined wing box through an access hole. However, the fastener installation cannot be completed with the snake robots alone. The process requires another robot.
or transport system that carries the outside end effector, attaches it to the wing box, and aligns it precisely with the inside end effector at a desired location.

Asada and Menon proposed an effective approach to robotic wing box assembly [12]. Unlike the paired robots proposed by Sato et al in [20], the new design concept exploits the paired nature of the end effectors. Two robots – one carrying the inner end effector and the other carrying the outer end effector – work together to support themselves against gravity and move along the fastener installation lines, as shown in Fig. 2c. Using strong magnets the paired robots attract each other across a thin panel, called a skin panel, and generate traction forces on the skin panel to move around. This self-supporting, paired mobile robot system can reduce needs for scaffolding and fixtures, as well as perform the manufacturing operations by directly engaging the inside and outside end effectors.

The paired robots capable of driving in the wing box developed in [12] are shown in Fig. 3. The inner robot is shown on the left, and the outer robot on the right. This figure was taken from reference [12].

![Image of robot system](image.jpg)

Fig. 3: Pair robot system developed by M. Menon and H. Asada.
In [12] the design and components of the inner and outer robot are thoroughly detailed. This work had important design aspects that will serve as the starting point for the next generation paired robotic system.

- The paired robotic system in [12] utilizes permanent magnets to perform two primary functions. First, the magnets provide the force to support the outer robot against gravity. Second the magnet pairs on the inner and outer robot’s chasses cause the robots to maintain proper alignment.

- The outer robot utilizes a differential drive system with two motors.

- The inner robot rolls on casters, passively being pulled by the magnetic restoring force between the inner and outer robots while the outer robot drives.

Some important aspects of the design presented in [12] that are not included in the next generation design are specialized magnet banks called Hall Bach Arrays and the Lorentz Force fine positioning system. It is assumed that these features could be integrated at a later time.

1.4. THE NEXT CHALLENGE

The complete wing box assembly cannot be performed by the original magnetic paired robots alone. The inner robot carrying the inner end effector must be placed within the wing box and engaged with the outer robot. This “loading” process, and its reverse “unloading” process, must be performed without human intervention. Furthermore, the inner robot must be able to go over many obstacles inside the wing box. As shown in Fig. 2a, structural reinforcement rails, called stringers, run across the bottom skin panel. The paired robots must negotiate these obstacles while supporting themselves.
To meet these challenging requirements, this thesis presents a new design of the magnetic paired robots. The main features include:

- The new design allows us to automatically load and unload the paired robots to a wing box;
- The inner robot can pass obstacles; and
- The paired robots can freely move across a skin panel.

These accomplishments must be achieved while holding the outer robot against gravity at all times. This thesis presents the basic principle and mechanism of the paired robots, followed by a kinematic and static analysis. A prototype robot demonstrates the functionality of the approach in experimental testing.
2. Paired Robots

2.1. Functional Requirements

A typical task procedure and functional requirements for the robot system are presented in Fig. 4. A wing box is shown with a mobile loading system below the structure. The solid arrows represent the motions of the robot in the wing box interior, and the dotted path, following the arrow path on the exterior of the wing box, represents the motions of the robot on the wing box exterior. The task can be separated into four distinct operations. The following steps, A through D, define the task the robot pair is to complete.

First, paired robots are brought with the mobile loading system to a 450mm x 225mm access hole on the bottom skin panel of a wing box: step A.

Fig. 4: A typical task routine.
For loading, the inner robot must go inside the wing box, while the outer robot must go to the outer surface of the skin panel. It is likely that a specialized loading jig would be used to facilitate the proper insertion of the inner robot into the wing box, while also allowing the outer robot to align on the outside of the wing box.

The two robots must be engaged so that the outer robot can be held against gravity: step B. The pair may disengage and reengage during the loading and unloading processes, or the pair may remain engaged throughout out the process. Regardless of the manner in which the pair becomes fully engaged, the outer robot needs to be fully supported such that the mobile loading system, or any other external support system, is not required during operation.

The pair must be able to move along the skin panel, while holding the outer robot: step C. Furthermore, the inner robot must be able to go over an obstacle, a stringer approximately 65mm tall, while holding the outer robot. This step poses a major challenge because the outer robot requires continuous support, yet the inner robot will need to lift from the wing panel to navigate over an obstacle. The ability of the robot pair to navigate the entire wing box is critical to utility of the design because the pair needs to be able to access all the points within the wing box that require a manufacturing operation to be completed.

After moving to all required locations on the skin panel, the pair must go back to the original access hole and exit the wing via the mobile loading system: step D. It is likely this step will be the same as step A, but in reverse.

### 2.2. Basic Robotic System Design

The robotic system designed must be able to complete the task described above, but it also should be simple and robust.
The basic design of the paired robotic system developed in this thesis is shown in Fig. 5. The outer robot is supported via permanent magnets that are engaged with corresponding permanent magnets on the inner robot. For simplicity the magnets are shown as a half-white and half-black square. The different colors indicate the north and south poles of the magnets. It should be noted that defining which color corresponds to which pole of the magnet is not crucial for understanding robot functionality. The colors merely show magnetic pole alignment.

![Diagram of inner and outer robots engaged on the wing skin](image)

**Inner Robot**
- revolute joint
- body
- wing skin
- foot
- magnet

**Outer Robot**
- passive wheel
- driven wheel

*Fig. 5: Inner and outer robots engaged on the wing skin.*

The outer robot has powered wheels that provide the tractive force. The magnet force pulling the outer robot into the wing skin allows the driven wheel to generate traction such that the outer robot can drive. As the outer robot drives the inner robot is pulled along due the magnetic attraction. This basic design assumes the use of simple permanent magnet pairs to support the outer robot. Although another viable method of securing the outer robot from falling would be using suction cups such as in [5] and [15], the magnets perform the function of
supporting the outer robot, and keeping alignment of the inner and outer robot. It should be noted that magnetic wheels, such as the ones presented [1] and [7], have been used to accomplish the task of suspending a robot. Due to their ease of integration, this initial design will consider pairs of cube magnets. Advantages of permanent magnets are their ability to provide enough force in a lightweight compact package. They also require no power, which is ideal for mobile robot applications. The outer robot has two passive wheels to prevent it from tipping toward either magnet pair.

