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Self-Reconfigurable Modular Robot

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requirements for the Degree of Bachelor of Science by:

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Abstract

Natural disasters wreak havoc on populated areas around the world, in these situations quick informative responses are imperative to saving lives. Human involvement in these circumstances is strictly regulated for fear of increasing the number of affected persons. Therefore, there exists a demand for a fast, robust, dynamic robotic solution. The goal of this project was to design and build a self-reconfigurable modular robot for search and rescue applications. The MQP team investigated previous work and collaborated on three new innovative ideas. From these ideas, using an evaluation matrix, one specific design was chosen. These metrics required that each module move independently, identify and connect with other modules, and travel as a collective system. The chosen design is small, individually mobile, and capable of collaborated motion and dynamic system configuration. The rigorous constraints, small module size and untethered operation, necessitated an innovative design and required strategic placement of the internal components. Two different connection mechanisms, one magnetic and the other mechanical were researched, designed, and prototyped as viable methods for module connection. A final module was fabricated and individual module mobility was validated. A switchable permanent magnet connection mechanism was realized and developed for module integration.

Acknowledgements

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1 Introduction

Natural disasters occur in areas all around the world and strike with little to no warning, leaving chaos in their wake. In the mist of this chaos it is vital that organizations have quick informative responses in order to save lives. Response personnel currently do everything they can in these situations to arrive quickly and save every individual that they can. However, rescue personnel are not able to explore every area and locate all of the injured people in a timely manner. A solution to this problem is to use robotic systems designed for search and rescue [1]. Due to the dynamically unconstrained, complex environment typically associated with emergency scenarios, a flexible and adaptive capable of navigating constricting and irregular terrain is necessary. A fast, robust, and dynamic robotic solution for this task is a self-reconfigurable modular robotic system.

Modular robots are designed to have a number of base modules that are interchangeable with one another and capable of connecting in varying configurations. Some modular robots are able to operate as a single module moving around and completing tasks; while others require multiple modules to achieve any motion. Modular robots are more versatile and are able to dynamically adjust themselves when damaged unlike the robots designed for this specific task. The ability to self-reconfigure adds additional versatility and adaptability to the robot by allowing the system to change configurations when needed. This design allows one system to be applicable to multiple scenarios, and be able to complete different tasks or negotiate challenging obstacles.

1.1 Project Goals

The goal of this project is to design and build a modular robot system that is self-contained, small, and contains modules capable of individual and group movement, communication between modules, and the ability to self-reconfigure. While there are many robots that have one or more of these abilities, there is currently no public robot that can accomplish all these tasks.

1.2 System Requirements

In the design and construction of the modular robot, a set of system requirements that the robot had to meet were generated. The module system requirements include:

- Independent module locomotion capability
- Able to connect to other modules
- Smaller than 4”x4”x8”
- Lift two other modules
- Operational running time of at least 15 minutes

The cluster system requirements include:

- Able to move as a complete system
- Able to reconfigure system shape

1.2.1 Target Users and Audience

Self-reconfigurable modular robots have a wide range of potential uses and customers. However, the immediate target audience consists of emergency responders and rescue teams who could use the robots for search and rescue operations. For example, the modules could be used to examine hazardous material incidents or fire scenes instead of sending in humans. The modules could also be used for searching in small spaces such as inside collapsed buildings.

1.2.2 Economic Considerations

Since the target market for this robot is emergency responders and larger rescue organizations, the module needs to be reliable and affordable. The module will operate in hazardous conditions and could be damaged or destroyed. Modules must be made affordable so that they can be easily replaced. For smaller local groups like municipal organizations, the modules would have to be very rugged and inexpensive. An advantage of modular robots is that a wide range of specialized modules can be added onto the base modules. These special modules can be designed for a wide range of prices and functionalities to fit any potential market.

1.2.3 Health/Safety Considerations

Since the module is going to be used in search and rescue operations, it is vital that the module meets certain health and safety regulations. There should be operating guidelines such as inspecting the electronics for damage. Care should also be taken when operating or handling the module. The module should be able to distinguish between a person or animal and an inanimate object and give the former adequate space. It should also be fully encased so no objects can enter the module and cause damage or failure. Personnel operating the module should receive training in using the module. During the training the person would be informed about proper safety measures for transport and operation of the modular system.

1.2.4 Reliability Considerations

Since these modules are working in a search and rescue environment, the modules must be very reliable. All of the components used inside of the module will need to be rated to work in a wide range of environments, such as urban areas, deserts, mountains and forests. The module housing needs to be strong enough to make sure the housing will not fail during operation. The inside of the module will need to be sealed off from water, to allow the module to tolerate dampness and small amounts of standing water. Measures should also be taken to limit the amount of dust and dirt that can enter the module and cause damage.

1.2.5 Social Impacts

In order to be environmentally friendly the module housing will be made out of 100% recycled material and the housing will be able to be recycled when the module no longer works. And not having any liquids inside the module there will be no issues of polluting the environment that the module will be traveling in. Dealing with interactions with the environment there is the possibility that the robot could have animals interfere which could result in the animal getting injured or even killed. But the little cuddly bunny rabbits in the forest would be ever so kind to the robot and even cuddle with it.

With the robots job being for search and rescue there will be more emphasis put on the functionality aspect of the module then on its overall looks. There will be no loss of functionality to make the robot be more aesthetically pleasing. There will be a customizable coloring, in which the consumer can pick the color their modules will be. This feature is with both versions of the module.

1.2.6 Use of Standards

All electronic components, such as motors and controllers, will be purchased. This will ensure that the electrical system uses the same standards and protocols. This is a critical detail for programming the motors to generate motion. The module measurements will all be in standard units, since the design team is more familiar with this system. The gears will use the same measurement system as the motors, since the gears will have to fit on the motor shafts. Other hardware such as screws and bearings will use standard units, since a wider range of options is available than in the metric system.

1.3 Report Layout

The rest of the report is organized as follows. Chapter 2 reports on the methodology followed for this project. Chapter 3 provides information on modular robotic systems and the different design strategies. Chapter 4 provides information on the system design synthesis. Chapter 5 discusses the system rapid prototyping iterations and integration. Chapter 6 evaluates the system. Chapter 7 provides the summary of the project and future work in this field. Chapter 8 concludes the report.

2 Methodology

The goal of this project was to design and create a new modular robot, building off existing knowledge and incorporating innovative new strategies. To achieve this goal, a set of objectives were developed:

1. Research existing modular robots
2. Establish a set of design principles for the design of the modular robot
3. Create and evaluate concepts of modular robot designs and inter-module connect mechanism
4. Evaluate the final system with respect to the system requirements

2.1 Research existing modular robots

Initial research was conducted to determine what previous modular robot groups have constructed and how successful these robots were. When researching these published designs, special attention was given to the following defining traits: housing design, attachment strategy, movement/mobility, communication and power.

This information was recorded in the form of pros and cons, and placed in a design matrix to compare the different robot designs.

2.2 Establish a set of design principles

Current modular robots were studied to determine the design principles for this project. The following research questions were used as a guide in the process of developing the team's design principles:

- What was learned from the research of the existing robots?

- What are the design constraints?
- What areas could be improved on from existing robots?
- What are the overall goals of this robot?

Using the knowledge gained from the following research questions, design principles were then established:

- **Size** – The robot should be as small as possible to limit weight and to reduce individual module cost
- **Communication** – Each module must be able to communicate with the others, as well as enabling them to find one another if separated
- **Power** – Each module must have an onboard power source to operate for approximately 10-15 minutes
- **Connector** – Each module must have a way of autonomously connecting and disconnecting from other modules
- **Configurability** – Modules must be able to lift at least one other module and demonstrate self-reconfiguration

These design principles served as the basis of the development of the modular robot.

2.3 Create and evaluate Designs

The design process began by drawing up plausible housing designs for the robot. The housing design consists of the outer frame and the joints required for movement. Multiple housing concepts were designed, each with different outer frames and motion strategies. These designs were then compared to each other and to existing modular robots using team-created design metrics. These metrics helped evaluate the new designs and made sure the designs could accomplish the goals set forth by the project. The metrics can be seen in Appendix A: Design Metrics.

After deciding on the overall design, the focus was turned to other key components of the robot, including module-to-module connection mechanisms, a power supply, a communication device, motors and motion, and other electrical components. All of these had a metric created for them so they could be compared to other ideas and current existing items in robots. It was with the help of the design principles that the design team was able to determine a proper design to meet the set requirements.

3 Modular Robotic Systems

The first step of the project was to conduct research into self-reconfigurable modular robot systems and connection mechanisms. The design team looked at the history of modular robots, current designs and what methods these designs used to reconfigure.

3.1 History of self-reconfigurable modular robots

Early ideas for modular robots began in the 1980s; engineers believed that robots could use a cellular design that would not require the robots to be specialized pieces of hardware, focused on one individual task. Toshio Fukuda, a researcher at the Science University of Tokyo, proposed the idea that modular robots would have three types of modules or cells: LEVEL 1 consists of actuating cells like bending, rotating and sliding joints, mobile cells (wheel, crawler, etc.), and other modules used for motion. LEVEL 2 consists of branching cells, length adjustable arm cells between joints, orientation changing cells, power cells for heavy duty works, and other modules used for structure and power. LEVEL 3 consists of work cells (end-effectors, etc.) and special purpose cells. [2] It is this idea that helped form the basis of some of the more modern modular robots today.

Modular robots have since been categorized into one of three design architectures based on the geometry of the unit: chain type, lattice type, and hybrids. Chain type robots use modules that connect linearly from one module to the next, much like a chain. Communication and control is generally accomplished serially. Lattice type robots use modules that connect in a grid, much like atoms in a crystal lattice. Communication and control is accomplished in parallel. Hybrid type robots are a mix of the two. [3]

The first self-reconfigurable modular robot to be produced was the PolyPod in 1993 [4]. Though it did not have all the features of a true self-reconfigurable system, it did bring forth the idea of having multiple modules connected in different configurations that allowed the system to achieve different gaits.

The next major improvement to the style of modular robots was hybrid style robots. This style took elements from both the chain and the lattice style and put them into a single robot. Hybrid style is the most common in existing modular systems.

3.2 Existing Modular Robotic Designs

There are many existing designs for self-reconfigurable modular robots, all of which have unique features. This section highlights some of the more relevant designs to this project including: SuperBot, M-Tran, ATRON, iMobot, Miche and CKbot.

3.2.1 SuperBot

The first design the team researched was SuperBot, shown in Figure 1 SuperBot was designed by researchers at the University of Southern California (USC) beginning in 2005 [5]. The frame is machined out of aluminum, with each module having three large motors for movement and several smaller motors for actuation of the connection mechanism. The three powered joints give each module three degrees of freedom: longitudinal rotation of each side of the module and transverse rotation of each end of the module. It should be noted that the center rotational joint cannot rotate indefinitely. Therefore, to achieve large radial translations, the module must periodically stop, lift one half and reverse direction to prevent damage to the internal components. By using two side joints and one center joint, the module can inch along on its own or to crabwalk in pairs, in a motion where both ends swing out and pull the center of the

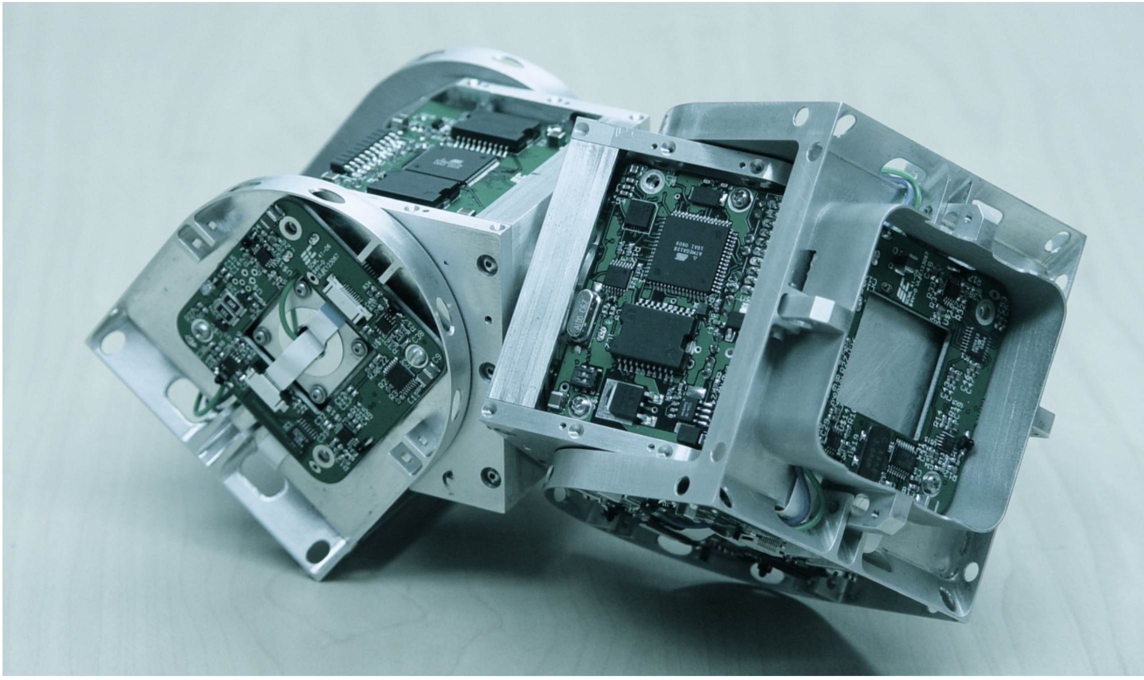


Figure 1. SuperBot

module forward. The frame design is 'common' among modular robots investigated in this project; consisting of two halves, each with a half-square, half-circle shape and connection points on three sides of each half.

The connection method for the modules uses one motor on each connection face that rotates a spiral cutout disc that pushes four hooks in and out, allowing each module to connect. This mechanical solution simplifies connection into one simple, continuous motion. The main drawback of this system is that in order to connect, the modules must be lined up with very little margin of error. Since this requires more precise motion control and accurate location of the modules, it creates additional challenges for the design team.

SuperBot is designed with a distributed computing architecture and an array of different sensors [6]. The main computing power for SuperBot comes from two Atmega128 processor chips. The two controllers use I2C to communicate between each other. One controller is used for power management, one of the motors, the other sensors, and RF communication, while the other controller is used for the other two motors. Each controller also communicates with the three docking faces on its module end. The sensors for each module include an accelerometer for measuring module orientation, potentiometers for each of the motor angles, four infrared receivers and one transmitting LED on each module face to facilitate wireless communication and localization between modules. There is also an RF communication system allowing remote control of the robot. The whole module is powered by a 7.4V, 1600mAh Lithium Polymer Battery.

A SuperBot module has three degrees of freedom, allowing it to move in any direction. Individual modules can utilize available sensors to locate and communicate with each other and then connect together without any outside assistance. Once together, the modules can self-reconfigure into a wide variety of shapes to accomplish different tasks.

3.2.2 M-Tran

Another prominent robot design is the M-Tran (or Modular Transformer), developed by AIST [7] since 1998. The M-Tran design is currently in its third generation, the M-Tran III, shown in Figure 2. This most recent design is compact, mobile and capable of repeated connect and disconnect operations.

Like Superbot, an M-Tran module consists of two cube halves connected by a central bar. Each half rotates about the central bar, allowing one half of the module to lift the other, as well as making the module capable of producing an inching motion along the ground. Unlike SuperBot, the central bar cannot rotate and consequently a single module is only capable of moving in a straight line. M-Tran is also very compact; each module half is only about 2½ inches. Although M-Tran lacks individual mobility, a group of connected modules exhibits nearly unrestrained motion. M-Tran modules have many different documented configurations and many motion solutions based on those configurations.

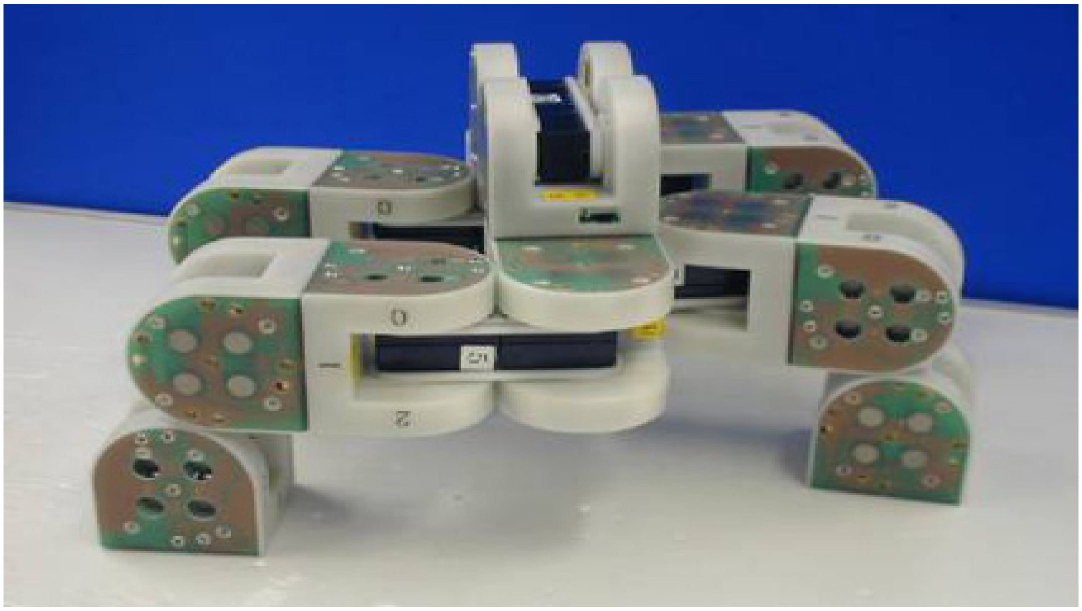


Figure 2. M-Tran

M-Tran has a set of sensors including onboard accelerometers and IR proximity sensors. These allow each module to accurately locate the other modules, which is very important given the chosen connection method. Each connection mechanism is controlled by a single slave processor, while the rest of the computing is done on one master microcontroller. Each module also has Bluetooth in order to communicate between modules and with an off board computer. The whole module is powered by Lithium Polymer batteries. Keeping the number of sensors down reduces the weight and power requirements, allowing for a smaller, simpler robot.

M-Tran's connection mechanism has gone through several different stages. The first and second generations of M-Tran used electromagnet connection mechanisms, while the third generation used a mechanical connection solution. The mechanical solution has two halves, a "male" half and a "female" half. Each of the three faces of the male half has four retractable hooks, while each face of the female half has corresponding openings. The hooks from the male end of the module are extended and retracted by a rotating cam system. This is an innovative design which remains compact, lightweight and repeatable. This design can reconfigure quickly and once the hooks are in place, they require no further electrical power to lock; an improvement over the previous electromagnet connection mechanism.

M-Tran is a simple yet effective design with the ability to easily and quickly reconfigure. Although each individual module lacks some of the more sophisticated features of other robots, grouped with other modules it has capabilities to reconfigure and accomplish many varied tasks. M-Tran also has the ability to reliably reconfigure multiple times.

3.2.3 ATRON

ATRON is a modular robot system designed as a joint effort between schools in the United States and Denmark [8]. The design of ATRON is a sharp departure from other modular robots. Shown in Figure 3, the most noticeable difference is that each ATRON module consists of a single sphere with two hemispheres that rotate about a center ring. Both hemispheres are identical to each other, allowing for “gender-less” connection methods. The module design allows the hemispheres to continuously rotate. A single ATRON module has no mobility on its

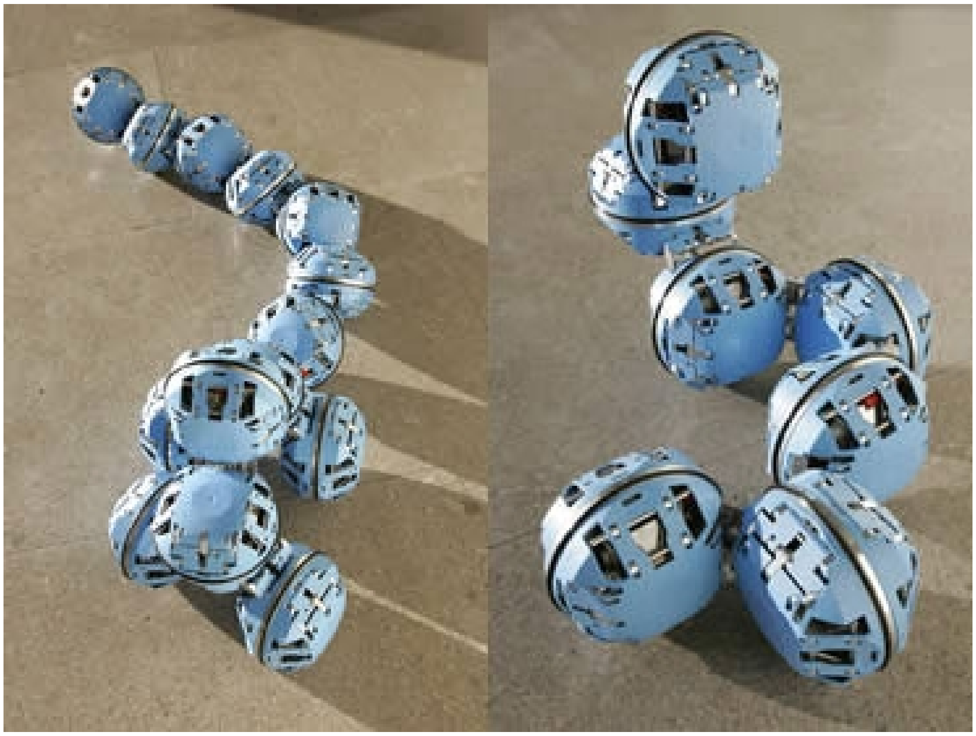


Figure 3. ATRON

own, since it has only one degree of freedom (the spinning center joint). ATRON modules are connected perpendicularly to each other, creating many degrees of freedom and allowing complex mobility.

A key design feature of ATRON is its connection mechanism. It has a universal connector, where each hemisphere has both the male and female connector components. The male connector consists of a set of three hooks that extend and rotate to grip the female connector, which is a metal bar. The connectors are distributed on the module so that the male and female connectors are perpendicular to each other. This allows one hemispheres to only rotate 90 degrees to align with another module and connect. This latching mechanism is simple and repeatable, allowing modules to connect over and over.