The inner robot has three sections: two feet with a body section joining them. The two feet are connected to the body via revolute joints that are each actuated with a separate servo motor. Because the inner robot translates by being pulled by the outer robot, casters are assumed to be integrated into each foot. Each foot has strong permanent magnets that engage the magnets on the outer robot.

2.3. Multifunctional Operation

The paired robots have three essential navigation operations: loading and unloading, driving/sliding, and stepping over an obstacle. Loading and unloading is necessary for the automatic installation and removal of the robots from the wing box. Driving/sliding is used to move between obstacles and along flanges for manufacturing and maintenance operations. Lifting and driving is used to step over obstacles within the wing box.
2.3.1. **Driving and Sliding**

The paired robots primarily navigate with the outer robot driving and the inner robot sliding, as shown in Fig. 6. This motion is possible because of the use of strong magnets. The small deviation in magnetic alignment creates a restoring force between the outer robot’s magnets and the inner robot’s magnets. Magnetic restoring force between the robots causes the outer robot to constantly pull the inner robot into alignment, while the attraction between the magnets provides adequate force to prevent the outer robot from falling. Navigating the wing box in this manner has been studied; therefore the analysis of the motion where the outer robot is driving is not the focus of this thesis. This robot system is similar to a design presented in [10] in that it utilizes magnetic feet in an articulating robot. But unlike the work in [10], the articulating robot must also support an outer robot and because of the known distances between stringers inside the wing box the robot does not need a variable step size.

Fig. 6: The outer robot is driving and pulling the inner robot.
2.3.2. Stepping

Overcoming an obstacle requires articulating the inner robot such that it can clear the obstacle. The inner robot steps over the obstacle one foot at a time in order to support the outer robot at all times. Servo motors in the joints between the body and the feet, and the servos that control the magnet orientation are coordinated to perform the stepping operation. A schematic of the navigating over an obstacle is shown in Fig. 7. The squares shown as half-black and half-white boxes represent the magnets. Here the black and white sides represent the south and north poles of the magnets, respectively. The direction of the motion proceeds from left to right as numbered. The arrows on the outer robot's wheels signify the pair driving forward together (steps 4 and 8).
Fig. 7 An illustration of the process for navigating over an obstacle.
The diagram of the robot pair in Fig. 8 shows the labels for the various parts of the robots.

![Diagram of robot pair with labels](image)

**Fig. 8** The labeled parts of the inner and outer robots.

To begin the process of navigating over a stringer, the inner robot is positioned on one side of the obstacle (step 1) by the outer robot driving up to the obstacle. Since the direction of progression is from left to right, the foot B must be lifted first. In order to lift foot B and the body, the magnet pair B must be disengaged. Lifting foot B straight off of the wing skin would require powerful actuators due to the large attractive force of an engaged pair of magnets. Instead, magnet B on the inner robot is rotated (step 2), which decreases the magnetic flux in the gap and therefore decreases holding force. This decrease in holding force between magnet pair B allows for slight lifting of foot B.
Foot B is lifted by rotating joint A counterclockwise and joint B clockwise allowing the edge of foot B to remain in contact with the wing skin (step 3). Sliding the edge of foot B along the wing skin gradually increases the gap between magnet pair B. Gradually sliding foot B requires less actuator control authority at joints A and B, than lifting foot B straight up. Additionally the moment that tends to tip foot A while lifting the body and foot B is lessened because foot B, is brought closer to joint A (reducing the moment arm length) while decreasing the force pulling foot B down (reducing the force causing the tipping moment).

With the attractive force substantially decreased between the magnet pair B, foot B is lifted (step 4). Joints A and B are at the correct angles to allow proper clearance between the obstacle and foot B. The robot pair, having been advanced forward, has the obstacle under the inner robot’s body (step 5). The ability of the pair to drive while the outer robot is partially engaged is critical in this step. The attractive force of magnet pair A must be large enough to support the outer robot and supply enough normal force to provide traction for the outer robot’s wheels.

The inner robot then reengages magnet pair B, straddling the obstacle (step 6). The robot pair is now in the fully engaged configuration, with foot A left of the obstacle. Foot A may be lifted similarly to the manner shown in step 3. If joint A cannot rotate counterclockwise due to foot A interfering with the obstacle, it can be rotated clockwise (step 7). Magnet A is rotated and the right edge of foot A is slid along the wing skin to gradually increase the gap until the foot can be lifted to clear the obstacle (step 8). The outer robot then drives forward such that foot A clears the obstacle (step 9) and the foot can be reengaged reverse of how it was lifted (steps 10-12). The process for navigating over an obstacle is complete. The procedure requires careful coordination of joints A and B, as well as the magnets in the feet.
2.3.3. Flipping

The ability to automatically load the paired robots significantly improves the automated fastener installation process with respect to previous iterations of the paired robotic system. In previous iterations the paired robotic system was manually installed on the wing skin, requiring a skilled operator and time. Automating the process frees a skilled worker for more critical operations. Loading into the wing box is automated via a flipping process.

A diagram of the loading process is shown in Fig. 9. The first step shows the inner and outer robots being lifted up to the wing box. The lift platform has magnets that are engaged with one bank of the inner robot’s magnets. The details of the loading platform mechanism will be explained more thoroughly in the fabrication section. The inner robot is placed though the access port on the wing box and the outer robot is placed below the wing skin, awaiting engagement with the inner robot (step 2). The inner robot lifts foot A by rotating joint B clockwise (step 3). Foot A was not engaged with the platform, and there is a magnetic engagement mechanism to keep foot B planted while flipping. Foot A is placed over the outer robot’s corresponding magnet banks by rotating joints A and B clockwise 180 degrees (steps 4-5). Note that the inner robot’s body is now pointing upward. Foot B is disengaged from the platform and the inner robot repeats the flipping procedure similar to steps 3-5 to become fully engaged with the outer robot (steps 6-8). With both foot A and B engaged with the outer robot, the outer robot is fully supported and the lift platform is lowered (step 9).
Fig. 9 Automated loading process
The loading procedure described in Fig. 9 can be carried out in reverse to automatically unload the robot pair.

An automated lift is important for successful loading and unloading. The lifted used would need to be mobile and also have a means to localize relative to the wing box access hole. The lift design is not within the scope of this research, so it is assumed that a lift capable of placing the robot pair on the wing box is available, but it will be described in detail.

By combining the three modes of operation the robot pair is able to navigate the entire wing box, positioning itself to perform manufacturing operations.
3. Modeling and Analysis

In order for the paired robot concept to be successful their coordinated motion and parameter values must be determined. This section discusses mechanical factors and failure scenarios, and describes conditions for successful execution of intended operations. The two risks, or failure mechanisms investigated are:

- outer robot falling
- tipping of the inner robot

The risks discussed are failures where the paired robot system is unable to carry out the necessary steps for its own operation. Note the term failure is not used to describe mechanical failure such as fracture.

3.1. Modeling

Parametric models of the inner and outer robot are developed in the following section. The models will aid in the analysis and description of the robots.

3.1.1. Inner Robot

The inner robot with variable parameters is shown in Fig. 10. The dashed vertical lines represent the centerlines of each of the feet and the body. The black and white circles depict the location of the centers of gravity of the inner robot's two feet and body.
Fig. 10 Dimensioned inner robot.

Inner robot variables:

\( \ell_1 \) - The length from pivot A to pivot B, which is regarded as the inner robot body length.

\( \ell_2 \) - The length from pivot A to point D, also the length from pivot B to G. This length is the height of the body from the wing skin.

\( \ell_3 \) - The length from pivot A to the center of the magnet in the foot.

\( \ell_4 \) - The length from pivot A to the center of gravity of the foot at I, also the length from pivot B to K.

\( \ell_5 \) - The perpendicular length from line segment AB to point J, the center of gravity of the body.

\( \ell_6 \) - The length from point C to point D on the base of the foot, also the length from G to H.

\( \ell_7 \) - The length from point D to point E on the base of the foot, also the length from F to G.
The angular orientation of the inner robot is shown in Fig. 11. The inner robot is shown with all angles positively displaced in the counterclockwise direction.

![Diagram of robot orientation](image.png)

**Fig. 11** Angles defining inner robot orientation.

Inner robot angular orientation definitions:

- **XYZ** – The fixed coordinate system.
- **x_1y_1z_1** – The body-fixed coordinate system of the inner robot’s body section.
- **x_2y_2z_2** – The body-fixed coordinate system of foot B.
- **x_3y_3z_3** – The body-fixed coordinate system on magnets of foot B.
3.1.2. OUTER ROBOT

The outer robot has many fewer variables, as its mechanisms are much simpler. A diagram of the outer robot is shown with its lengths in Fig. 12. Again the center of gravity is depicted with a black and white circle. Points P and Q are the locations where the casters contact the wing skin.

![Fig. 12 Dimensioned outer robot.](image)

Outer robot variables:

- \( \ell_8 \) - The length point P to point Q.
\( \ell_9 \) - The length from point P to the center of gravity of the outer robot. This is also the length from point Q to the center of gravity of the outer robot.

\( \ell_{10} \) - The length point P to the center of the magnet in magnet bank A. This is also the length from point Q to the center of the magnet in magnet bank B.

\( \ell_{11} \) - The length perpendicular to line segment PQ to the center of the outer robots magnets.

\( \ell_{12} \) - The wing skin thickness.

The outer robot angular orientation definitions are shown in Fig. 13. The outer robot is shown with the orientation angle positively displaced in the counterclockwise direction.

![Fig. 13 Outer robot orientation.](image)

Outer robot angular orientation definitions:

\( x_0y_0z_0 \) – The body-fixed coordinate system of the outer robot.

\( \theta_0 \) - The angle \( x_0y_0z_0 \) is rotated counterclockwise from XYZ about the z-axis.

### 3.1.3. Magnet Force Modeling

The values of \( F_5 \) and \( F_8 \) are due to the magnetic force. Magnetic force as a function of position and orientation has been well developed in [7] and [8] using the principles from [1] and [13]. The magnet force is proportional to the square of the magnetic flux, as show in (1).
\[ F = \frac{B_g^2 A}{2\mu_0} \]  

\( B_g \) is the magnetic flux in the gap in Tesla. \( A \) is the area of the magnetic surface in \( m^2 \). \( \mu_0 \) is the magnetic constant equal to \( 4\pi \times 10^{-7} \frac{H}{m} \). Accurately modeling how the flux changes in the gap as the inner robot's magnets rotate is very difficult, and requires specialized software. Instead of developing a computationally complex model to account for angular rotation, a simplified model was developed based on experiments. The magnetic flux was measured in the gap on the top of the wing skin for various angles of \( \theta_3 \), while \( \theta_1 \) and \( \theta_2 \) were zero, as shown in Fig. 14.

**Fig. 14 Flux measurement experimental setup**

The flux was measured at multiple angles with a F.W. Bell Model 4048 Gauss/Tesla Meter. The results are plotted with a curve fit in Fig. 15. Experimentally it was not feasible to measure the flux in the gap past 90 degrees. The final three points on the plot at 120, 150, and 180 degrees
are pseudo-measurements. They were created by making the 180 degrees pseudo-measurement the negative value of 0 degrees measurement, the 150 degrees pseudo-measurement the negative value of the 30 degrees measurement, and the 120 degrees measurement the negative of the 60 degrees measurement.

![Flux measurement results](image)

Fig. 15 Flux measurement results

The curve was fit to the experimental data, and is shown as the green line in Fig. 15. The maximum magnetic field using the 0.0245m x 0.0254m x 0.0254m cube N52 Neodymium Iron Boron magnetics was 0.5T corresponding to the maximum holding force at a gap of 0.045m of 64N for a magnet pair. The force is nullified at 90 degrees, when the magnets are perpendicular to each other and the flux drops to zero. The flux is a minimum at 180 degrees, which corresponds to the magnets repelling each other. The equation of the fitted curve is a scaled shifted error function given by:
\[ a = -0.5 \text{erf} \left( \frac{\theta_m - 90}{40} \right). \]  

(2)

\( \theta_m \) is the angle between the disengaging magnet on the inner robot's foot and the outer robot's corresponding magnet pair. \( \theta_m \) is used to characterize the rotational displacement between the inner and outer robot's magnets instead of \( \theta_3 \). \( \theta_3 \) only describes the rotational displacement when the base of the disengaged foot is horizontal, \( \theta_1 = -\theta_2 \), otherwise \( \theta_1 \) and \( \theta_2 \) affect the rotational displacement.