ATRON's electronics design is based around a distributed computing system [9]. Each module has two ATMega128 processors as masters and two ATMega8 processors as slaves. There is one master and one slave processor located in each hemisphere. One hemisphere has the master processor responsible for the behavior of the whole module and the connection method for that hemisphere, while the slave processor is responsible for sensor control and I/O control. Sensors include accelerometers to determine orientation, infrared transmitters and receivers for communication between modules as well as rudimentary proximity sensors. The other hemisphere has the second ATMega128 processor involved in inter-module communication and the connection method for that hemisphere, as well as a slave processor responsible for power management. The whole module is powered by two 3.7V LiPo batteries.

One of the main advantages of ATRON is its compact size, owing to its innovative layout. A second advantage of ATRON is the connection mechanism, which is a complex multifunction device. The connection mechanism has electronic contacts on both connectors which are connected to the microcontrollers, allowing the modules to communicate between one another without the expensive power requirements of wireless transmission.

Some of the drawbacks for ATRON's design are its movement and connection capabilities. A single ATRON module cannot move; the most it can do is spin in place. It therefore must be paired with another module initially to operate. One drawback concerning the connection strategy is how securely the modules connect with one another. Unlike traditional cube-type robots which have a face to latch onto, the ATRON modules attach edge-to-edge, resulting in a smaller area and a potentially less stable connection.

3.2.4 iMobot

iMobot was developed at the University of California Davis and combines many of the more common design features of a modular robot with some new ideas [10]. iMobot has a conventional housing design composed of two cube-like module halves connected by a center joint, as shown in Figure 4. Like Superbot and M-Tran, each module half rotates about a center axle, allowing each half of the module to rotate collinearly independent of one another. iMobot

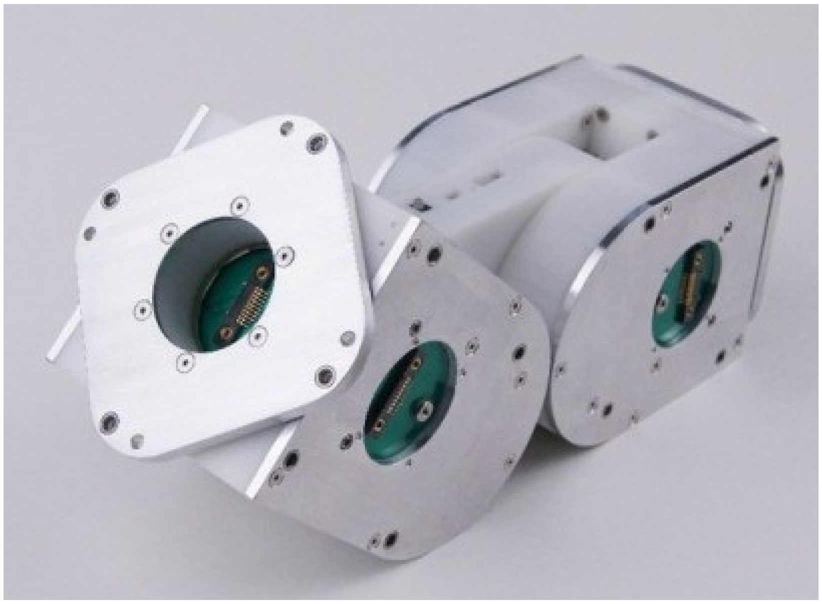


Figure 4. iMobot

also has continuously rotating endplates on the end of each half which can perform multiple functions. This gives a single IMobot module four degrees of freedom. The rotating endplates can be used as faces for connection mechanisms, wheels for driving the module, or to rotate the module relative to whatever surface the endplate is attached to.

iMobot stands out in terms of mobility due to its innovative use of rotating endplates. While iMobot has added degrees of motion provided by the rotating endplates, it also currently lacks a method to self-reconfigure and instead must be manually reconfigured or connected before each task. Despite this, iMobot modules are capable of performing many functions individually.

One of the main consequences of having such a capable system is that all the components add to the weight and space requirements. As a result, a single iMobot module measures about 8" long, almost twice as large as M-Tran. This could potentially limit where iMobot can physically travel or what tasks it can accomplish. Another disadvantage is the lack of any self-reconfiguration capability which could severely limit iMobot's usefulness, requiring more human interaction and limited response to unexpected obstacles.

3.2.5 Miche

The Miche modular robot was designed by MIT [11]. Miche's design is very different from many of the more traditional modular robot designs, demonstrating other possible modular robot strategies. Unlike other conventional modular robots, Miche cannot move on its own. Instead, Miche uses its environment to actuate organization and localization. This is called Brownian motion.

Miche's key advantage over other modular robots is its size; a Miche module is comprised of a single cube that measures 1.77in per side and weighs only 4.5 oz. Miche is shown in Figure 5. Without the need to move under its own power, Miche does not use motors or other means for rotation. The modules does however have motors on board, there are three small pager motors that are used to manipulate the permanent switchable magnets used as the connection method. When a module receives the command to disconnect, the small motor inside the robot rotates the magnet, causing the magnetic force between the two modules to "turn off", allowing the module to break free. This is known as assembly through disassembly.

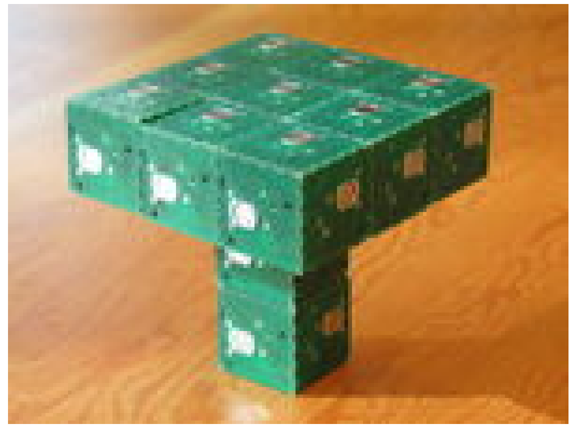


Figure 5. MICHE

Since Miche cannot move on its own, it relies on its operating environment to move toward and away from other modules. Initial design was based around the use of gravity to cause unneeded modules to drop away. Since the current project only requires a module to disconnect once, this is the only force required.

Perhaps the most innovative feature of Miche is the integration of the module circuitry into the mechanical frame. Instead of mounting circuits inside the module, the outer walls of the frame are the circuit boards. This reduces interior space and allows the module to be one of the smallest robots investigated in this project.

Despite its small size, Miche has a full set of sensing and computing components built in. An accelerometer is used to determine orientation, an infrared transmitter/receiver set on each side of the cube is used for both communication and proximity sensing between modules, and the computing for each module is accomplished using an ARM processor and a programmable system on a chip (PSoC) and the whole module is powered by two LiPo batteries in parallel providing a nominal 3.7v with a combined capacity of 340mAh.

Despite its unique and innovative design, Miche has a few major drawbacks. Despite technically being a self-reconfigurable modular robot, Miche modules self-propel and as such cannot reconnect once they have disconnected from another module. Instead the modules rely on a dynamic environment or outside forces that would bring the modules back together.

3.2.6 CKbot

CKbot was developed by the University of Pennsylvania, Mod Lab [12]. While CKbot cannot connect with other modules on its own, it is capable of movement and locating other modules. CKbot uses a cube shaped housing design that is 6 cm (~2.4 in) in size, with one servo rotating the outer set of faces, shown in Figure 6. As a result, CKbot is small and lightweight (~140g) which would allow a single module to travel almost anywhere in its intended search and rescue application.

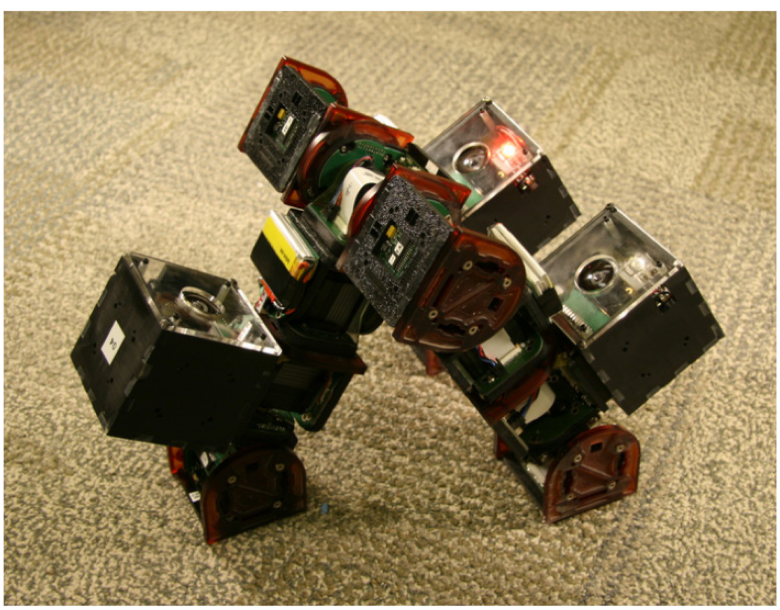


Figure 6. CKbot

A unique feature of CKbot is the use of specialized modules for localization, communication and other tasks. These module types include wireless communication, IR proximity sensors and grippers. While the specialized modules may be large, the capability of the standard modules can be greatly increased by attaching specialized modules. Also, the concept of different types of specialty modules means the capability of the modules can be quickly changed to adapt to different conditions.

3.3 Modular Robot Component Strategies

Many different modular robots have been produced, but only a handful of these are self-reconfigurable; therefore, the design of a modular self-reconfigurable robot should include research into non-self-reconfigurable modular robots. Current modular robot designs are very diverse with each different robot featuring unique designs and solutions to problems [4]. The major design considerations of modular robots are housing design, connection method, communication, movement and mobility, processing, and power.

3.3.1 Housing Design

The housing is a critical starting point when designing a modular robot. The configuration of the housing can determine several key attributes of the robot, including weight, center of gravity, module mobility, and degrees of freedom. This in essence defines what the robot can accomplish; for example, a group of modules may be able to self-reconfigure, but single modules might not be able to move independently of another module. Housing design is full of trade-offs, design teams want more space inside each module for battery packs, motors and computers; but weight and size considerations quickly come into play as a smaller, lighter robot will fit into smaller spaces and use less power. The same tradeoffs apply to degrees of freedom and mobility. A robot with more degrees of freedom will require additional components. As a result of these tradeoffs, modules are tightly packed with batteries, microcomputers, circuitry and motors.

3.3.2 Inter-Module Attachment Strategies

When designing a self-reconfigurable robot, the attachment/detachment mechanism is a high priority; the robot modules cannot just be manually bolted together. This task of attachment is deceptively simple and while it is taken for granted when performed by humans or another external source, it becomes one of the main focuses of the design team. The challenge is straightforward, but solutions are often complex and reflect the aforementioned constraints on space and weight. Research and designs for an attachment strategy were divided into two subcategories: mechanical mechanisms and magnetic mechanisms.

3.3.2.1 Mechanical Attachment Mechanisms

Mechanical Attachment Mechanisms use physical constraints (hooks, clips, locks, etc.) to physically attach separate modules together. These mechanical mechanisms have the advantage of requiring little to no power to stay connected once actuated. In general the mechanical mechanisms are stronger and more durable than most other solutions. However, they are often complicated to manufacture and in general are heavier and larger than other solutions.

A. M-Tran Cam Design

One very effective mechanical attachment mechanism was the cam-driven connector found on M-Tran III. This connection mechanism had four hooks, one on each corner of the face, which slid into, and connected with, a slot on the opposing face, as seen in Figure 7. The four hooks were all actuated by one motor in the center of the face which pushed linear actuators outwards towards the corner of the face. This linear motion moved the hooks on an internal cam and rotated them into a locked position.

This design fully retracts into the module when not in use and extends and locks onto another module with one motion, using only one motor for actuation of each face. Due to this design the entire mechanism is fairly compact and easy to fit in the module. The design was not universal, but a male/female setup, where one half of the module had the connectors and the other half had the slots for the connectors.

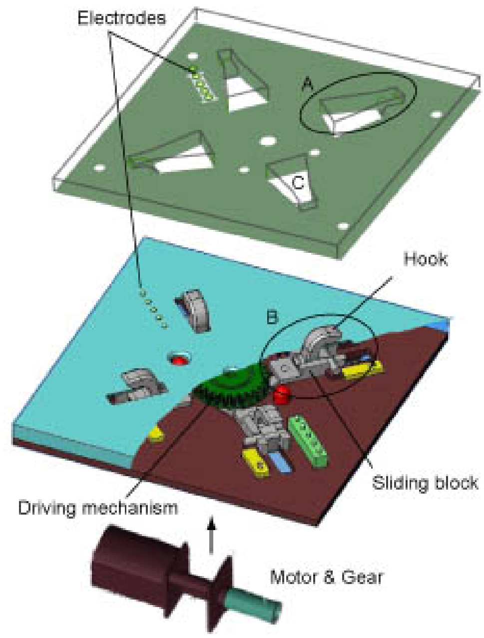


Figure 7. M-Tran Connector [41]

The primary concern with this connection mechanism was the cam that controls the motion of the hook. While the linear action would be easy to generate, the motion required by the hook and cam would be fairly complex. The design and manufacture of both the cam and the hook were also concerns. Since both components would need to be very small, it would have been difficult to guarantee the accuracy of these components. A third concern was the accuracy required for the two modules to connect. With a design like this, the two modules would need to be positioned very close to one another, with little margin of error. This would require the sensors used for determining the modules and the method of motion to be very precise.

3.3.2.2 Magnetic Attachment Mechanisms

Magnetic Attachment Mechanisms use magnetic forces to hold the separate modules together. These mechanisms are in general smaller and lighter than mechanical solutions. Magnetic force is generally more than adequate to hold together smaller modules. In order to connect and disconnect, the magnetic force needs to be switched on and off. There are a few strategies to accomplish this, including electromagnets and switchable permanent magnets.

A. Permanent Magnets

Permanent magnets are made of ferromagnetic material and have distinct North and South poles that in general are permanent. There are four main types or classes of permanent magnets: Neodymium Iron Boron (NdFeB or NIB), Samarium Cobalt (SmCo), Ceramic, and Aluminum Nickel Cobalt (AlNiCo). Each magnet class has different properties, with important differences shown in Table 1.

Table 1. Magnetic Properties

Material	B_r (kGauss)	H_c (Oersteds)	BH_{max} (MGOe)	T_{coef} of Br (%/°C)	T_{max} (°C)	T_{curie} (°C)
NdFeB	12,800	12,300	40	-0.12	150	310
Alnico 5	12,500	640	5.0	-0.025	540	860
Alnico 8	8,000	1,480	5.0	-0.025	540	860
SmCo	10,500	9,200	26	-0.04	300	750
Ceramic	3,900	3,200	3.5	-0.20	300	460

B_r is the maximum magnetic flux density of the material, which is a measure of the strength of the magnet. H_c is the coercive force (hardness) of the material, which is a measure of the demagnetizing force. BH_{max} is the overall energy density, measured in Mega-Gauss*Oersteds. $T_{coef}\ of\ Br$ is by what percentage the flux density changes per degree Celsius. T_{max} is the maximum operating temperature of the material such that no demagnetization occurs. T_{currie} is the temperature at which the material becomes demagnetized.

Neodymium magnets are the strongest and hardest, but these values are fairly dependent on temperature. Alnico magnets are strong and very temperature resistant, but are much softer and easier to demagnetize.

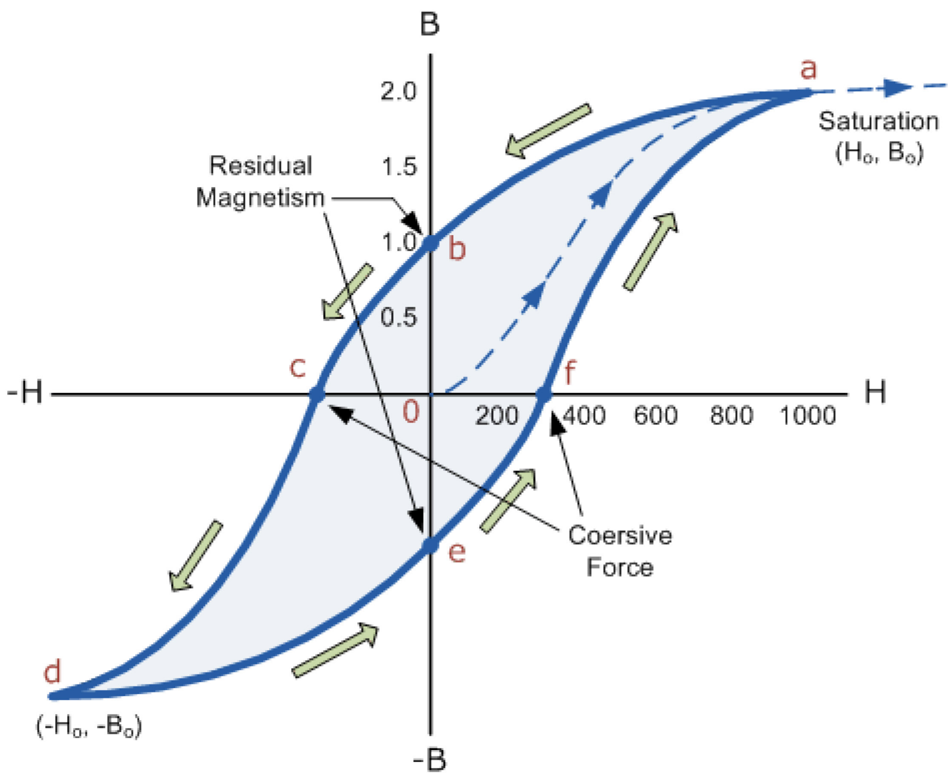


Figure 8. Example B-H Curve. [29]

The flux density (B) and coercive force (H) of any ferrous material are related through a "B-H curve", also called the magnetic hysteresis curve, for that material. The relation between the two is usually denoted as $\mu = \frac{B}{H}$. An example B-H curve is shown in Figure 8. Points a and d are the points at which $B = B_r$ and $H = H_c$, and where the energy density is at a maximum. This is when a magnet is considered "saturated" and is at its strongest.

The one disadvantage of permanent magnets is the apparent inability to easily manipulate the magnetic field. However, there are three methods that were researched to create magnetic fields that are easily manipulated. These include electromagnets, mechanically switchable magnets, and electrically switchable magnets.

B. Electromagnets

Electromagnets use electricity to create a magnetic field. Current flowing through a wire creates a magnetic field around the wire. This field can be concentrated and directed by coiling the wire with the ends of the coil becoming the poles of the magnet. The strength of an electromagnet is directly proportional to the number of coils and the current through that coil. This strength can be further increased by having a ferrous core inside the coil of wire. The main advantage of electromagnets over permanent magnets is the easy manipulation of the magnetic field. The drawback is the continuous current required to create the field.

The magnetic field created by an electromagnet at a distance of L_{gap} is based on a reduced Ampere's Law:

$$NI = B\left(\frac{L_{core}}{\mu} + \frac{L_{gap}}{\mu_0}\right) = H_{core}L_{core} + H_{gap}L_{gap}$$

where N is the number of turns of the coil, I is current through the coil, L_{core} is the length of the core (or coil), and B, H, and μ are properties of the core material, as determined from the material's B-H curve. Assuming that the electromagnet is in contact with the other object ($L_{gap} = 0$), the equation reduces to:

$$NI = \frac{BL_{core}}{\mu} = H_{core}L_{core}$$

Solving for B results in the equation:

$$B = \frac{NI\mu}{L_{core}}$$

This shows that the magnetic field is directly proportional to the number of turns of the coil and the current through the coil.

The force exerted by a magnet in direct contact with a magnetic material is:

$$F = \frac{B^2 A}{2\mu_0}$$

where A is the surface area of the field and μ_0 is the permeability of free space and is equal to $4\pi(10^{-7})\frac{N}{Amps^2}$.

Many robots use electromagnets so that the modules can quickly be connected and disconnected. However, these require a constant supply of power to maintain their magnetic force and can quickly drain a module's batteries.

C. Mechanically Switchable Permanent Magnets

Mechanically switchable magnets are another way to easily manipulate the magnetic field. This method uses two permanent magnets, one fixed and the other rotating. Figure 9 shows the general concept of this method. When the poles of the two magnets are aligned, the flux is directed outside of the magnet and the whole device acts as a single magnet. This causes the overall magnetic strength to be greater than that of one single magnet. When the center magnet is rotated, so that the poles of the two magnets are opposite, the flux follows the internal path between the two magnets, reducing or even negating any external magnetic strength. This allows a permanent magnet to be turned "off". Unlike electromagnets, permanent switchable magnets only require power to switch. Once the magnet is set, the system requires no further power. The disadvantage is that a mechanical force is required to physically move the magnet (either manually by hand, or through the use of a motor).

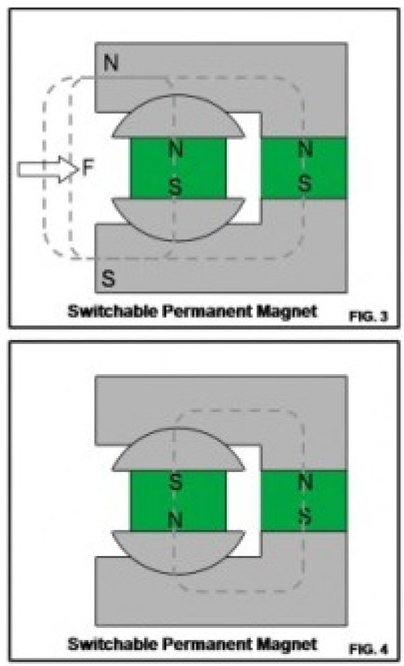


Figure 9. Switchable Permanent Magnet [31]

Mechanically switchable permanent magnets are commercially available and used as temporary mounting and attachment devices for industrial and commercial settings [13]. Miche was one modular robot that implemented this type of switchable magnet as its attachment mechanism.

D. Electrically Switchable Permanent Magnets

A third method that can manipulate magnetic fields is similar to the method by which magnets are originally created. A ferrous material is surrounded by electromagnetic coils and a large current is run through the coils. This creates a magnetic field that, when strong enough, aligns the material, imparting a permanent magnetic field on the material. Similarly, by surrounding a permanent magnet with these coils and running enough current through the coil, the magnetic field of the permanent magnet can be negated or even reversed. The current and number of coils required to reverse the field of a permanent magnet is calculated using the following equation:

$$NI = H_c L_{magnet}$$

Since Neodymium (NIB) magnets have a very high coercive force (H_c), they require an extremely high current to magnetize or demagnetize. Since Alnico magnets have much lower coercive forces compared to the NIB magnets, the current required to change their magnetic poles is much lower. This phenomenon can be used to create a magnet that can be turned "off". This concept is shown in Figure 10.

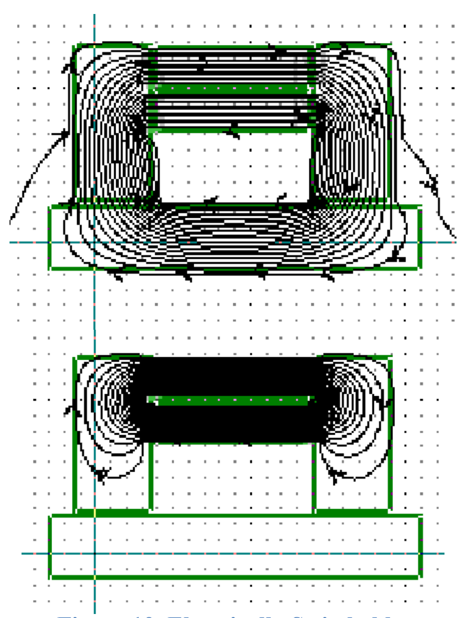


Figure 10. Electrically Switchable Permanent Magnet

This concept requires power only switch the magnet, and also does not require moving parts or mechanical actuators.

3.3.3 Communication Strategies

Communication is an important aspect of any robot system. There are three different systems that modular robots need to communicate with: internal communication (between a single module's components), communication between different modules (both when connected and when disconnected) and any other external communication (such as with a base computer or remote).

3.3.3.1 Intra-Module Communication

Communication between all the different electronic components in a single module is a complicated endeavor. Most internal communication is implemented through wired systems. There are many different wired communication protocols, including Serial, PWM, SPI, UART, I2C, and CAN. Serial communication is the simplest protocol and uses two wires, transmit (Tx) and receive (Rx) to send data. Data is sent serially from the Tx register on one device to the Rx register on the other device. PWM, or Pulse Width Modulation, uses a square wave of varying frequency and duty cycle to send information between two devices. SPI, or Serial Peripheral Interface, uses a 4-wire bus to communicate. The wires are clock (CLK), chip select (CS), master-in-slave-out (MISO), and master-out-slave-in (MOSI). The clock is used for synchronization, the chip select is used to enable the device, MOSI is used for the master device to transmit to the peripheral devices, and MISO transmits data from the peripheral back to the master. UART, or universal asynchronous receiver/transmitter, utilizes two wires; one to transmit and one to receive data. I2C (also known as TWI, or Twin Wire Interface), utilizes two wires, SDA and SCL. SCL is the clock line used to synchronize the two devices, while SDA is used to send the peripheral address and the data to that peripheral. CAN uses two data lines, CANH and CANL. CAN is a differential protocol, meaning that the high or low logic signal is based on the difference between these two data lines.

3.3.3.2 External Communication

Modular robots need a way to either communicate with external computers or get input from humans, this is done through wireless communication. Three main wireless technologies are WiFi, Bluetooth, and ZigBee. WiFi is significantly faster and has a longer range than both Bluetooth and ZigBee, but also uses more power and is more complex. In addition, WiFi can transmit and receive data simultaneously, while Bluetooth and ZigBee cannot.

3.3.3.3 Inter-Module Communication

Modular robots also require communication methods between the different modules. This form of communication can implement either wired or wireless systems, or a combination of the two. Wired communication methods generally have much faster data transmission rates, but also require a physical connection. Wireless methods are generally more complex, more power hungry, and larger due to the components involved. Many modular robots utilize a combination of both wired and wireless methods. A popular alternative wireless technique uses Infrared transmitters and receivers to implement a wireless serial communication protocol. This method is simple to implement, but requires line-of-sight to operate.

3.3.4 Mobility Strategies

Mobility of the system is one of the most important design considerations for the modules. As part of the design, it is assumed that the modules will need to be able to move towards one another in order to connect and form an assembly. While an individual module is not expected to travel very far, it still needs to move quickly to connect with other modules and to reconfigure. The existing solutions to this problem vary greatly, from some modular robots incapable of moving as single modules, to other modular robots that can travel rapidly over open ground with wheel-like endplates. The most common method for moving the modules is to rotate motors located in each side joint of the module, one joint per half, to rotate the outer faces up and down. By controlling the way the joints rotate, the module can inch along the ground. This is a slow, but simple and effective motion solution. This is an acceptable method since the module achieves motion by using the same mechanism used to position the module during reconfiguration. This makes up for the slow speed by allowing the module to have a simpler design. IMobot is a robot that uses a wheel-like endplate on both ends of a module that is driven by a motor. These endplates serve a dual purpose of connection points and can continuously rotate to create a driving motion, which is much faster than inching.

Full system mobility is necessary for individual module design. Individual module weight versus connection mechanism strength and lifting strength because, each module may have to be lifted by other modules; the less each one weighs, the less power needed to lift the module. In this area, the main objects of concern are the motors, the degrees of freedom each module has and the connection method and its ability to work repeatedly, reliably and quickly. When grouped together, simpler modules gain an advantage over more complex modules. While by itself, a module with only one or two degrees of freedom may be limited in its functionality, when grouped with other robots, the group of robots can move the individual modules around to any position required. This allows smaller, simpler modules to function as effectively as a group of more complex robots that have up to three degrees of freedom.

4 System Design Synthesis

The major design considerations for this modular robot are housing design, connection method, communication, movement and mobility, processing, and power. The housing design was the foundation for all additional considerations since it limits the usable components. The remaining considerations: connection method, processing, communication, sensing, and motion, were limited by the available power and space.

4.1 Housing Design

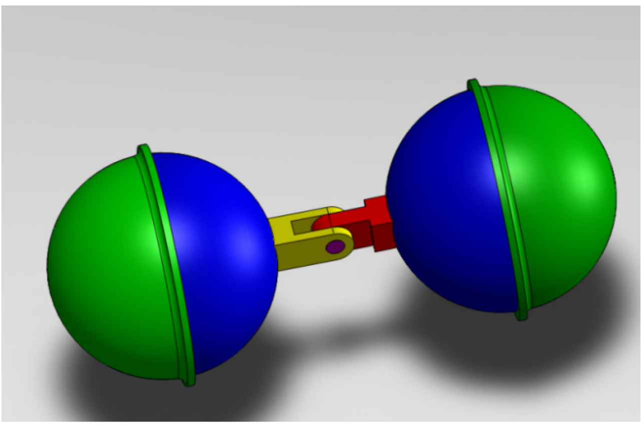
Using the background knowledge gained from studying existing self-reconfigurable modular robots, three separate modules were designed.

AM-Tran: The first housing concept was the AM-Tran, shown in Figure 11a. This concept blends the housing forms from both M-Tran and A-Tron. It includes a pivoting center link that connects the two halves of the module. Instead of the halves being cubes, the design for the AM-Tran used two spherical halves. These spherical halves would be able to spin along their centers. With the pivoting center link and the two spinning spherical halves, this design gives the robot three separate degrees of freedom, allowing complex motion from both a single module and multiple connected modules.

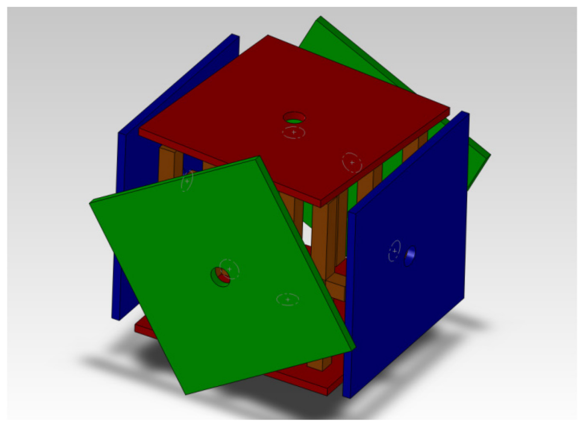
Super-Tran: The second housing concept was the Super-Tran, shown in Figure 11b. This concept took inspiration from both M-Tran and SuperBot. Super-Tran is made up of two cube halves connected by a rotating center joint. This design gives the robot three degrees of freedom from both a single module and multiple connected modules.

Spaceframe: The final housing concept was the Spaceframe, shown in Figure 11c. Inspiration for this modular concept came slightly from Miche and Robot Pebbles and was aimed at thinking outside the box, compared to the other concepts. The focus for Spaceframe was to make a housing design that consisted of only one cube, making the module smaller. Each of the six sides of the Spaceframe is capable of rotating a full 360 degrees. These six spinning sides give the module two degrees of freedom both as a single module and as multiple connected modules. However, there is no way for the modules to lift each other.

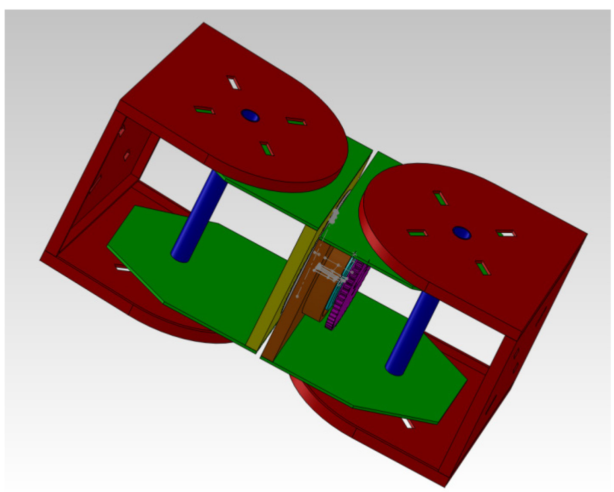
The team then took these three concepts and compared them to the existing self-



a) AM-Tran



b) Supercube



c) Spaceframe

Figure 11. Initial Prototype Designs

reconfigurable modular robot designs to see which one of the three concepts was the best. Through the background research we determined the design metrics for this comparison:

- Completely self-contained in the module or not
- Overall module size
- Individual Mobility
- Group (or connected) mobility
- Ability to self-reconfigure
- Ability to localize and find other modules

The individual and group mobility metrics were broken down into two subsections: speed and degrees of motion. The metrics were on a scale of 0-10, with 0 being the worst and 10 being the best. The analyses of these metrics are shown in Appendix A: Design Metrics. Based on these metrics, the Super-Tran housing design was chosen for this project.

4.1.1 Overall Module Size

The module size was based off research into existing designs and input from project advisors and changed multiple times as the project progressed. The size of a module face is used to identify the size of the module (i.e. a module with a 4" face is called a 4" module).

The initial prototypes were designed to have 4" square faces on each half module. This would result in an overall module size of 4" wide x 4" tall x 8.25" long. The extra .25" of length is a result of the center joint that connects each half module. Since these prototypes were meant primarily for visualization and would only hold Vex motors for movement, size was not critical. A 4" size was chosen since it would allow the mounting of the Vex motors and would give the team a rough idea of the final module size.

Later prototypes retained the 4” size, since these modules were built to test the center joint and side gears that would be used in the final module. These modules also held only motors for testing. The objective of the team was to make the module as small as was feasible, while meeting all other requirements. Early on in the project, the team established that the final module would be between 3” and 3.5”. Once specific components were selected based on this requirement, the team was able to pick a final module size.

Beginning with the RP (rapid prototype) module, the module size was reduced to 3”. This was an ambitious step for the project, as a 3” module would be just large enough to fit all the necessary components. A few iterations of the module were made and assembled to test the design. The module was capable of holding all the components, but was never fully outfitted. Namely, the battery and microcontroller did not need to be mounted since the module would run tethered and the mounting hardware for these parts was not yet finalized. After the RP module was sorted out, an aluminum version of the module was made. This metal module could not be used due to problems related to the machining process having different tolerances than the RP process. After this module was machined, the team made a decision to increase the size by 1/8” to compensate for the tolerance issues and to make assembly easier. This resulted in a 3.125” module, which is comparable to existing modular robots such as SuperBot (3.3”) and M-Tran (2.5”).

4.1.2 Center Joint Design

Once Super-Tran was chosen as the housing design, work began on designing the center and side joints, to allow the module to move. The center joint would have to be able to rotate at least 270 degrees in either direction from a neutral starting position. It would also need to have numerous wires run through it for power and signals to the motor controllers.

An initial idea for this was to construct a continuously rotating joint that utilized electric conduction rings, like the ones used in ATRON. This would eliminate the wires and by doing so, remove the limiting factor in rotating the center joint. Unfortunately, this idea was unfeasible due to the complexity of the joint and the number of connections the joint would need to have between the two halves. It was determined that these drawbacks outweighed the advantages we would get from using it.

Another idea, and the one used on the final design, uses a protruding cylinder from one halve that fits into a circular hole on the other halve. A Teflon sleeve goes in between the two halves (around the cylinder) to reduce friction. There will also be a thrust bearing located between the two halves of the module and another one located on the inside of the female end of this connection. This bearing will be placed there because the two halves will be pulled together/held in place by a gear being mounted to the cylinder sandwiching the two halves together. A picture of the joint can be better seen in Figure 12.

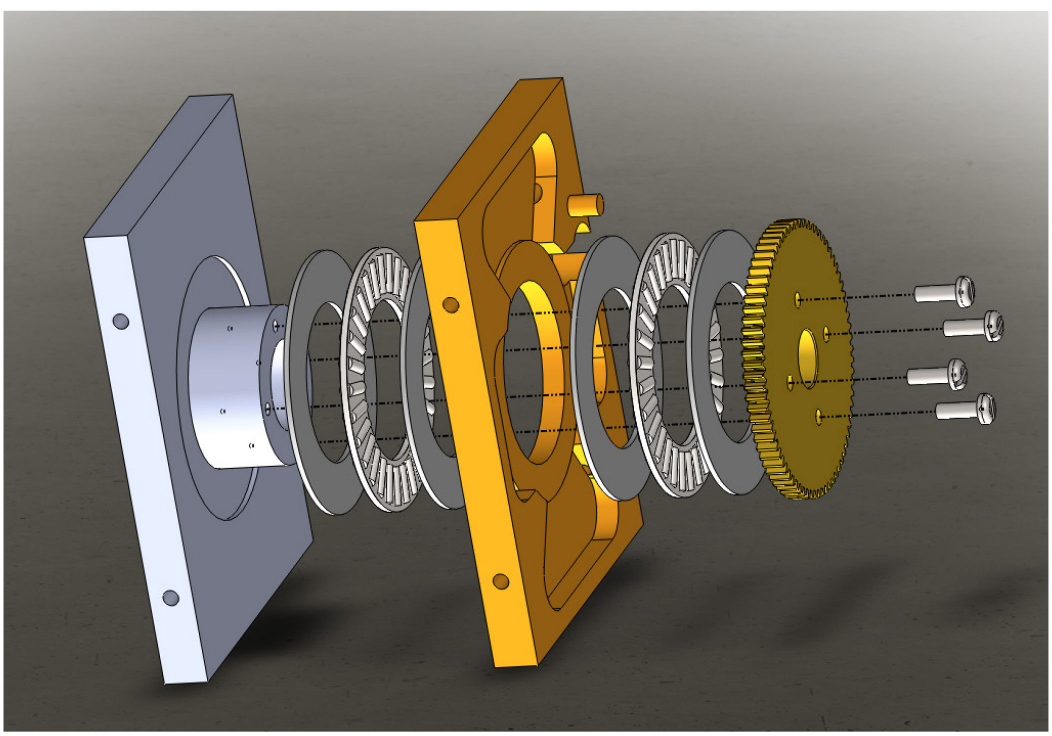


Figure 12. Center Joint

4.2 Connection Mechanism

The next step was to design the connection mechanism. There were many ideas tested for the connection of the modules. The connection mechanism must be capable of repeated connects and disconnects, be strong enough to hold one module against gravity, and must connect and disconnect quickly. The ideas and designs this project team looked at fall into two main categories: mechanical connectors and magnetic connectors.

4.2.1 Mechanical Connector Designs

Many different and innovative mechanical connector designs were discussed. While mechanical connectors usually take up more space and are generally more complex than magnetic solutions, they also have the advantages of requiring no power once connected and generally connecting and locking much more securely.

4.2.1.1 Slots

The first possible design used four slots cut into the face, making a female face of the module. The male half would then have four connectors that stick out of the module face. These would be able to extend as the two faces approached each other until they were through the slots cut out of the female face. Once inside, the connectors would then rotate 90 degrees and slide into shallow cutouts on the inside face of the module. The mechanism would then pull the two modules together and lock in place.

This design was more practical than the cam design, but a little less elegant. This connection mechanism would need a lot of space to fit all of the mechanics. The area required would have been roughly the same size inside the module, but would have also taken up additional space on the outside of the module. The main advantage of this design was that it would have a much larger margin of error for the modules when lining up to connect. This was achieved by the connectors and slots were designed so that the module faces could be apart by as much as 1/4" and did not have to be exactly aligned to connect. A concept of this design is shown in Figure 13.

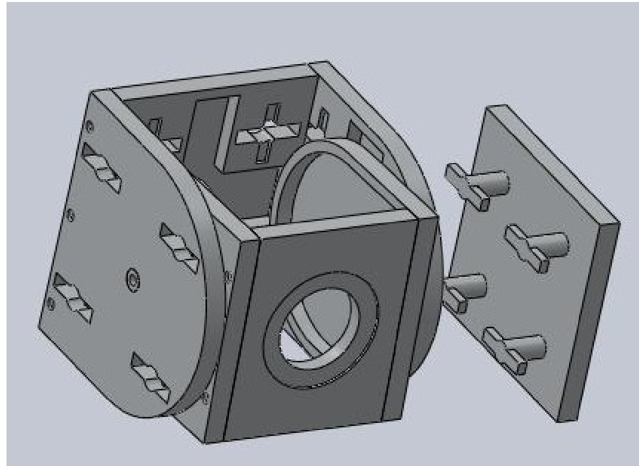


Figure 13. Slot Connector

As mentioned above, this design was not universal, but had a male/female design. Also, this design involved both linear and rotational motion of the connectors using one motor, which was another problem. Early designs involved using one motor to push the connectors in and out and another to rotate the connectors. This would, at a minimum, require two motors per side, which would have taken up too much space and added too much weight.

As more work was done, additional changes were made to the slot concept. One major change was to change from a male/female setup to a universal setup. This was achieved by mixing 2 slots and 2 connectors on each face, with the slots at opposite corners of the face, giving each face the ability to be both male and female at the same time, as shown in Figure 14. This idea was not without its challenges,

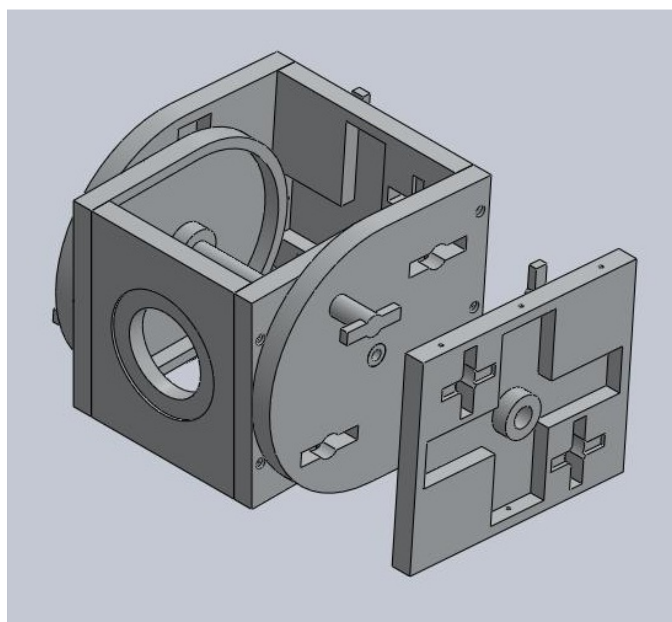


Figure 14. Universal Slot Connector

since one of the module faces would likely need to rotate 90 degrees in order for the connection to take place. However with the rotation capability of the center joint, this challenge could be dealt with easily.

The next iteration of this basic design used a slot cut into the connector to achieve linear and rotational motion with one motor, as shown in Figure 15. This slot was curved along its length; a wheel driven by the motor travelled in the slot. As the wheel turned, the connector would move in or out and rotate according to the curve in the track. Although this did not allow the connector to rotate independent of position, it combined the linear and rotational motion, cutting down the number of motors needed.

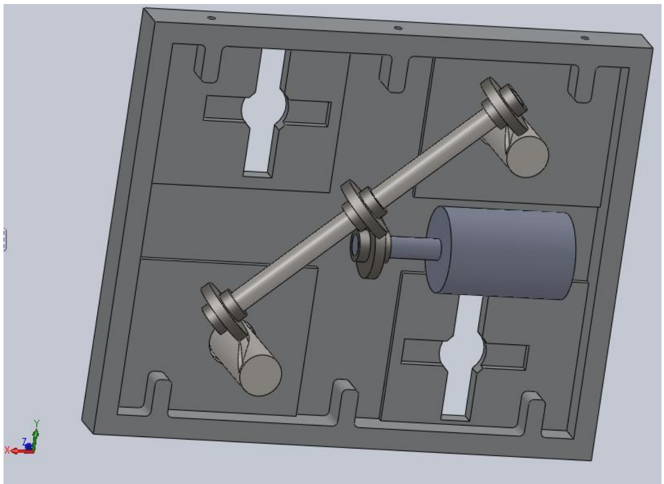


Figure 15. Slot Connector with Cutout

This new idea had challenges of its own. In addition to not being able to control the rotation separate from linear motion, there were doubts that such a small cutout could be made accurately. There were also questions about the wheel being used to move the connector and if it would be able to follow the cutout. As a result, despite the promise of this design, the problem of linear motion and rotation had to be resolved before this design could be used.

4.2.1.2 Drum Brake/Hooks

After the slot based design was ruled out due to problems with moving the connectors, a new idea loosely based off the slot design was considered. This design would be similar in that it would have connectors that stuck out from the module. Here the design takes a different turn.