Modeling the force as a function of the location of the magnets relative to each other was accomplished by following the procedure used in [7] and [8]. The model described in [7] and [8] describes how the force between a pair of magnets varies based on horizontal and vertical displacement. The model is then scaled by, \( a' \), to account for the varying flux in the gap as the magnets rotate:

\[ a' = 4 \cdot \text{sign}(a) \cdot a^2. \]  

(3)

The scaling factor, \( a' \), is proportional to \( a^2 \) because the force between the magnets is proportional to the flux squared as shown in (1). The scaling factor is proportional to the sign of \( a \), allowing the flux variations between its minimum and maximum values. A constant factor of four is used to normalize the maximum magnitude of \( a' \) to one. A diagram of the displacements that affect the holding force is shown in Fig. 16. The horizontal displacement is shown as \( \Delta x \). The vertical displacement is shown as \( \Delta y \). The magnet model parameters, \( \Delta x \), \( \Delta y \) and \( \theta_m \), are defined in terms of the inner robot angular position values, \( \theta_1 \), \( \theta_2 \) and \( \theta_3 \).

\[ \Delta x = 2\ell_{10} + \ell_8 \left( \cos(\theta_1) - 1 \right) + \ell_3 \left( \sin(\theta_2) \cos(\theta_3) + \sin(\theta_1) \cos(\theta_2) \right) \]  

(4)
The forces that act on the inner, $F_s$, and outer robot, $F_8$, due to the magnets shown in Fig. 16 are equal and opposite. Plots of how the magnetic force varies with $\Delta x$, $\Delta y$ and $\theta_m$ are shown in Fig. 17. Plot A, B and C have $\theta_m$ equal to 0, 70 and 85 degrees respectively, while $\Delta x$ and $\Delta y$ are varied. The $\Delta y$ axis starts at 0.0254m because that is the closest physical distance the magnets can be apart without intersecting. As expected, the force decreases as the magnet is rotated between 0 and 85 degrees.

\[
\Delta y = (\ell_2 + \ell_{11} + \ell_{12}) + \ell_8 \sin(\theta_1) + \ell_3 (\sin(\theta_1) \sin(\theta_2) - \cos(\theta_1) \cos(\theta_2))
\]

(5)

\[
\theta_m = \theta_1 + \theta_2 + \theta_3.
\]

(6)
3.2. FAILURE ANALYSIS

There are two primary failure modes for the paired robotic system. The inner robot can tip while attempting to lift one of the feet due to a large moment. The outer can fall from the wing skin due to lack of magnetic attractive force to the inner robot. This section outlines the important conditions that prevent these failure modes.

Fig. 17 Magnet force
3.2.1. **INNER ROBOT TIPPING**

The inner robot is most likely to tip in the partially engaged configuration. This is due to the combined center of mass of the inner robot being offset from the engaged foot, and the disengaged foot’s magnet creating a moment that tends to tip the inner robot. A diagram of the inner robot tipping about point E is shown in Fig. 18.

![Diagram of inner robot tipping](image)

**Fig. 18 Inner robot failure scenario**

We will take the sum of the moments about point E to determine the condition such that the inner robot does not tip. The free body diagram of the inner robot with the tipping forces is shown in Fig. 19. Values of the forces in the free body diagram are given at the end of this section in Table 1.
Assumptions made are that the foot A is engaged and sitting flat, and the only force from the magnet of the disengaged foot that significantly contribute to the inner robot tipping is in the vertical direction. The sum of the moments about point E is:

$$
\sum M_E = \left( -\ell_6 (F_1 + F_2) + \left( \frac{\ell_4}{2} \cos(\theta_1) - \ell_7 \right) F_3 + 
\begin{pmatrix}
-\ell_6 (F_1 + F_2) + \left( \frac{\ell_4}{2} \cos(\theta_1) - \ell_7 \right) F_3 + \\
(\ell_1 \cos(\theta_1) + \ell_4 \left( \sin(\theta_2) \cos(\theta_3) + \sin(\theta_3) \cos(\theta_2) \right) - \ell_7) F_4 + \\
(\ell_1 \cos(\theta_1) + \ell_4 \left( \sin(\theta_2) \cos(\theta_3) + \sin(\theta_3) \cos(\theta_2) \right) - \ell_7) F_5
\end{pmatrix}
\right)
$$

The moment that stabilizes about point E is clockwise; therefore a negative moment is desirable:

$$
\sum M_E < 0.
$$

Equation (7) and in equality (8) can be rearranged as:
\[
\begin{align*}
&\left(\frac{\ell_1}{2} \cos(\theta_1) - \ell_7\right)F_3 + \\
&\left(\ell_1 \cos(\theta_1) + \ell_4 \left(\sin(\theta_2) \cos(\theta_1) + \sin(\theta_1) \cos(\theta_2)\right) - \ell_7\right)F_4 + \\
&\left(\ell_1 \cos(\theta_1) + \ell_3 \left(\sin(\theta_2) \cos(\theta_1) + \sin(\theta_1) \cos(\theta_2)\right) - \ell_7\right)F_5 < \ell_6 \left(F_1 + F_2\right)
\end{align*}
\] (9)

Inequality (9) has the moment that prevents tipping caused by the magnetic attraction of the engaged foot and the weight of the engaged foot on the right, and the moment that tends to tip the inner robot on the left. This condition must be satisfied such that the inner robot does not tip with a single foot engaged.

### 3.2.2. OUTER ROBOT FALLING

The limiting case for the outer robot falling is in the partially engaged configuration, when one foot of the inner robot is being lifted. A fall could occur when the weight of the outer robot and the force on the disengaged magnet pair causes a moment that cannot be balanced by the engaged pair of magnets. A diagram of the outer robot falling is shown in Fig. 20. The outer robot is intentionally shown tipping off of the wing skin about point P, and not falling straight off of the wing. The engaged magnets’ magnetic force must exceed the force required to support the outer robot’s weight to ensure the outer robot does not fall from the wing skin. The failure scenario to be evaluated is when the moment pulling the outer robot from the wing skin is not balanced by the moment from the magnetic attraction of the engaged pair.
We will take the sum of the moments about point P to determine the condition such that the outer robot does not fall. A free body diagram of the outer robot with the forces causing and preventing falling is shown in Fig. 21. Values of the forces in the free body diagram are given at the end of this section in Table 1.
The sum of the moments about P is:

$$\sum M_p = \ell_{10}F_6 - \ell_9F_7 + (\ell_8 - \ell_{10})F_8.$$ \hspace{1cm} (10)

The moment that stabilizes the outer robot is counterclockwise; therefore:

$$\sum M_p > 0.$$ \hspace{1cm} (11)

Combining equation (10) and inequality (11) yields:

$$\ell_{10}F_6 - \ell_9F_7 + (\ell_8 - \ell_{10})F_8 > 0.$$ \hspace{1cm} (12)

Satisfying condition (12) ensures the outer robot will not fall from the wing skin. This condition is also useful in determining the value of $\ell_{10}$. When the disengaged foot is sufficiently far from
the outer robot’s chassis $F_8$ decreases to approximately zero. In this configuration (12) simplifies to:

$$\ell_{10} > \ell_9 \frac{F_7}{F_6}.$$  

(13)

This condition limits the minimum value of $\ell_{10}$. The value of $\ell_{10}$ (0.0699m) chosen is approximately five times the minimum. This translates directly to the moment that the outer robot can support, meaning that the outer robot can support a payload approximately five times the current payload (assuming the center of gravity does not move).