Instead of having a two part connection system with a connector and slots the connectors fit into, this system has a set of 4 hooks on each module face, as shown in Figure 17. These hooks cannot move in or out, but can move side to side along the face.

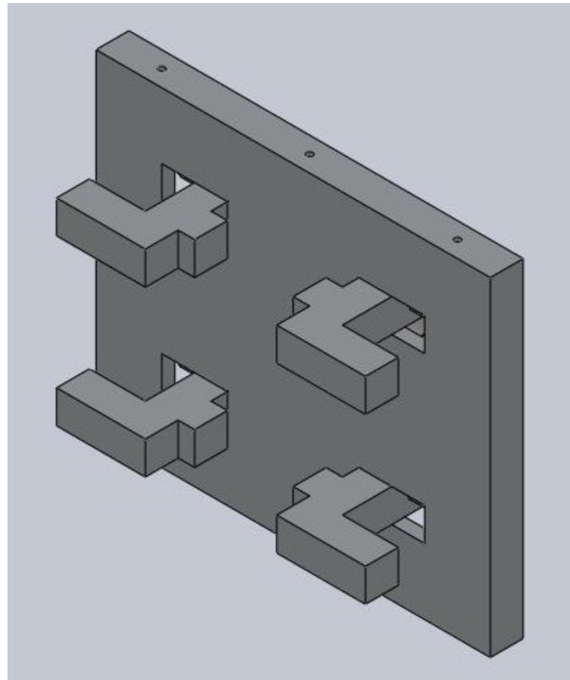


Figure 17. Hook Connector

As one module approaches another, both sets of hooks would be in their 'dead' position. Whether this position is towards the outside of the face or to the inside is somewhat arbitrary. Assuming this position is to the outside, then as the two modules approach, then the hooks of the 'male' module would move inwards until the two faces were in contact. At this point, the hooks would then slide outwards until they connected with the hooks on the 'female' face. The hooks cannot pull apart unless the 'male' set is retracted back towards the center of the module. The mechanism to drive the hooks is shown in Figure 16. One motor drives two threaded bars to move the hooks in and out. Using only one motor per module face makes this mechanism more compact than previous ideas.

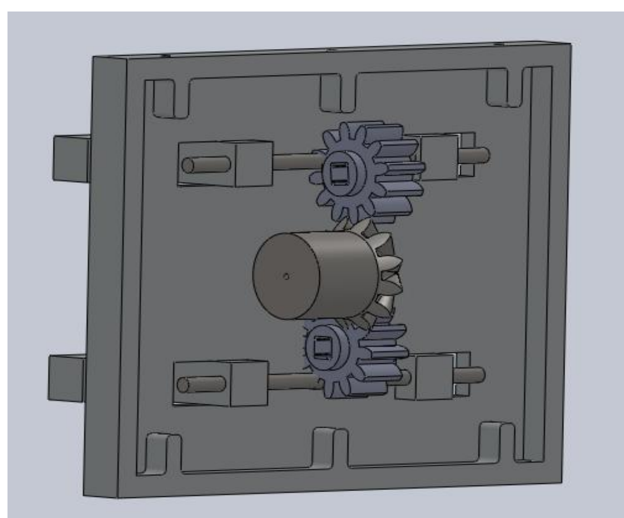


Figure 16. Hook Mechanism

Another version of this design uses the same mechanism to drive it, but instead of hooks, uses a connector shape that looks like a half circle, as shown in Figure 18. This connector would provide more area to hold on to and would also have fewer components.

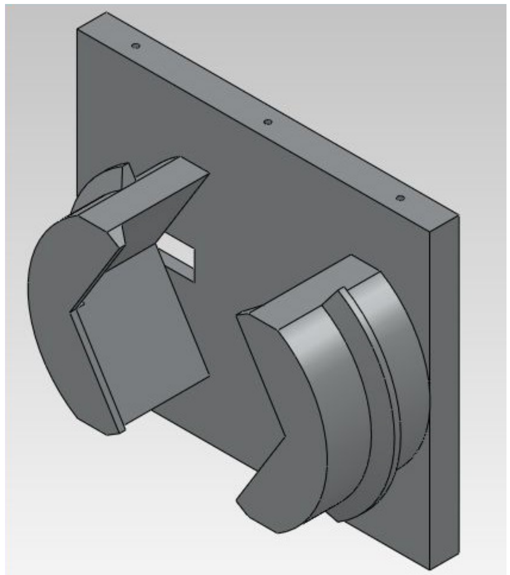


Figure 18. Drum Connector

4.2.1.3 Screw Connector

Another mechanical connection design uses the idea of pushing screws inward and outward to connect and disconnect from another module. The mechanism would use a single big gear which would drive four smaller gears with a screw running through each of those four gears. In order to have this work the point of the screw would be screwed into the outer housing wall as well. As the gears turned the screw it would use the ‘bite’ it has into the outer connecting face to be able to screw inward and outward.

This connection mechanism would be able to fully retract into the module when not in use to and it would create a very strong connection to the other module by having a four point connection. For this design we would also need to have male and female connectors which would require male and female parts. This male and female connection style would limit possible connections and require all the connections to be done in the certain male/female order.

There were many problems with this connection mechanism. For this connection mechanism we would have to have the modules line up exactly with each other. If the modules did not line up exact we would have the issues with the screws not properly being able to get a 'bite' of the other module and connect properly. Along with that we would have issues with making sure the screws stay 'bitten' into the gears and the module on the male side. For through using the mechanism numerous times the screw would adjust itself inside the gear and the housing that it has the "bite" of and would possibly cause issues with continuing to run reliably and how we want it to.

4.2.1.4 Spiral Connector

Another attachment design idea utilized a flat wheel that contains four intertwined spirals that meet at the center of a flat disk. The module has 4 teeth, one per spiral, that ride in a cut out "X" path meeting in the center of the module face. The teeth are constrained to the path and the spiral is used to both push the "teeth" both towards the center of the face as well as towards the outer edge. To interlock, each module rotates the motor controlling the connecting face, the first module pulling the 4 "teeth" inward while the opposing modules rotates it's "teeth" outward to interlock the two. This design was designed to have the teeth follow a shallow incline such that when fully retracted, the teeth would be flush with the outer face and when pulled inward the teeth would protrude out of the face of the module to attach to the opposing module face.

4.2.1.5 Current mechanical connector (prototyped)

A mechanical connection mechanism was design using four hooks that would actuate in and out of the model. These hooks, illustrated in Figure 19, would be driven by a single Pololu micro metal gearmotor [14]. This motor was chosen due to its miniature size, and the amount of torque they are able to produce. There are two rods running the length of the connection mechanism which the hooks are mounted directly to. These rods are then actuated by the motor through a one to one gear ratio. The hooks were made to be able to hid completely inside the

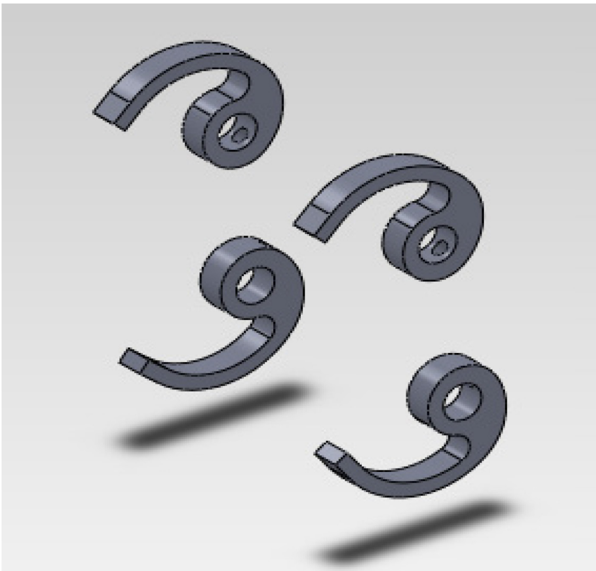


Figure 20. Mechanical Connector Hooks

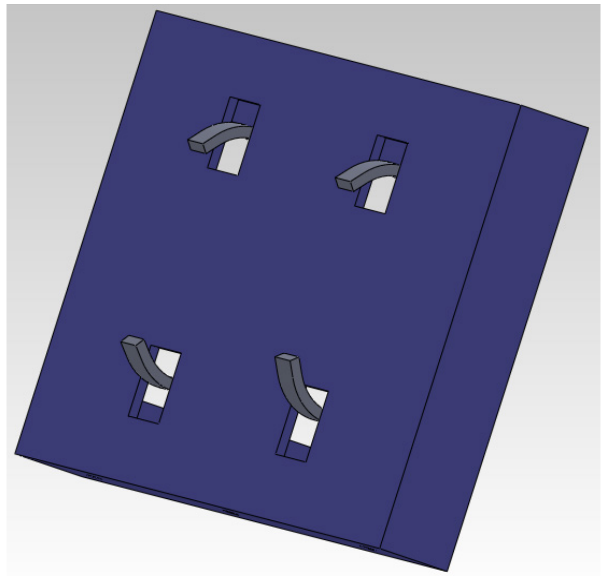


Figure 19. Mechanical Connector Face

module, yet be able to extend in a manner to be able to grab onto the module it was connecting to at a distance of 0.125 inches away and pull the two modules together so their faces are flush. A picture of the connection mechanism design can be seen in Figure 20.

4.2.2 Mechanical Switching Magnet

In addition to looking at purely mechanical connectors, ideas were also discussed that would use magnets as the connector. The first idea was to use permanent magnets to hold the modules together, since these require no power to do so. An obvious disadvantage is the apparent inability to then disconnect. A solution is to physically reorient the magnets so that they are then opposing the other module.

One of the first ideas for this concept was to have 8 magnets on each face, two at each corner and to move these to disconnect. When in their normal state, the magnets would be oriented so that they would attract the magnets on the other module face and therefore connect. To disconnect, one magnet on each corner would be flipped or spun so that now each pair of magnets would cancel each other out, thus effectively turning the magnets "off". This would then allow the modules to pull apart. The concept behind this idea was tested and proven in many industrial settings; however the problem of rotating the individual magnets would have required a complex mechanism, defeating the purpose of the physically switchable magnets.

The idea then evolved to only use 4 magnets, as shown in Figure 21 and Figure 22. Two would be on the module face and two would be on a rotating disc mounted on the module face.

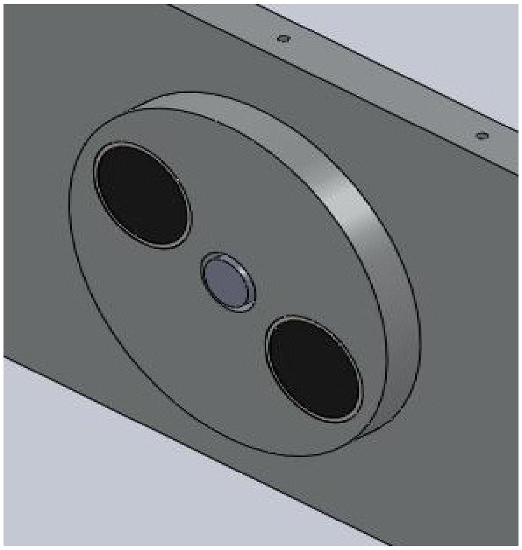


Figure 21. Switchable Magnet Concept (front)

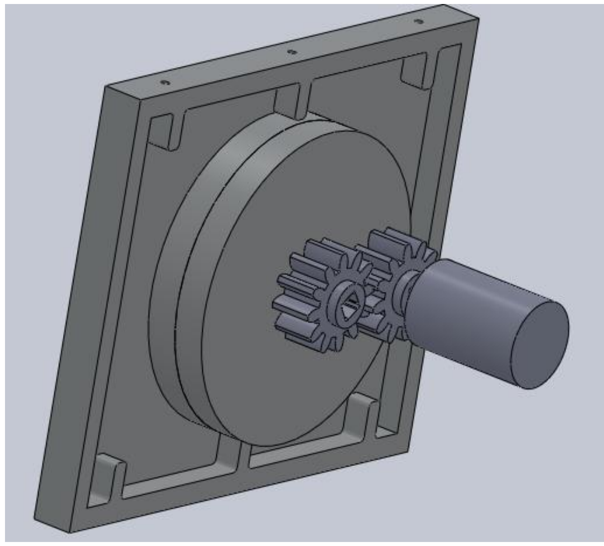


Figure 22. Switchable Magnet Concept (back)

The disc would rotate, reversing the poles of the magnets and turning them "off". The main challenge for this connection strategy was to determine how to best position the discs and how to direct the force of the magnets. Due to space constraints, special diametric magnets were ordered. Unlike traditional magnets that are shaped like a bar with one end North and the other South, these magnets are disc shaped with one half of the disc North and the other half South. This has the advantage changing the magnetic pull by simply rotating the set of magnets, rather than by flipping the magnet, which would be more difficult.

4.2.3 Electrical Switching Permanent Magnet

In addition to looking at using a mechanical solution to switch magnets, an attachment mechanism using electrically switchable magnets was designed. While this had already been done on a much smaller scale with MIT's robot Pebbles [15], the viability and implementation of a design for 6 inch modules needed to be determined.

4.2.3.1 Magnet Design

Of the classes of magnets shown in Table 1, Alnico is the best choice for the switching magnet. It has a high magnetic density, which translates into a strong pull force, while also having a relatively low coercive force, requiring less current to manipulate the magnet. There are multiple grades of Alnico magnets, and in general the higher the grade, the higher the coercive force and the lower the magnetic density. With this in mind, the second round of tests used the Alnico 5.

A couple ideas were designed and tested. The first involved using the poles of two 1" magnets as the corners of the attachment mechanism, as shown in Figure 23a. This would require only two magnets per face and would take up less space, but it also would not be as strong as the second design. The second design would use the poles of four ½" magnets paired with Neodymium magnets, as shown in Figure 23b. This design would be more complex and require 8 magnets per face, but would also be much stronger.

Both designs were tested and it was found that each magnet in the first design had a pull force of 575g against steel and each magnet pair in the second design had a pull force of 425g against steel. The magnets in the first design required a voltage of 90V to switch, while the magnets in the second design required only 40V to switch. The realized magnets from the second design are shown in Figure 24.

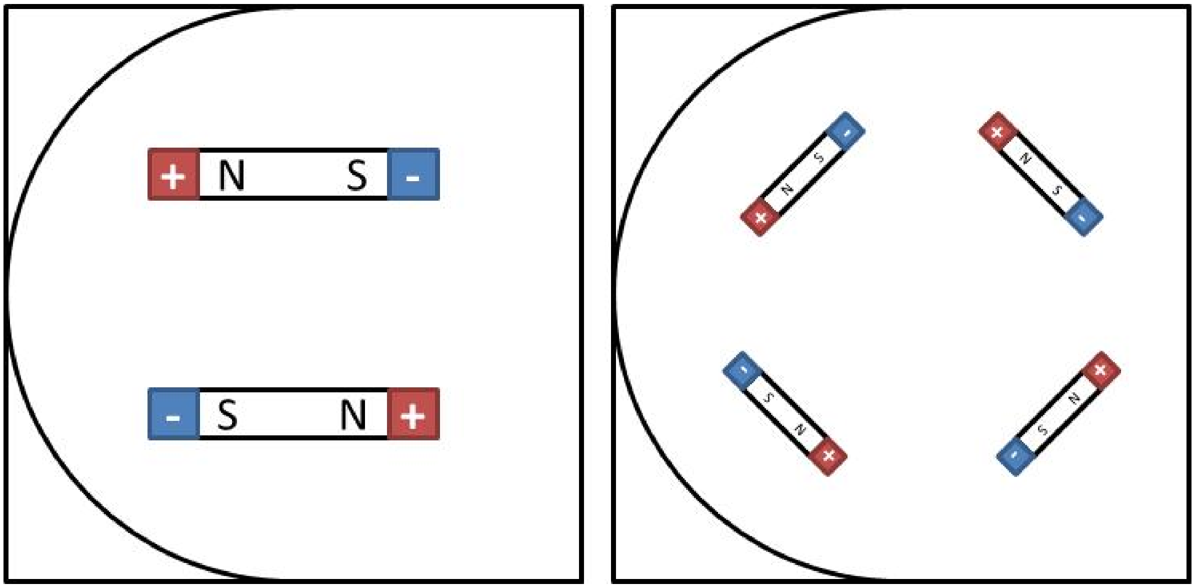


Figure 23. (a) Design 1. (b) Design 2.

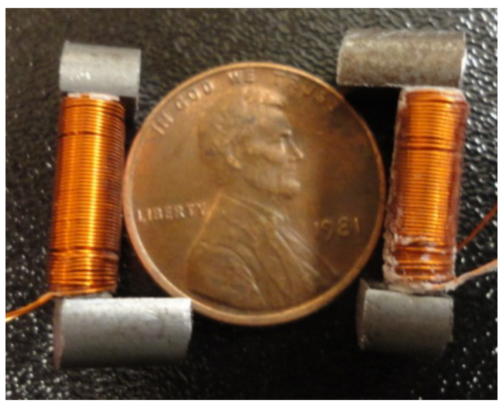


Figure 24. Magnet Design 2

4.2.3.2 Circuit Design

The circuit to electrically switch a permanent magnet requires a couple key concepts. First, the direction of the current through the coil around the magnet must be switchable in order to switch the poles back and forth. Third, the circuit needs to produce a high energy pulse that is discharged through the coil. Finally, the circuit components need to withstand a short, high current spike.

The basic plan behind changing the direction of current through the coil uses the same configuration as most DC motor controllers; an H-bridge. This basic circuit configuration is shown in Figure 25. It consists of four switches connected in an “H” around the motor (or in this case, the magnet coil). When the opposite corner switches are turned on, the current flows through the motor. Depending on which corners are turned on, the current will flow in one direction or the other.

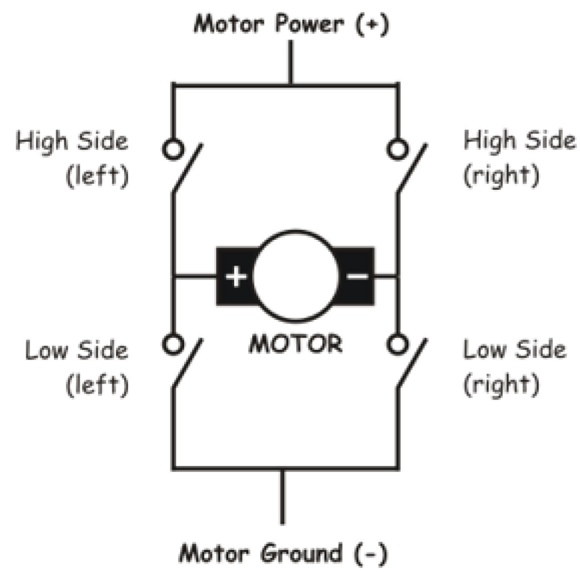


Figure 25. Basic H-bridge Circuit. [34]

The next part is creating a single, high voltage pulse to deliver the proper current through the coil. This is accomplished through charging a capacitor. In order to step up the voltage from a low battery voltage to the required voltage for switching, a step up transformer circuit is used. For early prototypes, the charger circuit from a disposable camera was used to charge the capacitor. This circuit charges the capacitor, which is then used as the source for the coil circuit. The capacitor is able to generate the high energy pulse required to switch the magnetic poles.

The final constraint is finding circuit components that can withstand very high, short, current pulses. This constraint is not terribly difficult, since most electronic components can withstand much higher pulsed currents than their rated continuous currents.

4.2.3.3 Early Prototypes

In order to determine the possibility of being able to electrically switch larger permanent magnets, some Alnico grade 8 magnets were bought. They were 0.5x.25" cylinders that were axially magnetized (meaning that the poles were on the ends of the cylinder). One of these magnets was then wrapped in 120 turns of 32 gauge copper magnet wire. This first test was just meant to replicate the effect that was used in Pebbles' mechanism. This used a 100µF capacitor charged to 20V that then dumped the charge through the coil, ideally switching the magnet. Unfortunately, since the magnet grade was higher and the magnet length was longer, the current required to switch the magnet (and thus the charged capacitor voltage) needed to be much higher than expected. In order to simulate the switching, a transformer circuit was used to increase the charged voltage (and thus the discharging current). Voltages from 20-200V were tested and caused switching at greater than 100V. This showed that the concept was possible.

4.2.3.4 Prototyping

Once the early prototype confirmed the feasibility of electrically switching magnets, an iterative process was started between designing and improving the circuit in Multisim and building and testing the circuit with physical components. The main problems arose with being able to control the direction of the current pulse through the magnets and having those same components able to withstand the high current pulse required. There were two types of electronic switching components tested to determine the best switches for the H-bridge: SCRs and MOSFETs.

SCRs (or silicon controlled rectifiers) function similarly to a normal diode, but also include a gate (Figure 26). When there is no gate current, the SCR is "off" and only allows a leakage current through from the anode to the cathode. When the gate to cathode voltage becomes high enough, the SCR turns "on" and allows current to flow, just like a normal diode. Once the SCR is on, it cannot be turned off until the current drops below the latching current. There are a few main advantages of an SCR. First, the diode characteristic prevents current from flowing in the opposite direction. Second, the breakdown voltage and allowable through current

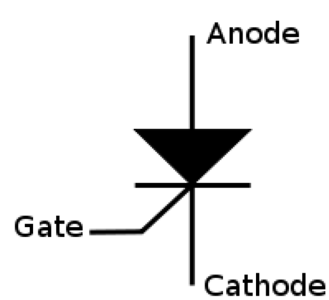


Figure 26. SCR circuit symbol

are both usually very high (100-1000 volts and 10-50 amps). Third, the gate voltage required to turn the SCR on is relatively low (usually between 1 and 4 volts).

MOSFETs (or Metal Oxide Field Effect Transistors) are voltage controlled switches (Figure 27). When the gate voltage is low, the MOSFET is "off" and only allows a leakage current between the drain and source. Once the gate-to-source voltage becomes high enough, the MOSFET turns on and allows current to flow. In the final design, MOSFETs were chosen due to the ability to switch them both on and off.

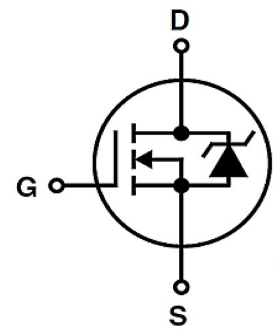


Figure 27. MOSFET circuit symbol

The next issue was getting both MOSFETs to fully turn on and allow the current pulse to flow through the electrically switchable permanent magnets (ESPMs).

4.2.3.5 Functional ESPM Design

The final iteration of the switching circuit is shown in Figure 29 and Figure 28. It shows one face of the ESPM attachment mechanism. The H-bridge configuration is accomplished by the four N-channel MOSFETs (IRF840). One face has four ESPM magnets connected in series in place of R1. All of the 100kΩ resistors are used to pull down the MOSFETs, forcing them "off" until switching is required. Control of the h-bridge is accomplished through two optocoupler transistors. These are used to isolate the high voltages required to activate the MOSFETs and the digital outputs of the microcontroller. A digital output to one of the optocouplers turns on both U6 and U2, causing the current to flow through the magnets in one direction, while a digital output to the other optocoupler turns on both U3 and U7, causing the current to flow through the magnets in the opposite direction.

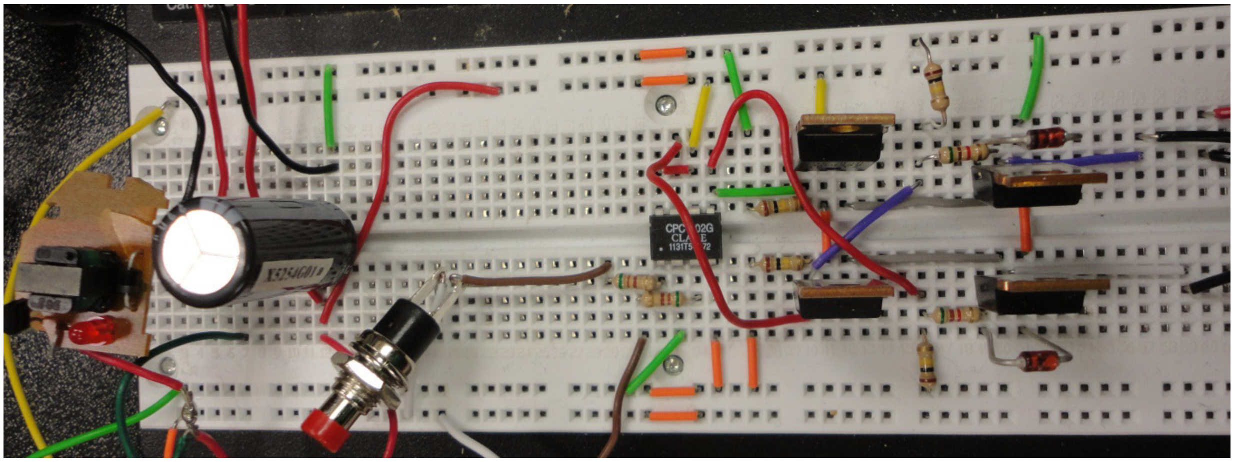


Figure 29. Realized Switching Circuit

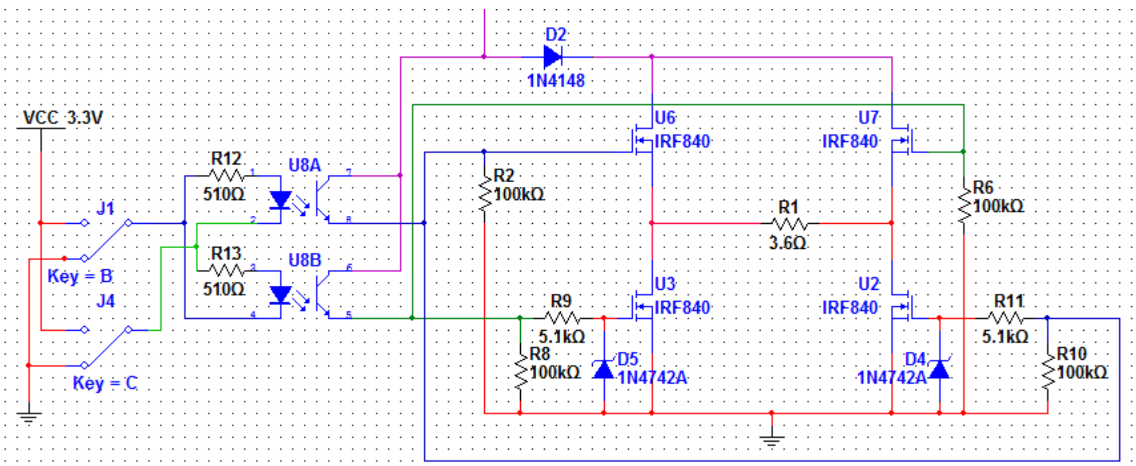


Figure 28. Switching Magnet Circuit (Multisim)

There were a couple of strategies tested to charge the capacitor and generate the current required to switch the ESPM. The first method uses the charging circuit for a flash from a disposable camera. The charging circuit diagram is shown in Figure 31. The charging circuit was meant to step up the voltage from a single AA battery (1.5V) to over 300V, which was then used to power the camera flash. The second method uses a MAX8622, an IC developed by Maxim designed to charge the flash in higher-end cameras [16]. The MAX8622 is a flyback switching regulator that is used in conjunction with a transformer to step up the voltage from a battery.

PCB boards were designed and printed using ExpressPCB [17] for both the switching circuit and the charging circuit using the MAX8622. The PCB switching circuit and charging circuit layouts are in Appendix E. Printed Circuit Boards. A pin out is used to inform the microcontroller when the circuit is ready to discharge. The charging voltage of the capacitor can be chosen. The final soldered switching PCB is shown in Figure 30.

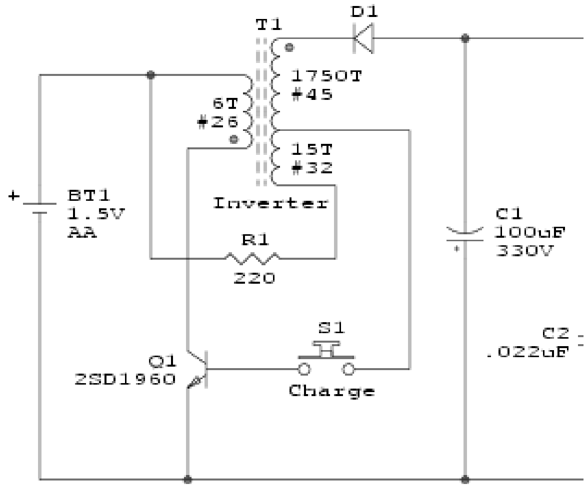


Figure 31. Flash charging circuit

In addition, a Solidworks model of the module faces was redesigned to incorporate the ESPM design into the faces. The CAD models are shown in ?reference?. The pieces are designed to have a special mount for the ESPMs so that the system is universal and simple to change if the housing is modified. The faces and mounts for the ESPM were 3D printed and built to test the feasibility of the system. This final assembly is shown in Figure 32. The ESPMs were then connected to the switching and charging circuits and switching was tested.

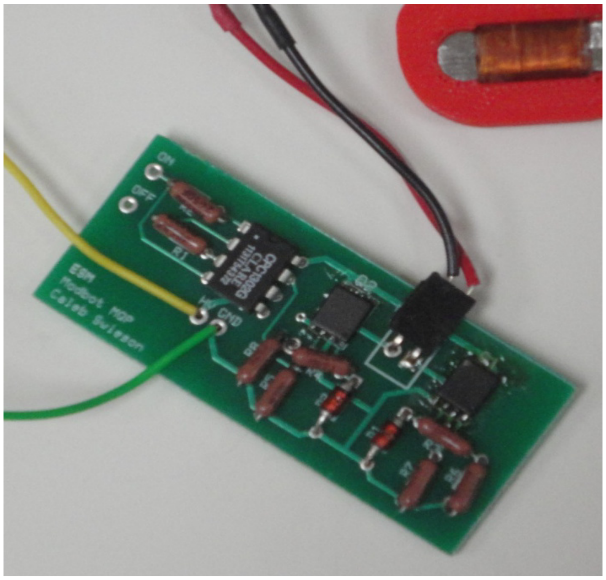


Figure 30. Soldered Switching PCB

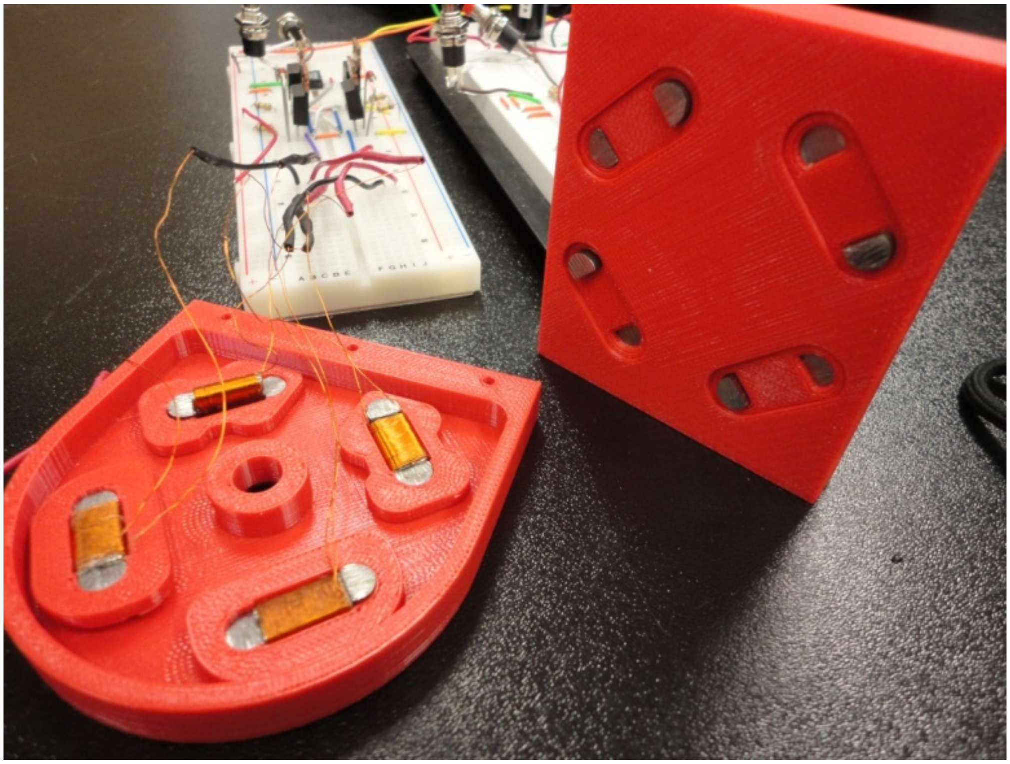


Figure 32. 3D printed ESM faces

4.3 Motor Requirements & Selection

Based on the module housing design chosen, and the preliminary torques calculated for the movement of the module, motors were researched. Joe Martino, a sales representative from Maxon Motor Company, was contacted both for motor suggestions and purchasing. The original problem statement required that each module be able to facilitate 3 degrees of freedom. This required each module to contain at least 3 motors, all controlled independently.

The initial requirements for the mechanical aspect of the robot also required that the robot be able to lift itself and one other module. Due to the tight confines inside the module, the motors needed to be as small as possible. To simplify the programming, the team decided to use the same model motor for both side joints and the center joint. The center joint would use a similar gear reduction to the side joints and would have much lower torque requirements.

4.3.1 Torques Required

Each module was designed to be 3" x 3" x 6". Assuming a construction material of 6061 Aluminum, and using the Solidworks mass calculator the team was able to estimate the module housing weight of approximately one pound, adding in the additional weight of motors, assumed weight of gears as well as assembly materials, bearings, batteries, and other electrical components the team was able to estimate a module weight of two pounds fully assembled. Using a safety factor of 1.5 to account for any unforeseen weights, each module was estimated to weigh three pounds and assumed to be uniformly dense. Assuming that the two modules would be connected with no space between them there would be a total of 4.5 inches between the rotational joint of the "driving" module and the center of gravity of the "driven" module. Given this distance, estimated torque was calculated. A distance of ~12cm between rotation and the center of gravity of the other module, a mass of 1.02kg and gravity, the lifting force required would be greater than 1.2Nm at the rotational joint. This value was decreased by altering the state of the driven module such that it would reorient itself vertically prior to being lifted, effectively reducing the distance between the rotational joint and the center of gravity of the second module to a 3in distance. Given this new distance of 7.6cm, a mass of 1.02kg and gravity, the joint would require an output torque of ~.76Nm to lift the driven module. This information was used to make decisions on both the

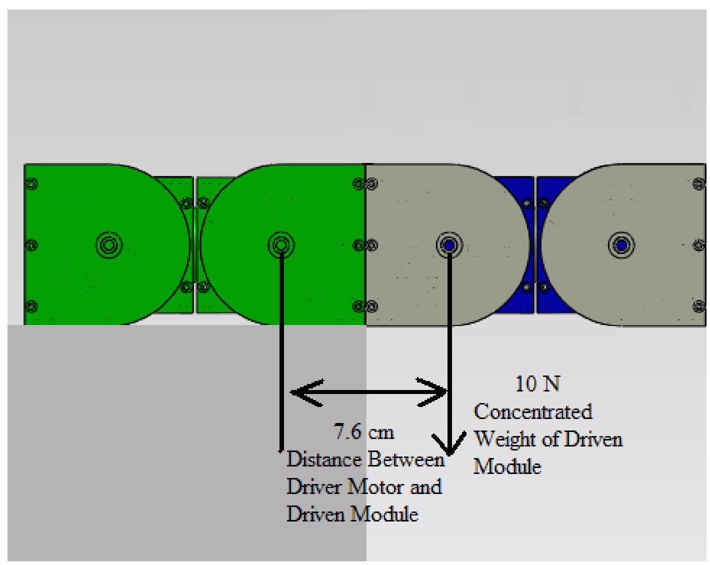


Figure 33: FBD of Lifting Module

motors and gearing. Constrained by motor torque, the team decided to implement both a gearbox on the motor as well as a second gear reduction system between the motor output shaft and the module wall.

4.3.2 Motor Selection

The motors were required to fit into a space two inches in length and one inch in diameter. Through conversation with Maxon, the project group decided that based on the design requirements and the time constraints of the project, the Maxon motors chosen would need to be currently in stock. Based on these updated criteria the group decided on Maxon package #392885. This package includes motor, gearbox, and encoder. The motors are 3 pole DC brushless motors (part #283828); they are 16mm (0.63") in diameter and 24mm (0.94") in length with a weight of 30.0g. They have a nominal operating voltage of 12volts with a no load current

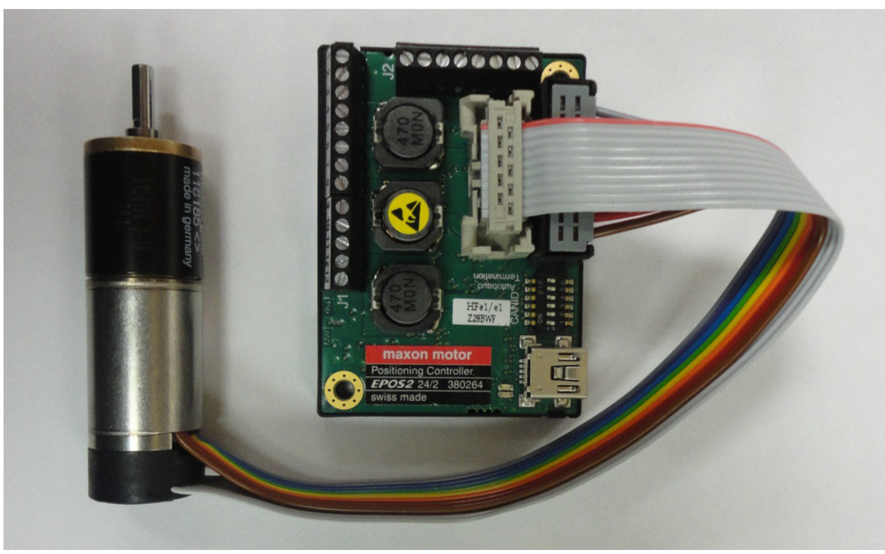


Figure 34. Motor & Motor Controller

of 48.8mA. The no load speed of the motor is 11600rpm with a nominal torque of 3.46mNm and a stall torque of 6.27mNm. The motors are geared down using a 2 stage metal planetary gear system that rides on solid bearings with a 29:1 gear ratio (part # 118185). The gearbox has a weight of 23.0g, a continuous torque with these motors of 0.15Nm, and an efficiency of 81%.

For control purposes a quadrature encoder was also added to the assembly. The encoder has 512 counts per turn, 3 channels, and a max speed of 37500 rpm. The overall assembly is 50mm long excluding output shaft and 16mm in diameter with a weight of 60g. The motor and motor controller are shown in Figure 34.

4.4 Power Management

Every electronic component has certain power requirements, and they all need to be met and integrated together. Batteries will be used in module and thus need to be selected and monitored to remain within safe operating limits. The power must also be correctly distributed to every component.

4.4.1 Component Power Requirements

Table 2 shows a list of the electronic components used in this module and their respective power requirements. These power requirements were used to determine the voltage and capacity requirements of the battery.

Table 2. Component Power Requirements

Component	Input voltage	Expected current	Worst-case Current
Microcontroller	4.5-9V (3.3V)	200mA	500mA
Accelerometer IMU	2.5-5.5V (3.3V)	10mA	10mA
Wireless Transceiver	1.9-3.6V (3.3V)	18mA	18mA
Potentiometers	Any	Negligible	Negligible
Limit switches	Any	Negligible	Negligible
Motor controller	9-24V	10mA	15mA
Motor	12V	453mA	763mA

4.4.2 Battery Selection

Since the modules are supposed to be fully contained, batteries are required to power the module. Batteries come in many sizes, types, and configurations. The important characteristics for this project are size, voltage, capacity, chemistry, and discharge rate.

Size is a very important since the battery must fit within the module. Working within this constraint, the longest side of the battery needed to be less than 55mm (2.17”). This is the size that was found to fit within the Solidworks model.

Voltage and charge are important since they determine whether there is enough power to run the robot, and how long the robot will run. Battery chemistry is not important on its own, but does affect the size and capacity of the battery. Alkaline, Nickel-Metal-Hydride (NiMH), Nickel Cadmium (NiCd), Lead Acid, Lithium Ion (Li-ion), and Lithium Polymer (LiPo) are a few of the main battery chemistries commonly used. Table 3 shows a comparison of these chemistries.

Table 3. Battery Chemistry Comparison [18]

	Reusable Alkaline	NiMH	NiCd	Lead Acid	Li-ion	LiPo
Energy Density (Wh/kg)	80 (initial)	60-120	45-80	30-50	110-160	100-130
Cycle Life	50	300 to 500	1500	200 to 300	500 to 1000	300 to 500
Fast Charge Time	2-3h	2-4h	1h typical	8-16h	2-4h	2-4h
Overcharge Tolerance	Moderate	Low	Moderate	High	Very low	Low
Self-discharge / Month (room temperature)	0.3%	30%	20%	5%	10%	~10%
Cell Voltage(nominal)	1.5V	1.25V[6]	1.25V[6]	2V	3.6V	3.6V
Load Current **- peak** **- best result**	0.5C < 0.2C	5C < 0.5C	20C 1C	5C 0.2C	>2C < 1C	>2C < 1C
Operating Temperature	0 to 65°C	-20 to 60°C	-40 to 60°C	-20 to 60°C	-20 to 60°C	0 to 60°C
Typical Battery Cost (US$, reference only)	$5 (9V)	$60 (7.2V)	$50 (7.2V)	$25 (6V)	$100 (7.2V)	$100 (7.2V)
Cost per Cycle(US$)	$0.10-0.50	$0.12	$0.04	$0.10	$0.14	$0.29
Commercial use since	1992	1990	1950	1970	1991	1999

Of these types, Lithium Polymer batteries were chosen because they have the highest energy density.

Since the motors run most efficiently at 12V, which is the highest voltage required by any of the components, the batteries were picked to be close to that voltage. Since Lithium Polymer battery cells are each 3.7V, a 3 cell (3S), 11.1V battery pack was chosen. The required battery capacity was based on the worst case power draw of the various components and the design choice of a robot run time of 15-20 minutes. Worst-case scenario, all components are continuously drawing the maximum current, and all three motors are running at stall current. This results in a continuous current draw of $500mA + 10mA + 18mA + (3 * 15mA) + (3 * 763mA) = 2{,}862mA$ continuous. In order to run for 15 minutes, the minimum battery capacity needs to be $2862mA * 15min * \frac{1hr}{60min} = 715mA * hr$.

Many battery brands were researched to find the best fit for size, voltage, and capacity (See Appendix C: Electronics Decisions). The battery chosen was the ThunderPower TP730-3SPL25J. It's a 3-cell/3S LiPo battery with a capacity of 730mAh and a discharge rate of 25C. This means that the battery can be discharged at a rate 25 times the capacity [19], or at a rate of $730mA * 25 = 18.25A$ continuously, which is much higher than the 2.9A max worst-case current calculated. The size of the battery is 19 x 31 x 54mm, which will fit into the module. The expected run time for the module using this battery would be

$$\frac{730mAh}{\left(200 + 10 + 18 + (3 * 10) + (3 * 453)\right)mA} * \frac{60min}{hr} = 27\ minutes$$

4.4.3 Battery Voltage Monitoring

Lithium Polymer batteries must be closely monitored in order to keep them within safe voltage ranges. As a general rule of thumb, each cell of a LiPo battery should not drop below

3.2V and should not be charged above 4.2V [20]. Since the battery pack is 3-cell, the operating voltage of the pack is between 9.6V and 12.6V. An external charger will be used, which automatically monitors each cell voltage, balances the pack, and charges the pack to the correct upper limit. Each individual cell must then be monitored by the robot in order to suspend operation at the low voltage threshold.