The force between the magnets in the foot being disengaged and the corresponding magnets on the outer robot’s chassis is complex. This force cannot be approximated by a single value, instead force fluctuation needs to be modeled as a function of the magnetic properties, and the inner robot’s orientation angles $\theta_1$, $\theta_2$ and $\theta_3$. Variance in magnetic force based on the combination of $\theta_1$, $\theta_2$ and $\theta_3$ can determine whether conditions (9) and (12) are satisfied. The following section describes how the correct trajectory for $\theta_1$, $\theta_2$ and $\theta_3$ is selected.
### Table 1: FBD Force Values

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>F_1</td>
<td>=</td>
</tr>
<tr>
<td>$F_2=F_4$</td>
<td>8N</td>
<td>The weight of a single foot of the inner robot.</td>
</tr>
<tr>
<td>$F_3$</td>
<td>12N</td>
<td>The weight of the body of the inner robot.</td>
</tr>
<tr>
<td>$F_5$</td>
<td>$f(\theta_1, \theta_2, \theta_3)$</td>
<td>The force exerted on the inner robot’s disengaged magnet by the outer robot’s magnets.</td>
</tr>
<tr>
<td>$F_7$</td>
<td>15N</td>
<td>The weight of the outer robot.</td>
</tr>
<tr>
<td>$F_8$</td>
<td>$f(\theta_1, \theta_2, \theta_3)$</td>
<td>The force exerted on the outer robot’s disengaged magnet by the inner robot’s magnets.</td>
</tr>
</tbody>
</table>

### 3.3. Trajectory Design

In this section, joint trajectories will be designed in order to transition from the engaged configuration to the disengaged configuration. A trajectory is the coordinated motion path of the joints on the inner robot. The trajectory must not violate inequalities (9) and (12) to ensure the outer robot does not fall, and the inner robot does not tip. Additionally, the trajectory is subject to physical constraints. There are multiple trajectories that will satisfy the constraints. This section will describe one method of determining the optimal trajectory.

The important parameters that affect the failure conditions must be understood to formulate the cost function. The trajectory selected will keep the robots the furthest away from the failure conditions. The optimal trajectory minimizes: the peaks of the tipping moment on the inner robot, the moment acting on the outer robot’s disengaged magnet pair, and the total
moments over the trajectory. The tipping moment is given as the left hand side of the inequality in (9):

\[
M_{tip}(\theta_1, \theta_2, \theta_3) = \left( \frac{\ell_i}{2} \cos(\theta_i) - \ell_i \right) F_3 + \left( \ell_1 \cos(\theta_1) + \ell_4 \left( \sin(\theta_1) \cos(\theta_1) + \sin(\theta_2) \cos(\theta_2) \right) - \ell_5 \right) F_4 + \left( \ell_1 \cos(\theta_1) + \ell_3 \left( \sin(\theta_2) \cos(\theta_2) + \sin(\theta_3) \cos(\theta_3) \right) - \ell_5 \right) F_5(\theta_1, \theta_2, \theta_3) \right).
\]

The values of \( \theta_1, \theta_2 \) and \( \theta_3 \) change the moment due to the varying moment arm lengths, as well as force due to the magnet. The length of each of the moment arms for the forces \( F_3, F_4 \) and \( F_5 \) can increase and decrease depending on \( \theta_1, \theta_2 \) and \( \theta_3 \) as shown in Fig. 22. The magnitude and direction of \( F_5 \) also can vary, which impacts the tipping moment.

Fig. 22 Tipping moment parameters
The outer robot will fall when the moment from the disengaging magnets pushes the robot off of the wing skin. The moment on the outer robot due to the disengaged magnet is given as:

\[
M_{\text{mag}}(\theta_1, \theta_2, \theta_3) = (\ell_8 - \ell_{10}) F_8(\theta_1, \theta_2, \theta_3).
\] (15)

The moment on the outer robot due to the disengaged magnets only varies with \( F_8 \), because the lengths, \( \ell_8 \) and \( \ell_{10} \), do not vary with \( \theta_1, \theta_2 \) and \( \theta_3 \). \( F_8 \) pushing the outer robot off the wing skin is shown in Fig. 23.

![Diagram of robot falling parameters](image)

**Fig. 23 Outer robot falling parameters**

The moments that cause failure of the robots are given in (14) and (15). The peaks of these moments must be minimized to ensure the trajectory being executed never violates the conditions. Also, it is desirable for the moments over the entire trajectory to be minimized to
ensure the trajectory being executed keeps the robots as far away from a failure scenario as possible. Two cost functions are combined to create the appropriate penalty for a given trajectory. The first cost function is a weighted sum of the moments:

\[ J_1(s) = M_{mag} + M_{rip} \]  

(16)

The second cost function is the sum of the moments over the entire trajectory:

\[ J_2(s) = \int_{0}^{t_f} J_1(s) ds \]  

(17)

The optimal trajectory, \( X^*(s) \), is given as the trajectory, \( X(s) \), that minimizes the maximum value of the sum of the moments, and minimizes the total sum of the moments over its entirety:

\[ X^*(s) = \arg\min_{X(s)} \left[ \max_{0 \leq s \leq t_f} J_1(s) + cJ_2(s) \right]. \]  

(18)

The weight, \( c = \frac{1}{s} \), makes the units conform in the optimal trajectory equation. The index through the trajectory is \( s \). A diagram of a possible trajectory in the three-dimensional state space is shown in Fig. 24. The variable \( s \) represents where the robots are in the trajectory, i.e. a specific configuration of the inner robot.
At each index value of $s$ there is a specific value associated with the states $\theta_1$, $\theta_2$ and $\theta_3$. The initial angles $\theta_1$, $\theta_2$ and $\theta_3$ represent the inner robot in a particular configuration before detachment and lifting begins. The trajectory progresses in $s$ until arriving at the final configuration, $(\theta_1, \theta_2, \theta_3)_{\text{final}}$.