Multiple-cell LiPo batteries have a balancing plug and a power plug, as shown in Figure 35. The balance plug is used by chargers to measure each cell voltage individually and balance the voltages to allow proper charging. This plug can also be used by the robot to monitor the

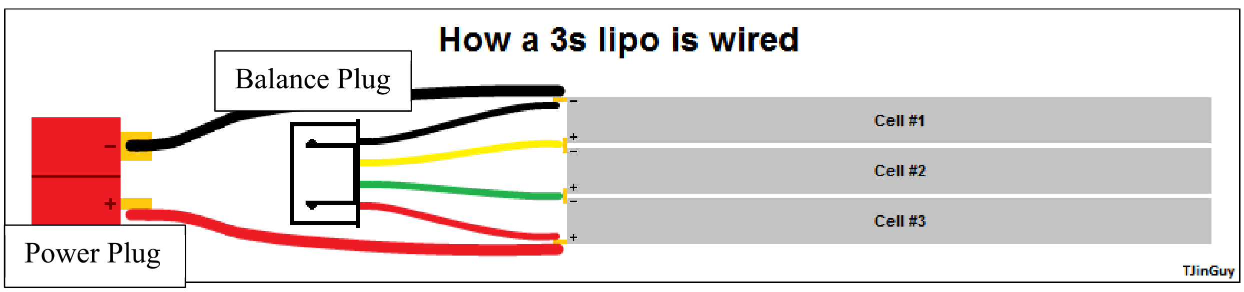


Figure 35. LiPo battery wiring [39]

voltage of each individual cell in the battery. A circuit was then designed to convert the voltages from the balance plug leads into signals that the microcontroller can measure. This circuit is shown in Figure 36.

The voltage dividers lower each voltage so it falls within the range of the mbed ADC's input voltage. The highest voltage, V3, which is the voltage of all three cells, is divided by 8 $\left(\frac{13k}{13k+90.9k} = \frac{1}{8}\right)$. The middle voltage, V2, which is the voltage of the first two cells, is divided by 4 $\left(\frac{13k}{13k+39.2k} = \frac{1}{4}\right)$. The lowest voltage, V1, which is the voltage of just the first cell, is divided in half $\left(\frac{13k}{13k} = \frac{1}{2}\right)$. Some simple math in the programming can then use these three voltages and calculate the voltage of each individual cell.

$$Cell\ 1\ voltage = 2 * V1$$

$$Cell\ 2\ voltage = 4 * V2 - 2 * V1$$

$$Cell\ 3\ voltage = 8 * V3 - 4 * V2$$

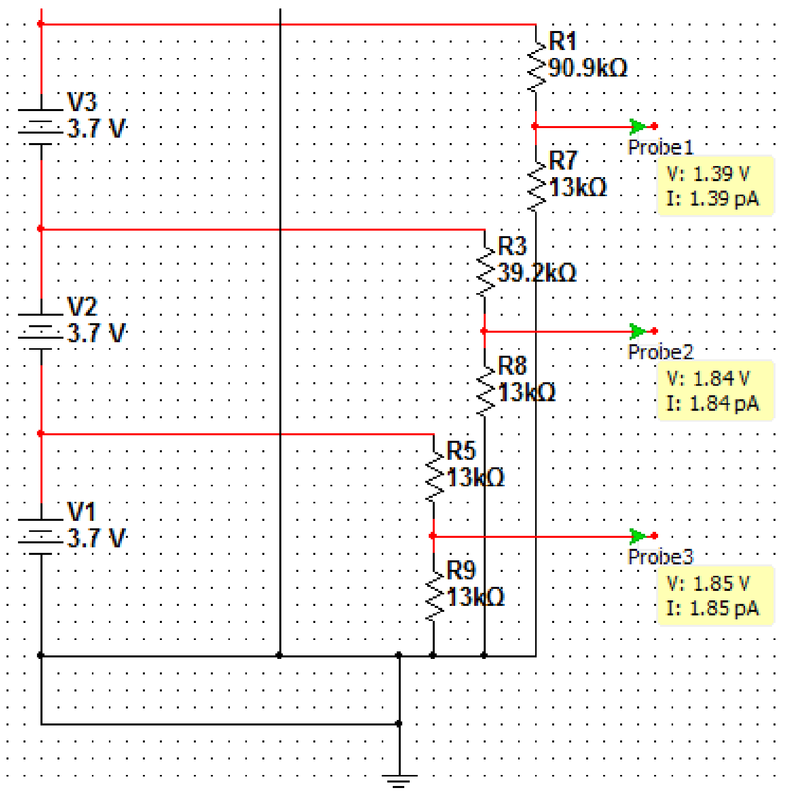


Figure 36. Battery Cell Voltage Monitoring Circuit

One important potential problem with this circuit is the loss of resolution due to using the voltage divider and multiplying it back. The ADC is 12-bit and has a full-scale range (FSR) of 0-3.3V. This means that the resolution of the ADC is $\frac{3.3}{2^{12}} = 0.80mV$. For the first cell, this resolution is effectively reduced by one bit, since the value is multiplied by 2. Therefore, the resolution is $1.6mV$. The second cell will have a resolution of $3.2mV$, and the third cell will have a resolution of $6.4mV$. This is sufficient to monitor for the low threshold voltage.

4.4.4 Power Distribution

Each electrical component in the module has different power requirements, so a power management board was designed to convert the battery voltage into the needed component voltages and to distribute power to those various components.

Since the battery voltage will be between 9.6V and 12.6V, and the motor controllers can take an input voltage of 9-24V, the battery can directly power the motor controllers and the motors. The mbed microcontroller runs at 3.3V, but takes input voltages from 4.5-9V. Using a 5V input will be the most efficient for the mbed's onboard voltage regulators. There are many 5V regulators available and the one chosen was the RECOM R-78B5.0, a high efficiency switching regulator. The mbed then has a regulated 3.3V output pin that can be used for other peripherals.

All of the motor positioning sensors (the potentiometers and limit switches) can be directly connected to and powered by the motor controllers. The accelerometer requires 3.3V and can use the regulated output of the microcontroller. The wireless module can run at either 3.3V or 5V, and so can use either of the two regulated outputs.

Once the various power requirements were determined, a PCB board was designed to correctly control those requirements. This board includes the battery monitoring circuit, the 5V regulated output, and the direct battery voltage. The 5V regulated and battery outputs are both connected through a switch to turn the robot on and off. The PCB layout is shown in Appendix E. Printed Circuit Boards and the realized board is shown in Figure 37.

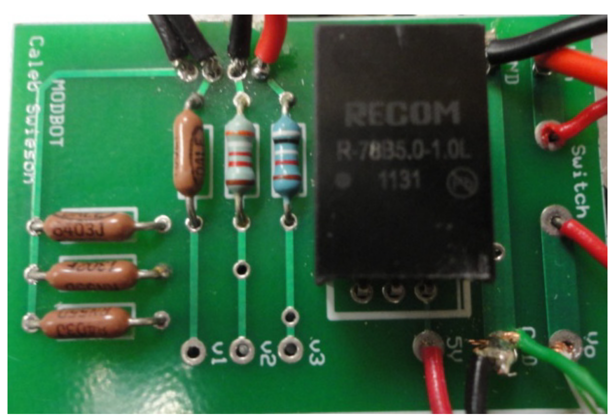


Figure 37. Power Management Board

4.5 Sensing and Communication

The following bullets are the forms of feedback and communication that were decided on to give the modules enough information to function.

- Position, angle, and speed of each motor. This is generally accomplished through encoders for speed and more accurate position, potentiometers for absolute angle, and/or limit switches for set positions and hard stops.
- Orientation and momentum of the whole module. This is generally accomplished by an accelerometer and/or gyroscope.
- Localization with other modules. This could be accomplished by using an IR camera and infrared LEDs.
- Wireless communication for at least one module to communicate with an external computer. This could be accomplished through many of the wireless communication protocols (WiFi, Bluetooth, ZigBee, RF, Infrared).
- Intra-module communication (either wired or wireless) to coordinate between modules.

4.5.1 Joint position sensors

The motors used on the module each include a quadrature, optical encoder that counts a discrete number of ticks as the motor rotates (Figure 38). This can be used to determine the speed of the motor. A quadrature encoder has two sets of ticks out of phase from each other, which can be used to also determine the direction of the motor as shown in Figure 39. The encoders can count 512 discrete ticks, and are therefore accurate to $\frac{360°}{512*4} = 0.176°$. Since encoders only measure speed and

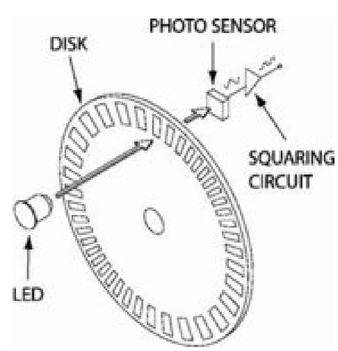


Figure 38. Encoder [37]

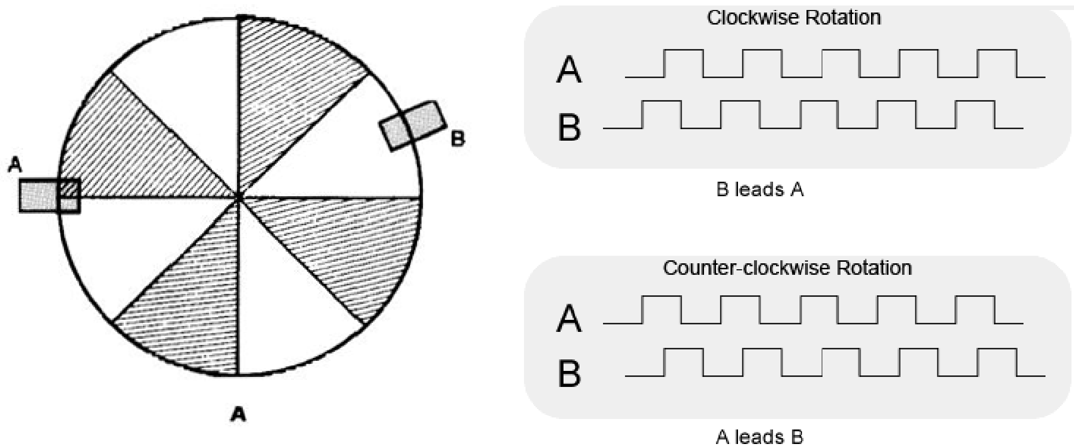


Figure 39. Quadrature encoder [38]

direction of the motor, other processing (analysis, sensing, etc.) are required to determine the position of the motor shaft and thus the joints. At least one position must be known as a reference to determine the absolute position. There are many sensors that can be used as this reference, including potentiometers and limit switches.

Potentiometer: A potentiometer is a variable resistor where the resistance changes based on the orientation of the wiper blade. Potentiometers can be used in a voltage divider circuit to outputs a voltage based on the resistance. The voltage can be easily measured and used to calculate the position of the motor shaft. Generally there are 3 types of potentiometers: single turn, multi-turn, and continuous. Single turn and continuous both have a measurement range less than 360°, while multi-turn potentiometers can measure more than one full rotation.

Limit switch: Limit switches are another option for determining a reference position. There are many configurations of limit switches, but the most basic are two position switches, where one position connects two electric leads and the other disconnects those leads. Limit switches are often placed so that they get pressed at a specific position. This can be used to determine when the motor is at a very specific, consistent point. In most cases, limit switches can only be used at the extremes of the range of motion. This allows them to also be used as a final failsafe so the joints do not over-rotate. This will work very well for the two outer joints, which can only rotate 180°. It will not work for the center joint, which can rotate more than 360°.

For the outer joint positioning, a limit switch at the extreme of motion is the simplest and easiest way to set up absolute position. The motor controllers can use this position as a "homing" position, and then base the motor position on the encoder values.

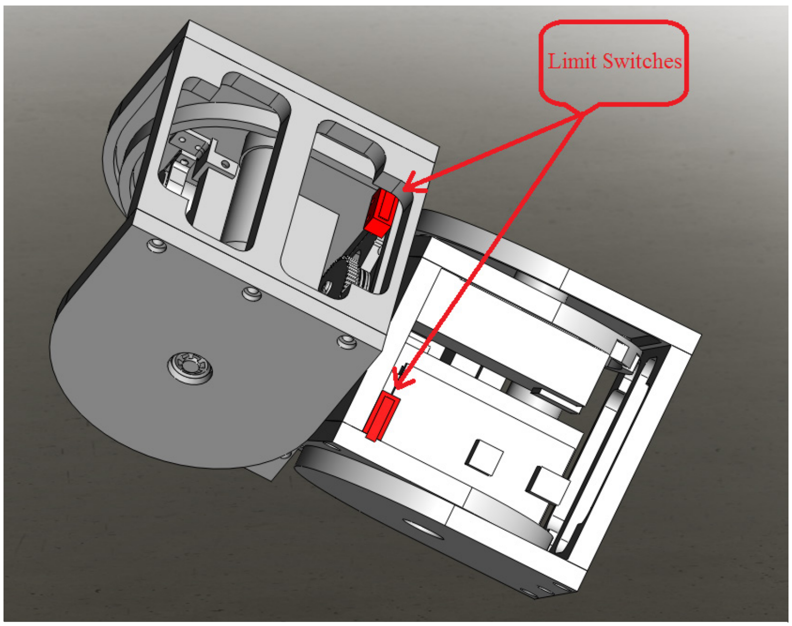


Figure 40. Limit Switches in Module

The center joint is a slightly more complex solution. Since the center joint was designed to rotate more than one full rotation, a limit switch cannot be placed at the extreme. It is also important to know the absolute position of the center joint, so the joint does not over rotate. The solution was to use a multi-turn potentiometer on the center joint. Size was the biggest constraint, and therefore a 12-turn trimmer potentiometer was chosen. The 12-turn was chosen because it was smallest number of turns that would still allow the center joint to rotate more than once in each direction. This will be connected to the center joint so that the potentiometer turns once for every rotation of the center joint. The ADC is 12-bit which means it can determine

$2^{12} = 4096$ different values. This will result in a resolution of for the center joint of $\frac{1440°\ center\ joint}{1440°\ pot} * \frac{4320°\ pot}{4096\ values} = 1.05°$.

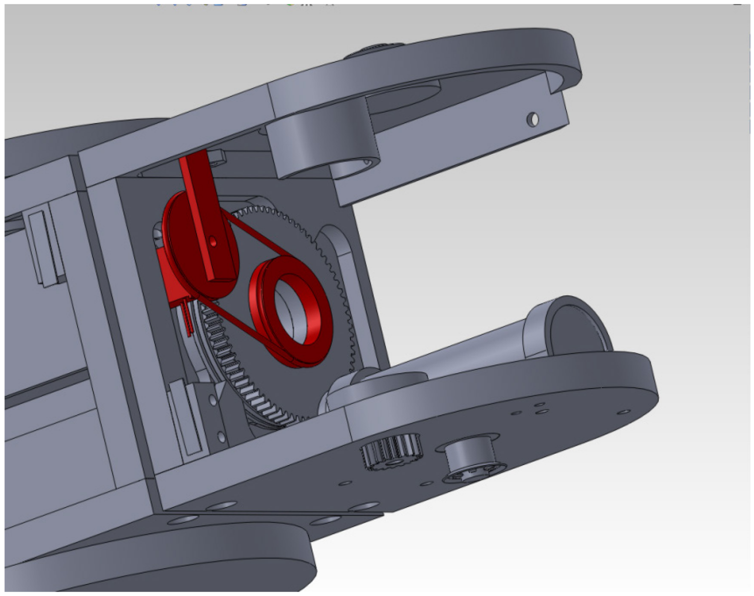


Figure 41. Center Joint Potentiometer Location

4.5.2 Module orientation sensors

For the orientation of the whole module, many accelerometers and gyroscopes were researched to determine the best one for this project (See Appendix C: Electronics Decisions). The main deciding criteria were the size of the sensor and the communication protocol between the sensor and the microcontroller. The sensor that was picked was the MinIMU-9 which is a 9-axis unit that has an accelerometer, gyroscope, and compass built onto one chip. It uses I2C to communicate with the microcontroller and is only 0.9×0.6″. It costs $49.95.

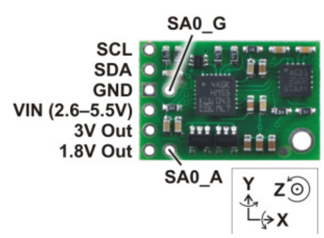


Figure 42. IMU

4.5.3 Module localization sensors

For localization of other modules, prior art have used infrared LED transmitter/receivers to determine general location of other disconnected modules. Another idea that this project is looking into is using the IR camera from a WiiMote to obtain more accurate locations. The WiiMote Camera has on-board processing that outputs the X, Y coordinates of up to four infrared sources through I2C. This can be used to accurately locate other modules.

4.5.4 External communication

For wireless communication with a base computer, many protocols were researched: WiFi, Bluetooth, ZigBee, RF, and infrared. For a wireless communication module on the robot, three main criteria were assessed: size of module, power drain, and data rate (See Appendix C: Electronics Decisions). One module that fits those categories well was the Transceiver nRF2401A with Chip Antenna. It uses the 2.4GHz Radio Frequency (802.15.4) to communicate and requires only 10.5mA in transmit mode and 18mA in receive mode. It communicates with the microcontroller through SPI and supports data rates of 250kB or 1Mb. Finally, the chip is only 0.5x0.675" and costs $24.95.

Figure 43. Wireless RF Module

4.6 Embedded System

The microcontroller is one of the most important electrical components in the robot. It handles all the computing and communication between sensors, peripherals, and other microcontrollers. Most microcontrollers consist of two parts: the processor and the development board. The processor is the chip that does all the computing, while the development board is the interface between the processor and the rest of the system. There are a huge variety of processors and development boards, and choosing one was an important decision process. These are the main criteria used to decide on the correct microcontroller.

- Size – since the microcontroller must fit within the robot, size is one of the most important criteria.
- Communication buses – many sensors and peripherals use one of three protocols to communicate with the microcontroller: SPI, UART, and I2C. In addition, they may also just be a digital signal (like a limit switch), or an analog signal (like a potentiometer).
- Input/Output (I/O) pins – the number of required I/O pins is based on what needs to be connected to the microcontroller. These pins include analog and digital I/O, as well as the communication buses and any other external peripherals.
- Memory – the available space for programs and computing. Since all computing must be done internally to the robot, the microcontroller memory should be high enough to handle all the processing. Since the memory required for the computing is still unknown, this criterion is not as important.
- Price – Obviously, a lower price is better. For the first few designs, price is not as important as the requirements of the microcontroller are still being determined.

4.6.1 Microcontroller Options

After compiling information on many different microcontroller development boards (Appendix B: Microcontroller Decisions), the choice was narrowed down to three. These three were the Arduino Pro Mini, the Maple Mini, and the NXP mbed LPC2368. These three were picked because they were small enough to fit within the constraints of the robot.

Arduino Pro Mini: The Arduino Pro Mini, shown in Figure 44, is a microcontroller board that uses the ATmega328 at either 8 or 16MHz, depending on which model. This processor has 32kB flash & 2kB SRAM. It has 14 I/O pins, 6 of which can be used for PWM and 6 of which are connected to an ADC. The I/O pins are also used for one I2C, one SPI, and one

UART communication buses. Programming is normally done through Arduino's Integrated Development Environment (IDE) and is loaded the board through a separate FTDI serial bus. Depending on the model, the board runs at either 3.3V or 5V with raw input voltages of 3.35-7V and 1.2-5.5V, respectively. The board can output up to 40mA per pin. The board is 0.7x1.3" and costs $18.95. [21]

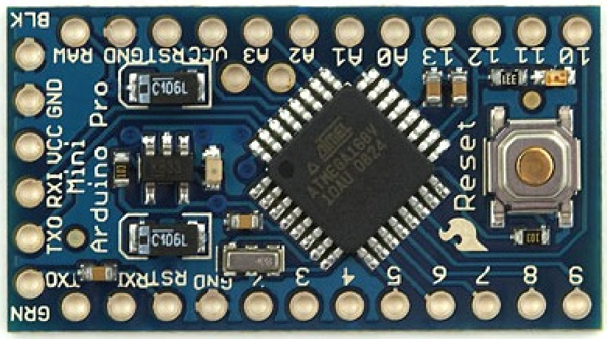


Figure 44. Arduino Pro Mini [22]

Maple Mini: The Maple Mini, shown in Figure 45, is a microcontroller board that uses a 32-bit ARM Cortex M3 at 72MHz. This processor has 120 KB Flash and 20 KB SRAM. It has 34 I/O pins, 12 of which can be used for PWM output and 9 of which are connected to a 12-bit ADC. The I/O pins are also used for two I2C, two SPI, and three USART communication buses. Programming is normally done through Leaf Labs' IDE and is loaded via a mini-USB connector. The board runs at 3.3V with raw voltages from 3-12V. The board can output a total 500mA at a 3.3V input voltage. The total size is 2.02" x 0.72" and costs $34.99. [22]

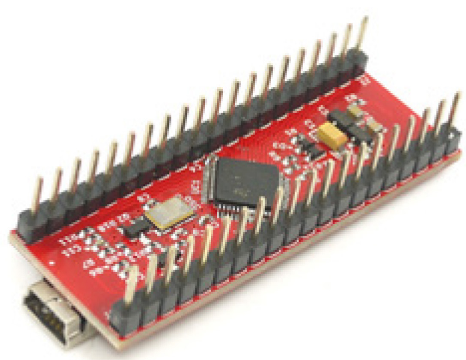


Figure 45. Maple Mini [36]

NXP mbed LPC2368: The NXP mbed LPC2368, shown in Figure 46, is a microcontroller board that uses the 32-bit ARM Cortex M3 at 96MHz. This processor has 512kB flash and 64kB RAM. It has 26 I/O pins, 6 of which can be used for PWM output and 6 of which are connected to the ADC. Other peripherals connected to the I/O pins include an Ethernet bus, a USB bus, a CAN bus, two SPI, two I2C, and three UART communication buses. Programming is done through an online IDE and compiler and loaded via mini-USB. The board runs at 3.3V logic, with voltage regulators to allow input voltages from 4.5 to 9V. The board can output a maximum of 40mA per pin, with a 400mA max total output. The board is 2.20” x 1.14” and costs $60.00. [23]

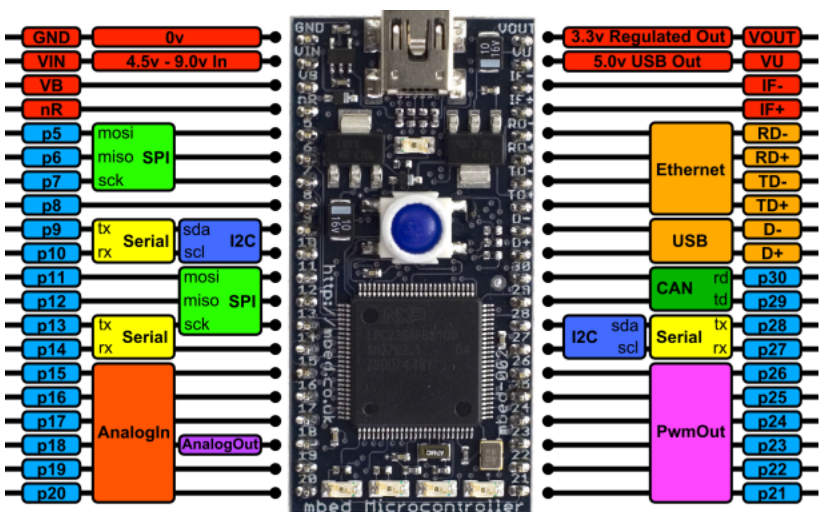


Figure 46. mbed Microcontroller [24]

4.6.2 Microcontroller Selection

From these three boards, the mbed was chosen because of its higher available memory and speed, as well as the capability to run a CAN bus. CAN is one of the communication techniques that the motor controllers use, so it was important to get a microcontroller that utilized CAN to test and explore that communication protocol.

4.6.3 Communication Breakout Board

The mbed has many different communication protocols, including CAN, I2C, and Serial, as well as both analog and digital input and output pins. Many of these will be used to communicate with the various peripherals that the module has. The motor controllers communicate over either CAN bus or RS-232, which is a standard protocol for serial communication. The wireless communication module uses a basic serial communication. The accelerometer IMU communicates over I2C. The battery monitoring circuit requires analog inputs. CAN, I2C, and RS-232 all require additional electronics to function correctly. The project group decided to create a microcontroller breakout board to incorporate these components, as well as to create a method for mounting the controller in the module. The PCB layout of this board is in Appendix E. Printed Circuit Boards. The realized board is shown in Figure 47.

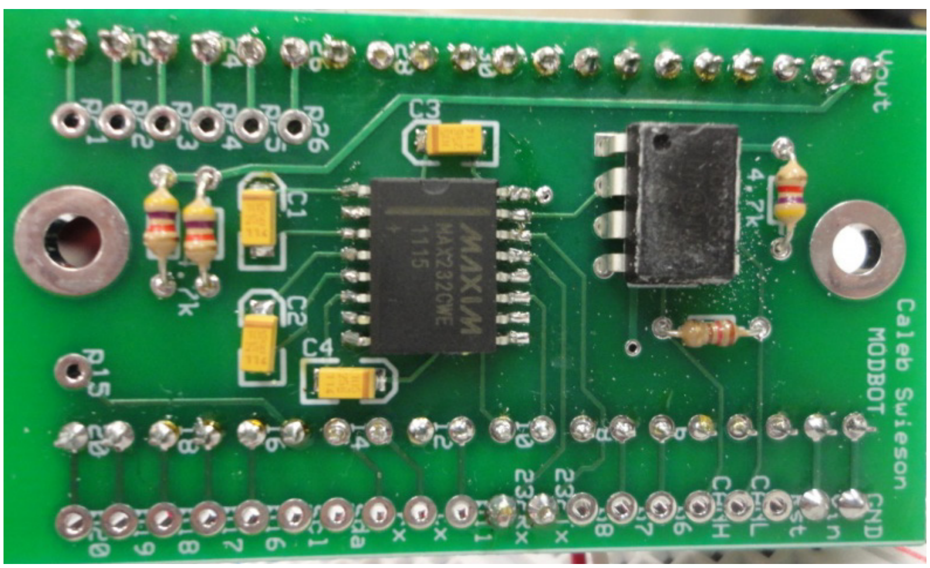


Figure 47. Microcontroller Breakout Board

The CAN IC transceiver converts standard serial communication into the correct levels required for the CAN bus protocol. The IC is the MCP2551 [24]. CAN is a differential protocol, meaning that the high or low logic signal is based on the difference between the two data lines (CANH and CANL).

The MAX232 is a Serial-to-RS-232 transceiver IC, which converts standard serial communication into the correct levels required for the RS-232 protocol. RS-232 protocol uses a high positive voltage (+5 to 15V) for a logic high signal and a negative voltage (-5 to 15V) for a logic low signal.

I2C is an active low protocol, where the devices pull the SCL and SDA lines low to send information. Therefore there are two pull-up resistors for the I2C lines. Also included on the board are many breakout pins for many of the various pins, including a standard serial communication pair, power, ground, reset, and 16 general purpose I/O (both analog and digital). The last feature on the board is the two mounting holes at the top and bottom of the board.

4.7 Software Design and Engineering

The software design for this project was comprised of two parts; the low-level software wrappers (software that functions as an adapter between devices), used to interface with all of the peripherals in a single module, and the second was the software written for simulations. The language C++ was used for the peripheral interface, as it was the provided language for the microcontroller, while Matlab was used for the simulations. Modularity was incorporated while writing the software for the microcontroller; the application programming interface (API) could be implemented in future projects, or ported over to other hardware, to interface with the peripherals used in this project. The software architecture was designed to be extensible. The embedded software was written using the online IDE provided by NXP Mbed.

Object oriented program design allows for the easy creation and destruction of object instances. Users are able to reference individual modules and specific component values with ease. Specifically, included in this project are: motor controller objects, which contain a predefined structure for all programmable values within the Maxon object dictionary. Users also have access to the onboard inertial measurement unit for orientation, acceleration and magnetometer readings, as well as a wireless module for communication between the onboard microcontroller and the external host computer.

4.7.1 Desired Software Functionality

Modular robot control requires a range of operations with increasing granularity depending on the desired level of control. The control levels include low-level module control, high-level module control, and cluster control. Abstraction layer and the cognitive load on the user are inversely proportional; higher levels of abstraction provide more autonomy for lower-level meticulous control.

Low-level module control provides users with access to individual peripheral parameters. Specific instances include, access to individual sensor data for unique function implementation. Users require access to read and write information to these peripherals, namely motor controller object dictionary values.

In a higher layer of abstraction, users require access to module movement, status, and localization. User control includes module movement; module forward speed, rotation, heading, orientation, neighbor proximity, etc. Functionality must allow the user to intuitively maneuver the module to avoid, traverse, or interact with other structures.

One layer of abstraction further would require user control of a mesh. The user would need many of the same control functions as those important to single module control but these functions would reference the system as a whole. Module gaits would be autonomously calculated for forward, reverse, and rotational motion of the system.

4.7.2 Communication Structure

Control for each module is established through an ARM cortex M3 microprocessor onboard each system. The microprocessor houses numerous communication buses including Ethernet, USB (host and device), SPI, I2C, and CAN. Figure 48 gives a visual representation of a complete module, including external communication sources.

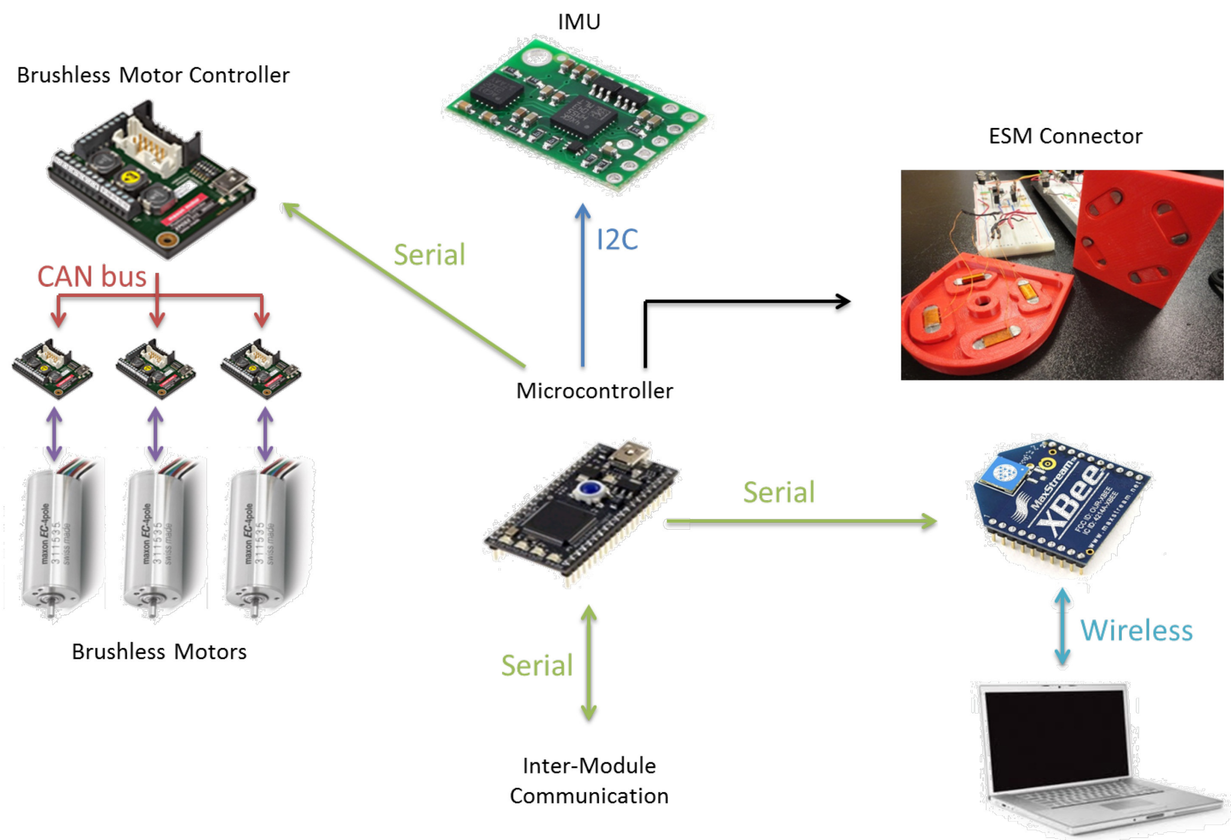


Figure 48: Module Control Diagram

The microcontroller in each module is the central hub for information, with every communication passing through it. The microcontroller commands motor movement, requests sensor data, enables and disables the connection mechanism, and communicates to the host computer.

User control to each individual module is established through a wireless signal. Individual module commands are based on a pre-assigned module node number. Users interface with the system from a host computer either wirelessly or over a serial direct connection. Once assembled into a mesh, the system is able to operate both autonomously as well as user controlled. The system is able to autonomously reconfigure either through direct user input, or intelligent situational assessment. Figure 49 is an overview of communication within the system.

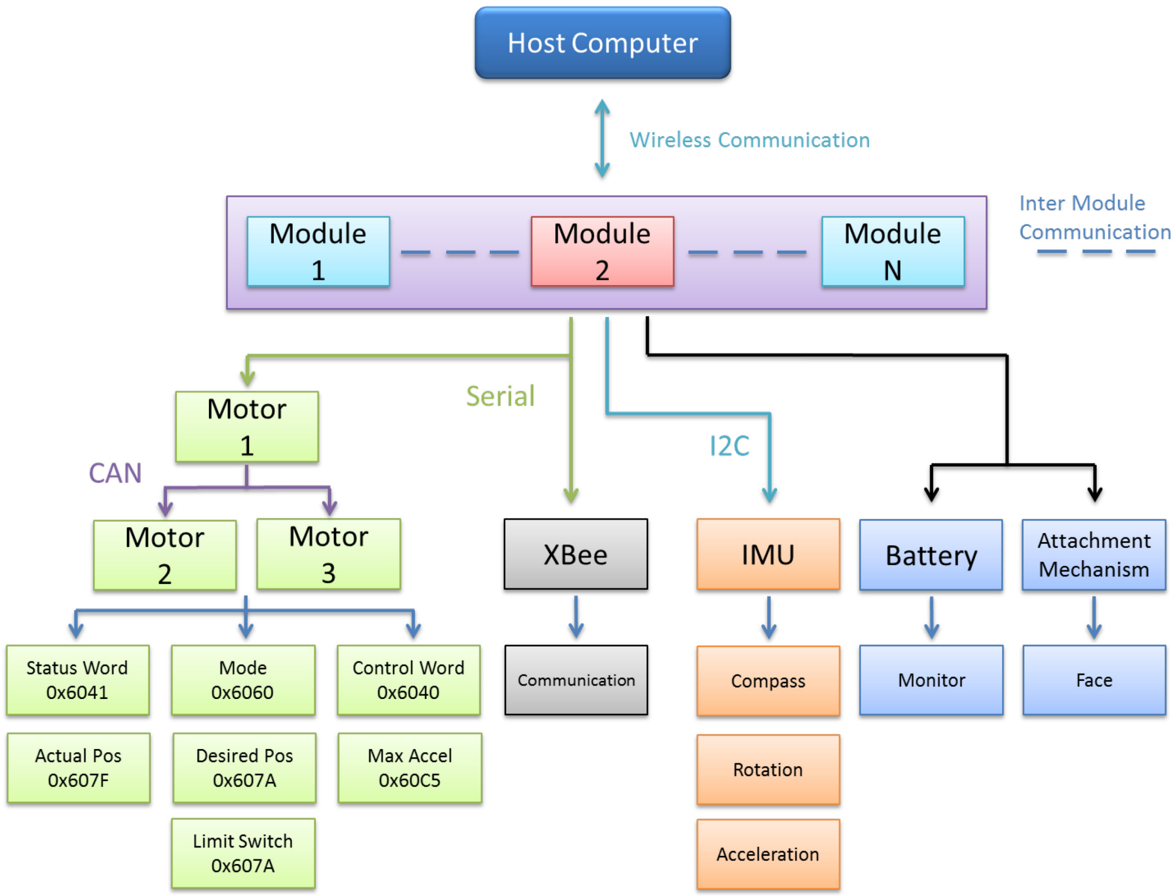


Figure 49: Communication Diagram

4.7.3 Communication Channels and Protocols

The two main communication protocols used in this project were CAN bus and Serial. CAN bus was used for motor controller to motor controller communication whereas Serial was used for microcontroller to motor controller, microcontroller to wireless, and inter-module communication.

4.7.3.1 CAN

CANOpen is a protocol created specifically for embedded systems used in automation. Slave devices implementing this protocol are required to have three main layers; a state machine for controlling the functionality of the device, an object dictionary containing all configuration variables (these are referenced using a 16bit index and an expandable 8 bit sub index), and finally a communication protocol for messaging with other nodes within the network. This communication bus also allows for multi-master network communication which would be essential for inter-module communication. When a mesh assembles, a single module with the lowest reference ID would assume the "brain" role and be the only module to communicate directly with a user.

There are many benefits to using CAN; the physical bus is differential, values are calculated by determining the voltage difference between wires as opposed to referencing a clock signal and a separate ramped line for value determination. This communication is less susceptible to interference that is common when high voltages and currents are passed through neighboring wires. This robust communication is specifically important to this project considering communication as well as power must be transferred between each half of the module and both the motors and electronically switchable magnets require high voltages and currents. CAN communication follows a common predetermined protocol, where each node is capable of sending and receiving messages however this cannot be done simultaneously. Each message is comprised of a set amount of information; an ID representing the recipient of the message, and up to eight data bytes. Due to incomplete framework libraries implemented on the microcontroller and given the scope and timeline of this project CANOpen communication to the motor controllers was abandoned and all efforts were spent on developing communication using RS-232.

4.7.3.2 Serial

RS-232 is a serial communication protocol; a sequential data transfer over two lines for asynchronous communication between embedded systems. The specifics of the electrical standard include voltage levels, signal rate, timing, signal slew-rate, short-circuit behavior, and maximum load capacitance. The standard allows for many different bit rates and is intended for those below 20,000 bits per second. The standard does not include however, character encoding, character framing, or error detection protocols. Details for these are often controlled by serial port hardware, and as such it is a much easier communication protocol to implement because of the reduced overhead.

4.7.4 Maxon Controller Interface

The Maxon motor controllers follow the CANOpen slave node standard protocol. The controller software implements a large bank of objects which a user can read and write to specifically information pertaining to motor control. Some example objects include values for maximum motor velocity, maximum and minimum motor position, etc. Values are accessed on these controllers through one of 3 different communication protocols, USB, RS232, or CAN. In the event that more than one motor controller is being used, these motor controllers implement a gateway communication (either RS232 or USB to CAN) in which the gateway motor controller relays all of the information through the CAN communication protocol to the rest of the controllers. Specific controller values and information are accessed first based on motor controller node ID (a maximum of 15 different nodes) then by object index, and finally by object sub index.

Each motor controller follows a predefined network management protocol (NMT). This protocol is composed of a state machine that cycle through numerous conditions each of which have specific read, write, and output functionality. By sending NMT "controlword" messages, users can advance through these states as long as the motor controller does not experience a fault which results in the controller reverting to a state of "limbo" until all faults are cleared. A diagram for the state machine can be found in the appendix under Maxon motor controller.

4.7.5 Wireless Communication to Host

ZigBee is a high level communication protocol that utilizes small low power digital radios for local area networks. The ZigBee protocol operates at 2.4GHz with a data transfer rate between 20 and 900 kilobits per second. The network layer supports both star and tree typical networks. Star networks incorporate a hierarchical dictatorship such that a central node communicates to all sub-nodes, whereas tree networks have a terraced structure; the central node communicates to tier directly below them and that tier in turn communicates to the tier below them. These two strategies are common among networks of individual modules and would likely be implemented to control a large group of modules.

4.7.6 Software Implementation

A large portion of this project timeline was spent investigating the use of CANOpen as a communication protocol between microcontroller and motor controller. Unfortunately it was determined, after the use of a logic analyzer, that the network protocol messages being sent from the microcontroller were both incomplete and incorrect. This led the team to discover that the API for CANOpen communication developed for the microcontroller was incomplete and as such was abandoned. Effort was then spent towards investigating the use of serial communication to establish a connection with the motor controllers.

4.7.6.1 ModBot Library

The Module class is comprised of two parts, a structure to house common motor values, and a group of member functions that correspond with the motor controller object dictionary. Figure 50 is a visual function prototype of the class structure values and the member functions written for the module class.

Module Class

Class Structure:

- Maximum Position
- Minimum Position
- Motor ID
- Actual Position

Member Functions:

- motor(): creates a motor
- reset(): resets the node
- move(): moves motor to a position
- home(): sets motor to home to a mounted limit switch
- enable(): sets motor to the enabled state
- disable(): sets motor to the disabled state
- quickstop(): stops the motor
- changeMode(): changes motor controller to given mode
- getPosition(): gets provided node motor position
- getMode(): gets provided node motor controller mode
- getStatus(): gets provided node motor controller status

Figure 50: Module Class

Member functions written for this class implemented two wrapper functions for communicating with the Maxon motor controllers, nodeRead and nodeWrite. These two functions are prototyped in Figure 51 along with the lowest level functions for passing data frames to and from the serial bus.

NodeWrite

Consumes:

- Recipient Node ID
- Object Dictionary Location
- Size of data to be transferred
- Data to be transferred
- Location to store error code

Executes:

- **Write()** data to given object dictionary location at given Node ID
- **Read()** error code

NodeRead

Consumes:

- Recipient Node ID
- Object Dictionary Location
- Size of data being returned
- Location to store return data

Executes:

- **Write()** command to read given object dictionary location at given Node ID
- **Read()** return data and stores information to given location

Write

Consumes:

- Size of data to be transferred
- Data frame to be transferred

Executes:

- writes over serial line to motor controller

Read

Consumes:

- Size of data being returned
- Location to store return frame

Executes:

- Reads data line for return data

Figure 51: Maxon Wrapper Functions

5 System Iteration and Integration

The scope of this project was not limited to just design and research, but also included building prototypes based on the design work. This was done with some sub-systems of the robot as well as with various iterations of the module. The realization of the module was one of the critical parts of the project; it gave the design team the opportunity to test their designs and to correct and flaws or shortcomings. The realization began with very basic prototypes and continued through several iterations. This work culminated in the final machined aluminum prototype.

5.1 Prototypes

In the process of creating our final design there were a total of three prototypes created in order to test out various aspects of a single module as a whole. The first prototype was built for visual awareness, the second for motion, and the third as a pre-final design. All three prototypes contributed important information to the final design.

5.1.1 Prototype 1

The first prototype created was made once the Super-Tran housing design was chosen. The overall goal of this prototype was to give a rough idea of what the robot would look like. This visual representation was used to find ways to design the key features of the module. This prototype contained manually controlled center and outer joints with no motors, controllers, or

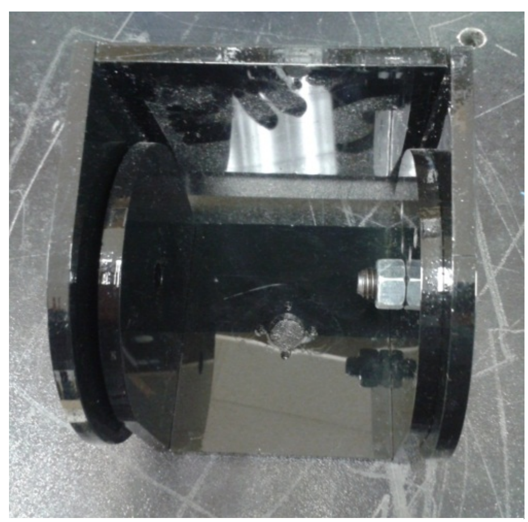


Figure 52. Prototype 1

electronics of any kind. Prototype #1 was created using black acrylic and can be seen in Figure 52.

5.1.2 Prototype 2

The second prototype was created to test the motion of a single module. This module was meant to be the first prototype with the motion of the module controlled by motors. Vex servo motors were used to try and test the possible gaits that a single module could use to move. This module was able to successfully crawl in a straight line across a table. The center joint was not used because the weight of the third Vex motor caused the robot to be unable to move at all. Prototype #2 was created using clear acrylic.

Figure 53. Prototype 2

5.1.3 Prototype 3

The third prototype was created to be a pre-final design. The goal was to make a module close to the actual size of the final design with motors similar to the ones used in the final design. This prototype was meant to also test working programs to control the motor movements, which could then be used in programming the final design. This prototype also implemented the center joint with the bearings and gears meant to be used in the final design.