An exhaustive search algorithm is utilized to find the optimal trajectory. The algorithm first generates a cubic spline trajectory, $s$. The spline is open and has five equal spaced control points in $s$. The initial and final values of the trajectories are defined. The starting points for the trajectory are determined by the starting configuration of the joint angles $\theta_1$, $\theta_2$ and $\theta_3$. The end points for the trajectory are defined by the desired final configuration the inner robot should assume. The three internal control points for each trajectory are three randomly generated values. The internal control point’s random values are limited to prevent physical interference of the inner robot’s sections. Also, the control points are sorted such that if the final control point is
greater than the initial control point, the internal control points will increase in value and vice versa. The control points have a limited range and are sorted such that the trajectories generated are always causing the inner robot to move toward the final configuration. The slope constraint on the generation of \( s \) is: \( \theta_1 \) and \( \theta_2 \) have zero slopes at start and end. Zeroing the start and end slopes of \( \theta_1 \) and \( \theta_2 \) minimizes accelerations in the robotic system. The cost of the trajectory is computed as described in (18). Note this algorithm is done discretely; therefore a sum is used instead of an integral. The computed cost is then compared to the previous smallest cost. Each trajectory with the smallest cost is then defined as the optimal trajectory. This algorithm is carried out for a set number of iterations.

The algorithm used to find the trajectory will, given an infinite number of iterations, converge on the optimal trajectory. It is not possible to run the algorithm infinite cycles, but it is possible to find a trajectory extremely close to optimum with a finite number of iterations. Experimentally one can find a trajectory close to optimal by iterating until the optimal trajectory changes very little. It is difficult and somewhat subjective to say when trajectory stops changing dramatically, but the trajectory remained very similar between 1000, 10000 and 100000 iterations of the algorithm. The optimal trajectory determined by the exhaustive search algorithm for lifting the foot of the inner robot is shown in Fig. 25. The trajectory uses parameter values from Table 1 and Table 2.
Several important constraints were included in the model to generate this trajectory. The trajectory starts at \((\theta_1, \theta_2, \theta_3)_{\text{initial}} = (0,0,0)\), and ends at \((\theta_1, \theta_2, \theta_3)_{\text{final}} = (35^\circ, -30^\circ, 90^\circ)\). The final configuration was selected to ensure the inner robot could clear the obstacle it is stepping over. The ranges of the inner robot’s body angle, foot B, and magnet are \(0^\circ \leq \theta_1 \leq 35^\circ\),
\(-30^\circ \leq \theta_2 \leq 0^\circ\), and \(0^\circ \leq \theta_3 \leq 180^\circ\) respectively. Ground and obstacle constraints were implemented by setting the cost function to infinity when the foot being disengaged entered the physical space where the object would be. The normal force the wing skin applied to the inner robot’s foot during disengagement, was modeled such that when the foot was in contact with the wing skin, no tipping moment was applied to the inner robot. The combination of the previous constraints and minimizing the cost function resulted in an intuitive trajectory. In the trajectory the magnet is slightly rotated and the foot is slid in toward the engaged foot along the wing skin. The foot is then lifted off of the wing skin as the magnet is rotated.

Depending on the parameters used to describe the robots, what is deemed an acceptable trajectory changes. An acceptable, not optimal, trajectory according to the previous parameters is shown in Fig. 26.

![Fig. 26 Possible trajectory](image)

This trajectory does not violate any of the constraints with the previous parameter values. Reducing the distance between the engaged magnet on the outer chassis and the rear caster to \(\ell_{10} = 0.019m\) will cause the outer robot to fall. This failure results from the outer robot’s decreased ability to support the moment due to the disengaged magnets, and the weight of the chassis itself. The moment from the disengaged magnets, \(M_{mag}\), is shown in Fig. 27.
The outer robot, with the new value of $\ell_{10}$, can only support a maximum clockwise (negative) moment of 0.6N-m. The trajectory produces a negative moment of 1N-m; therefore the outer robot would fall from the wing skin. The previous example illustrates the significance of the robot parameters while determining acceptable trajectories in the exhaustive search algorithm.
4. **Prototyping**

A prototype was constructed in order to demonstrate the functionality of the design of the paired robots. Meeting large number of design specifications outlined in the previous sections consumed most of the development effort for creating this paired robot design. In order to realize a design that was capable of completing the task, the prototype developed required extensive use of custom components. The prototype developed is shown in Fig. 28.

![Fig. 28 CAD paired robots](image)

The inner robot is shown on top of a thin panel engaged with the outer robot that is suspended below the panel.
The inner robot is constructed with three main sections; two feet and a body section. The
majority of the structural components on the inner robot are made of aluminum to minimize
weight. The inner robot is shown in Fig. 29. Mounted to the body of the inner robot is a mock
tool. Its placement within the assembly demonstrates how the inner robot might carry tooling
during a manufacturing operation.

Fig. 29 CAD inner robot

The body of the inner robot is shown in Fig. 30. The body is comprised of two motor that
actuate joints A and B connected together with thin water jet aluminum plates. The motors used
to actuate the joints are Harmonic Drive 50:1 34Dx125L mm 24V DC motors (600°/s no load
speed, stall torque 4.9N-m). The harmonic drive gear head eliminates backlash, allowing the
system to be more easily modeled, and controlled. The motor serves as a structural component
which joins both sides of the robot. Each motor housing is mounted to the body, and the output shafts mount to the feet.

Fig. 30 CAD inner robot body

The inner robot’s foot is shown in Fig. 31. The two upright side pieces and the horizontal servo motor mount plate are all cut from aluminum plate on a water jet. The magnet disengagement mechanism can be seen in the figure. A servo motor in the foot rotates a miter gear. The servo motors used are Hitech HS-M7990TH Monster Torque ME producing 44.0kg-cm of torque at 7.4V. Power is transmitted to two miter gears, one on each shaft of the magnet mounts. Each magnet is rotated by the amount the servo rotates creating the angular displacement $\theta_j$. The magnets used in the prototype are from K&J Magnetics, Inc. The magnets are 0.0254m x 0.0254m x 0.0254m Neodymium Iron Boron cubes with a maximum energy
product of 52 MGOe, and a residual induction of 1.2 Tesla. There is a total of eight magnets in the paired robots (four on the inner robot, and four on the outer robot).

Some unique features on the base of the foot are shown in Fig. 32. The base of the foot was CNC machined due to the complexity and large number of features. There are two cutouts in the base to allow the magnets in the foot to sit closer to the wing skin. By lowering the magnets in the base of the foot the total holding force between the magnets is increased due to the gap between the inner and outer magnets decreasing. In Fig. 32 six small ball bearing casters are shown. The casters in the base of the foot provide low friction, which allows the inner robot to closely follow the position of the outer robot while driving. The casters were custom designed due to the lack of small, robust, low friction casters currently on the market.
The outer robot was constructed with a focus on lightweight design. The model of the outer robot is shown in Fig. 33. The outer robot has two Pololu 131:1 Metal Gearmotors with 64 CPR Encoders (80 RPM no load speed, stall torque 18 kg-cm). The motors provide standard differential drive of two Bane Bots rubber wheels. Four magnets are mounted in thin aluminum cages, spaced from the waterjet aluminum chassis with 3D printed ABS standoffs. There are two casters on the outer robot that provide stability, and are spaced a distance of $\ell_s$ apart.
The prototypes constructed are shown in Fig. 34. The inner robot (Fig. 34A.) has a mass of 2.8kg. The outer robot (Fig. 34B.) has a mass of 1.6kg.

Both the inner and outer robots are controlled using a National Instruments CompactRIO (CRIO) System (chassis 9074) and LabVIEW software package. The outer robot’s motors used
closed loop velocity control in a simple proportional control feedback loop. The inner robot's joints A and B used closed loop position control in a proportional and integral feedback loop. The servo motors used to control magnet orientation were position controlled in an open loop. The CRio utilized a lower level FPGA for interfacing with the hardware. The FPGA uses an accurate 40 MHz clock for timing, but the closed loop control was done in the real time top level interface. Loop times were limited to 1KHz due to the complexity of the code and limited computational power of the laptop running the program. Since the analysis for the robots was done quasi-statically, slow loop times did not hinder the functionality of the system.

4.1. ROBOT DIMENSIONS

Determining the appropriate lengths for the dimensions specified for the inner and outer robots is critical for the functionality of the robots. Many dimensions of the robots are determined by physical size constraints in the work environment, and the components immediately available for construction. In general minimizing the robot's weight is beneficial; therefore the size of the robot is also minimized. A lightweight robot is advantageous for a number of reasons. Less weight translates into the actuators requiring less control authority, and power. Also, since the outer robot is suspended upside down, a lighter outer robot is less likely to fall from the wing skin. Any extra holding force from the magnetic attraction that is not supporting the weight of the outer robot is useful in making the paired robots more robust to unforeseen disturbances and decreases in the total holding force. A lighter inner robot is less likely to tip in the partially engaged configuration, as shown in Fig. 8, due to the decrease in cantilevered weight from the lifted disengaged foot. This section will briefly outline how some of the important dimensions were determined.
The inner robot is designed to step over an obstacle that is 38.1mm (1.5in) wide and 50.8mm (2in) high. These are approximate dimensions of the stringer in the wing box. The distance between the feet must then be larger than 38.1mm. The lowest point on the body of the robot can be no lower than 50.8mm. The distance between stringers that the inner robot will be navigating is 20.32mm (8in). The feet are made to be symmetric, $\ell_6 = \ell_7$ in Fig. 10, because the inner robot will be equally as stable while lifting its feet when the body is upright as it is when the body inverted. The symmetry assumption and the previously discussed physical constraints define:

\begin{align*}
2\ell_6 + \ell_1 &< 0.2032m \quad (19) \\
\ell_1 - 2\ell_6 &> 0.0381m \quad (20)
\end{align*}

and

\begin{equation}
\ell_2 > 0.0508m. \quad (21)
\end{equation}

Placing the magnets as close to the wing skin as possible is important for achieving the maximum holding force. The magnets cannot be placed right on the wing skin because they rotate. They need extra clearance such that their edges do not interfere with the wing skin while rotating. Using 25.4mm x 25.4mm x 25.4mm cube magnets defines:

\begin{equation}
\ell_2 - \ell_3 > \frac{0.0254m}{2} \sqrt{2}. \quad (22)
\end{equation}

Dimensions $\ell_4$ and $\ell_5$ are determined by the component’s weights and densities. These dimensions cannot easily be specified by the design. They are determined after the design is made.
The outer robot’s magnet banks need to align with the inner robot’s magnet banks; therefore:

\[ \ell_8 - 2\ell_{10} = \ell_1. \]  

(23)

The outer robot is symmetric:

\[ \ell_9 = \frac{\ell_8}{2}. \]  

(24)

The dimension \( \ell_{10} \) is unlike many other dimensions. Its length is not based on physical limitation, as many of the other dimensions are. Increasing \( \ell_{10} \) increases the distance that the caster is from the magnet bank. When the outer robot is in the partially supported configuration with one foot of the inner robot disengaged, \( \ell_{10} \) determines the load that can be born by the outer robot. The details of the selection of \( \ell_{10} \) are described in the Outer Robot Falling Section. The values of the dimensions discussed in that section are listed in Table 2. It should be noted that the dimensions selected would allow the robot pair to access 70-80% of the wing box. The robots would not be able to access the narrow sections near the wing tip, or sections where the stringers meet walls at acute angles.
Table 2: Dimensions

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \ell_1 )</td>
<td>0.1143m</td>
</tr>
<tr>
<td>( \ell_2 )</td>
<td>0.1103m</td>
</tr>
<tr>
<td>( \ell_3 )</td>
<td>0.0899m</td>
</tr>
<tr>
<td>( \ell_4 )</td>
<td>0.0770m</td>
</tr>
<tr>
<td>( \ell_5 )</td>
<td>0.0000m</td>
</tr>
<tr>
<td>( \ell_6 = \ell_7 )</td>
<td>0.0368m</td>
</tr>
<tr>
<td>( \ell_8 )</td>
<td>0.2540m</td>
</tr>
<tr>
<td>( \ell_9 )</td>
<td>0.1270m</td>
</tr>
<tr>
<td>( \ell_{10} )</td>
<td>0.0699m</td>
</tr>
</tbody>
</table>
5. EXPERIMENTAL TESTING

Experimental testing was conducted to verify the robot’s functionality. The testing was performed on a mock wing section. The wing section mimics an aircraft wing frame in terms of approximated size and materials, but unlike an actual curved wing the test frame wing skin is made from $\frac{1}{8}$th thick inch flat aluminum plate. The paired robots designed are not able to accommodate a curved surface. In order to work on a real wing, the robots would require a suspension system that allows them to operate on a curved wing.

5.1. OPERATION

Carrying out a mock manufacturing task tested the operation of the robots. The inner and outer robots were placed on a lift below the wing box, as shown in Fig. 35. The lift has a specially designed base with which the inner robot partially engages its magnets. There is also a limit switch that stops the lift once the inner robot has entered the wing box.
Fig. 35 Robots before loading

The lift is raised and the inner robot enters the wing box as shown in Fig. 36A. The inner robot flips into the wing box, engaging the outer robot (Fig. 36B, C). With the inner robot fully engaged to the outer robot (Fig. 36D), the lift can be lowered.
The robots can now drive to the locations where manufacturing operations will be performed. The inner and outer robot engaged while driving is shown in Fig. 37A. The outer robot is shown suspended below the wing skin in Fig. 37B. The robot pair drives along the wing panel to a flange where manufacturing operations will be performed. The mock tool is shown placed over the flange, demonstrating that the paired robots can carry and locate a tool in the wing box.
Next the inner robot must step over stringers in the wing box to reach more locations for manufacturing operations. The inner robot stepping over an obstacle is shown in Fig. 38.
The inner robot lifts the disengaged foot to clear the stringer and the outer robot drives forward (Fig. 38A). The disengaged foot is lowered on the other side of the stringer (Fig. 38B) and reengaged with the outer robot (Fig. 38C). With the first foot engaged on the opposite side of the stringer, the second foot can be disengaged and brought over the stringer (Fig. 38D).

These three detailed modes of motion demonstrate that the paired robots are able to successfully navigate the wing box.

5.2. Trajectories

The optimal trajectory algorithm was validated by implementing the generated trajectories on the prototype system. The most challenging trajectory is the one needed for magnet disengagement when lifting the inner robot's foot to clear an obstacle. Discrete waypoints were selected from trajectory $X^*(s)$ shown in Fig. 25. These waypoints were connected with a smooth function in LabVIEW to approximate the spline curves. The way points were used as the inputs to the control loops for the joint angles, $\theta_1$ and $\theta_2$, as well as the magnet angle, $\theta_3$.

The trajectory was successfully executed as shown in Fig. 39. The inner robot is shown in front of an obstacle in Fig. 39A. The magnets in the disengaging foot are slightly rotated and the foot begins to slide inward along the wing skin (Fig. 39B, C). The foot is then lifted until it clears the obstacle (Fig. 39D-F). With the foot clearing the obstacle the outer robot can drive forward and carry out the reverse procedure for reengaging the foot. The same procedure is done one more time to allow the other foot to be brought over the obstacle.
Fig. 39 Trajectory test
6. CONCLUSION

This work has described the design, analysis and construction of paired robots. The novelty of this work is derived from combining the need to overcome obstacles with an inner end effector, while simultaneously supporting an outer end effector. The paired robots were designed and constructed to house the two end effectors. The three ways in which the paired robots move allow it to perform the required tasks. The robot is capable of automated entry into the wing box. Driving/sliding is possible through the use of permanent magnets that pull the inner robot, allowing the inner robot to navigate the wing skin, while also supporting the outer robot. And, the inner robot is able to step over obstacles while supporting the outer robot.

The design is guided by the analysis of the failure conditions. The necessary conditions are derived to ensure the outer robot does not fall from the wing skin, and the inner robot does not tip during operation. The proper magnet disengagement conditions are determined, which are then used to define the optimal trajectory for the joints.

A prototype of the robot was constructed and tested. Testing demonstrated that the robot is capable of carrying out the task it was designed to accomplish. The paired robot was able to navigate a mock aircraft wing frame, reaching all of the locations where manufacturing operations would be performed.

The utility of the paired robots is not limited only to fastener installation manufacturing operations in an aircraft wing box. Many other operations in the manufacturing of an aircraft could utilize the robots. Sealant must be applied to all locations of potential leaks in the wing because the wing of an airplane is also the gas tank. The paired robots are particularly well suited to complete the sealant application procedure, as the robots are able to access the majority of the
wing box. The paired robots could also be used for inspection operations and repairs. The wing box is quite a toxic environment once the airplane has been used because the wings will have been full of fuel. Utilizing a robot to enter the wing box for inspection and repair operations could eliminate the need to put humans in the dangerous conditions within the wing box. The robots may also be useful in other industries where there is extensive used of sheet metal, and structures from plate metal, such as the auto industry and the ship building industry.

There are many areas for future work that will help take the robots from a prototype to a robot used in a real manufacturing environment. The prior paired robots presented in [12] utilized Lorenz force actuators, and Hall Bach array magnet banks. Integration of Lorenz force actuators into the robots would provide more precise control of the inner robot’s position. Hall Bach array magnet banks could provide even higher magnetic forces, while limiting stray magnetic flux. Additionally making the inner robot tetherless would provide even more mobility within the wing box by eliminating the cables that can be snagged.

The robots may also benefit from faster operation and control. In order to use the robots dynamically, the analysis would need to include the dynamic terms. Dynamic analysis would be more complicated, but there may be some modes of operation that could benefit from dynamics, such as loading and unloading, and disengaging the feet. The method of controlling the robot needs to be improved such that the time delay from the control system is not limiting the functionality. A communication system between the inner and outer robots may be helpful for relaying relative position data for locating the robots relative to each other.

It may be useful to actively monitor or estimate the holding force between the inner and outer robots too. Strain gauges could be integrated into the robots to measure the holding force.
Alternatively, or in conjunction Hall Effect sensors could be used to estimate the holding force. Some work was done attempting to use electro-permanent magnets (EPMs) instead of permanent magnets. Benefits of EPMs include the ability to switch the magnetic force on and off, as well as being able to modulate the amount of holding force. EPMs could not be made light enough for application in the paired robots in the given time.
7. BIBLIOGRAPHY