Prototype #3 was created using clear acrylic with a protective blue plastic covering that was left on. The three movable joints were connected to Faulhaber motors which would provide movement to the module. The completed prototype can be seen in Figure 54.

At the completion of this prototype, the final decision on motors was made. Unfortunately they were very different from the ones used in the prototype. The motors in the

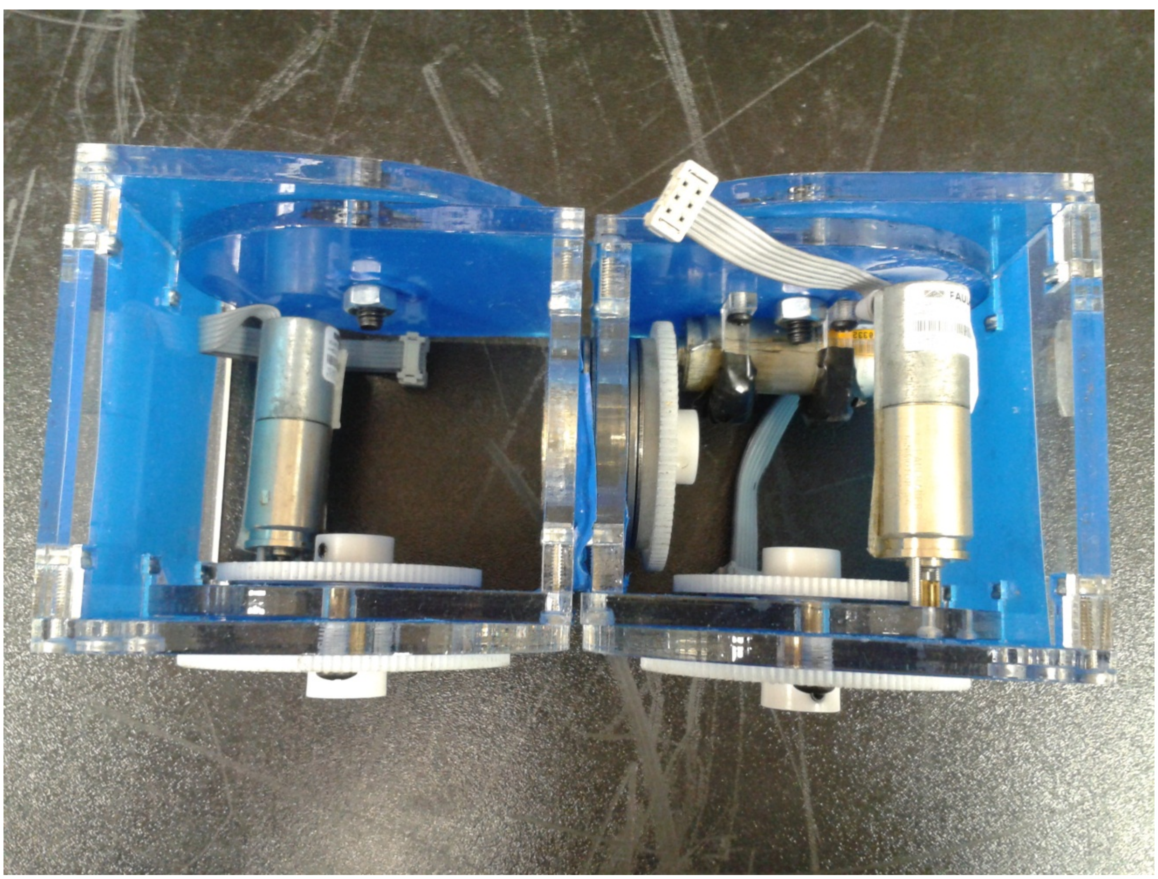


Figure 54. Prototype 3

prototype were brushed, while the motors chosen for the final design were brushless. This difference made it useless to program the prototype to move, since none of the work could be transferred over to the final design. Nonetheless, this prototype tested the center joint to see how it functioned and tested how the motors could be placed in the module so they would be out of the way and have room for the other components in the module.

5.1.4 3D Printed Prototype

After learning from each of the prototypes and making decisions on the various components for the robot, the construction of a final design was started. Once our final size was determined, work began on designing a housing of that size. This housing used the Super-Tran design we had decided on earlier, but had to be adapted to the smaller size. For this prototype, we chose to use WPI's rapid prototype machine, also known as a 3D printer, to manufacture it. The use of the rapid prototype gives this module the name "RP Prototype". This prototype was

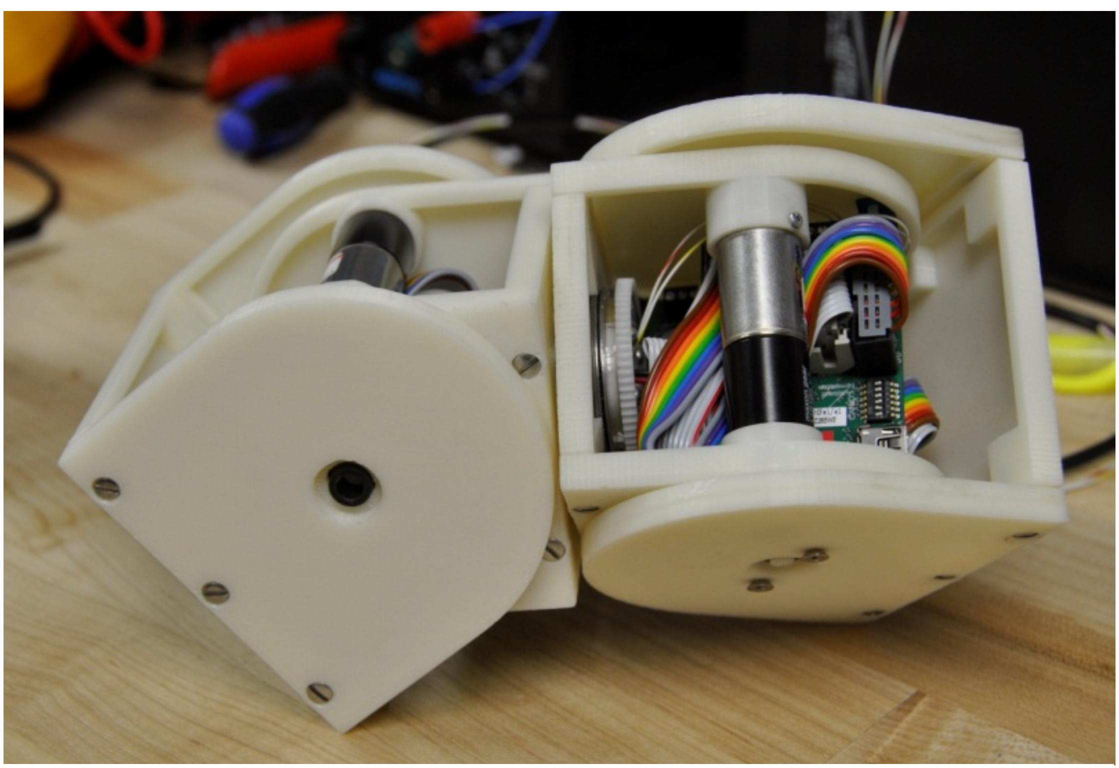


Figure 55. 3D Printed Prototype Module

3” in size and was designed to hold all the necessary components for untethered operation. The RP machine was chosen based on the need to create small, complex shapes that could not be made on the laser cutter. Additionally, the RP machine had a turnaround time of a few days, which made it much quicker than CNC machining and without the need to find materials. The ABS plastic used by the RP module was relatively soft and easy to modify, allowing minor changes to be made without repeating the printing process.

This prototype was the first attempt to fit all the components into a module, with the design work being done in SolidWorks. This part of the project consumed a large amount of time since some components had not yet been finalized. Other components required modification to the module in order to fit. As a result, a few iterations of this prototype were needed as the mounting strategy for the components changed numerous times. Despite these difficulties, the RP prototype was completed and capable of tethered operation; this did not require the module to have the battery or microcontroller inside. With this, the RP module had been finalized and work began on the final metal module.

5.2 Placement of Components in the Module

Since a small size was one of the design goals for this project, an essential part of the design is figuring out the placement of the components inside such a small module. The first pass for placement mounted the motors up against the wall of the module, requiring perpendicular motion transfer to the sides to allow them to spin. This would align the motors with the other components boards to allow everything to stack inside the module neatly. This method did not work because the motors were too long to fit inside the module with the proper gearing.

The motors ended up lying horizontally in the module with the motor shaft protruding through the first layer of the housing where connects to the secondary gear system located between the inner and outer shells. This places the gearing mechanism in a small, out of the way space. The motor for one outer joint and the motor for the center joint (and their respective motor controllers) were placed in the “female” half of the module. The other outer joint (and its motor controller) was placed in the “male” half of the module.

The microcontroller, batteries, and most of the electronics were placed in the “male” half. Positioning sensors for the joints are placed in the same half as that joint’s motor and controller.

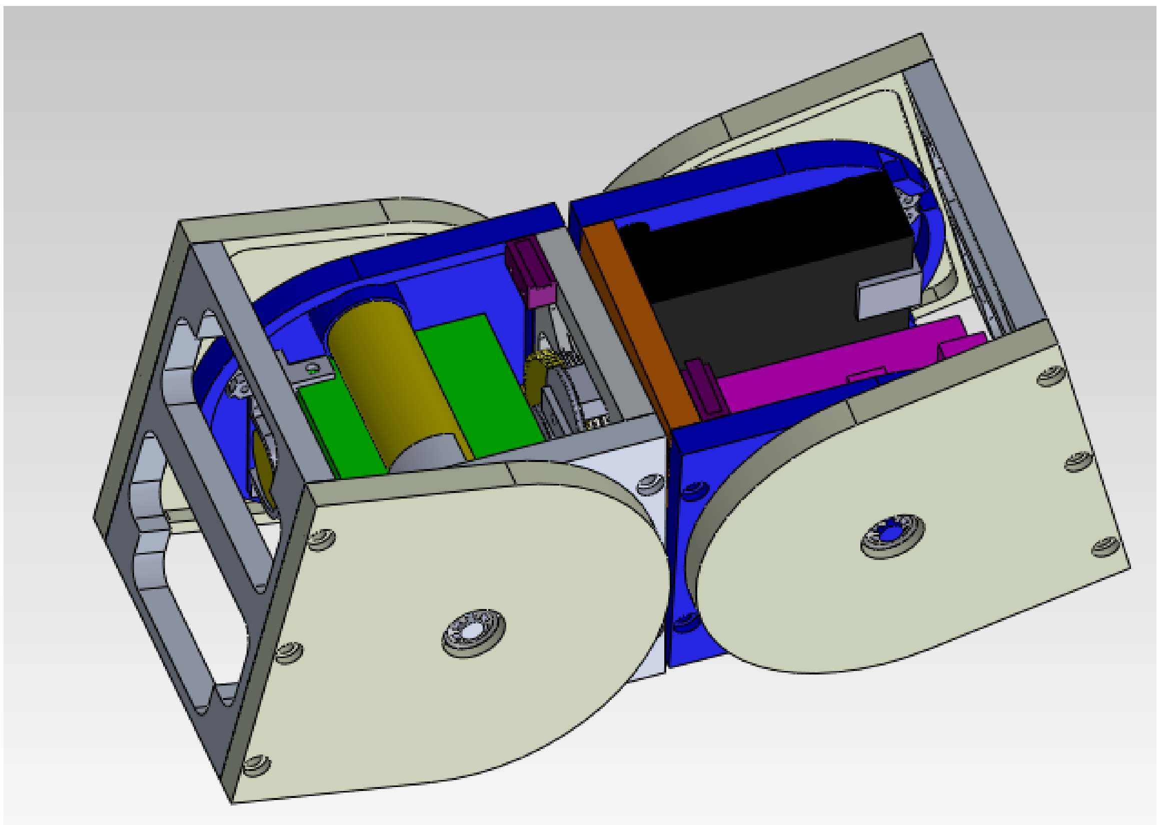


Figure 56: Final CAD Model

At present, the connection mechanism is mounted as a “clip on” mechanism attached to the outer faces of the module. Figure 56 depicts the layout of all of the components in the module.

5.3 Final Robot Module

5.3.1 Machined Aluminum Modules

Once the RP module was finished, work began to machine a final module out of 6061 aluminum. This material was chosen due to its lightweight, machinability and low cost and availability. The modules were machined using HAAS CNC (computer numerically controlled) mills in the WPI machine shop, which were accessible at all hours.

With assistance from the machine shop staff, the first metal module was machined. This module was 3" in size and used a similar design to the RP module. Interior corners were redesigned to be machined with a 3/8" end mill in order to aid in the manufacturing process.

Once the module was machined and assembled, several problems were discovered. One main problem was that the holes for the motor mount and pockets for the side joint bushings were too small. Another issue was that the inner halves of the module rubbed against the outside end plates when rotated. While the design was identical to the RP module, it was made using different manufacturing methods and material, thus causing the module to not fit together correctly. While the tolerances from milling versus the RP process should not have caused any issues; the use of aluminum, which is less compliant than the plastic used in the RP machine, was the most likely reason for the problems the module had.

Once the team understood what the causes of the problems were, the decision was made to redesign the module and to increase the size from 3" to 3.125". This was done to increase the volume inside the module to aid in assembly. As part of this redesign, the entire CAD model was rechecked and all clearances were increased to at least 0.01", the tolerance for machining, to ensure that even in a worst case scenario, the module would still work.

5.3.2 Final Module

With these changes made and the CAM appropriately updated, the module was machined and assembled and encountered no further problems. With the final module, the design team was able to incorporate all the necessary components. These components required mounting points and mounting hardware inside the housing. The most common method of mounting components was to make mount holes, and use plastic nuts and screws to hold the components in place. Holes were made where necessary and clearance was made for the mounting hardware. Special attention was paid to mounting the motors, due to their size and need to be securely held in place. The side motors were held in place by two mounts each. One mount was a hole in one housing face where the motor shaft could stick through. This mount supported the motor and kept the shaft in the correct orientation. The second mount was on the opposite housing face and supported the encoder end of the motor. This mount was a circular pocket that supported the end of the motor. This mount also had a hole for a screw that prevented the motor from rotating as well as clearance for the motor wires.

All the housing faces were pocketed for multiple reasons. The primary reason was to gain additional space inside the module without increasing the size. For example, the gears for the side joints are entirely contained inside one face's pocket. The inner faces were also pocketed to help fit the motors, battery and circuit boards. The second reason for pocketing was to reduce the weight of the module. The final, machined module is shown in Figure 57.

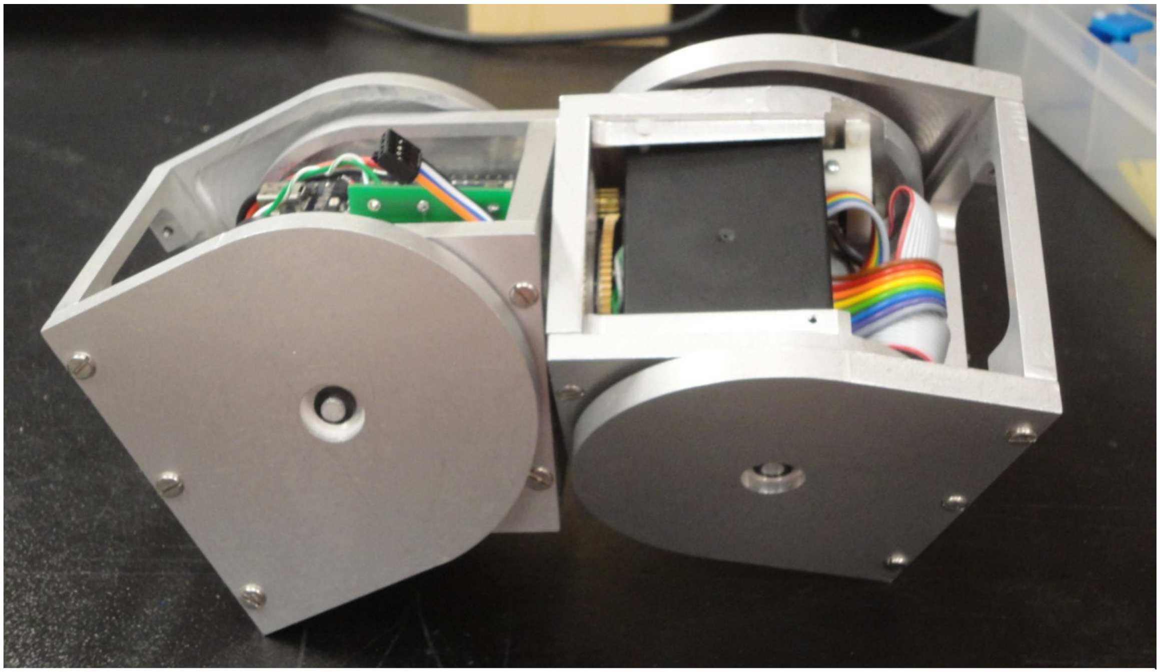


Figure 57. Final Module

6 System Analysis and Simulation

The following chapter discusses the results of the final module design. The first section discusses the overall module specifications, followed by the results of simulations, then a finite element analysis of the housing, and finally an analysis of the mechanical and electrical connection mechanisms.

6.1 Final Modular Robot Specifications

- Size: 3.125” x 3.125” x 6.25”
- Module Weight = 1.02 kg
- Two Side Joints
  - Speed = 304.8 Degrees/sec
  - Torque = 372.36 mNm
- Center Joint
  - Speed = 260.4 Degrees/sec
  - Torque = 620.6 mNm
- Components
  - 11.1V rechargeable LiPo battery
    - Run time (~1.5A continuous): 20-30min
  - Power management board with battery voltage monitoring circuit
  - DC brushless motors and motor controllers
  - Microcontroller & communication breakout board
  - 9-axis IMU (Accelerometer, Gyroscope, Compass)

Figure 58 is a picture of all the components that go into a single module. A full list of components is in Appendix D. Final Module Component List.

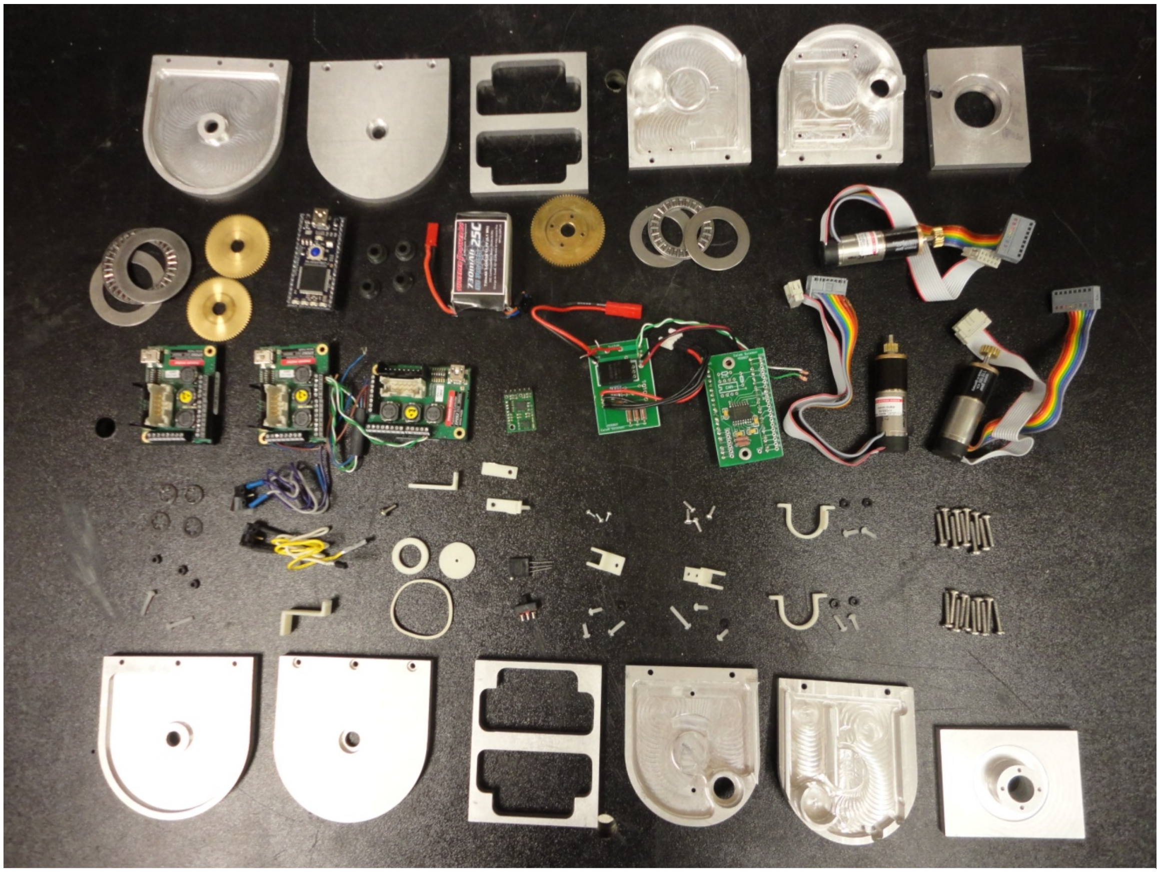


Figure 58. Final Module Components

6.2 Simulation and Analysis

An investigation into individual module gait simulation was conducted using Matlab. These gaits were created by adjusting the joint angles of the two ends of the module based on a time offset sinusoidal function for each for each of the two joints. Within the scope of this project again this investigation was directed towards modularity and as such the simulation is designed to implement an evaluation metric as well as a genetic algorithm in order to converge on the best gait for that metric.

6.3 Finite Element Analysis

To assess the strength of the module housing it was placed under a finite element analysis using the program SolidWorks Simulation. These tests were carried out on each separate piece of the module as well as on key assemblies of the module that were determined to experience the highest stresses and strains.

For each of the individual pieces it was determined that in a worst case scenario they would experience a 10lb force. This 10lb force would roughly be the equivalent of the weight of five modules, which is a theoretical force that the module should be able to endure. Two tests were performed on each piece. These two tests were performed on the sides that under normal use will undergo the worst stresses. All listed safety factors are for static loading. The worst stresses that were recorded in the module still allowed for a safety factor of over 2.5 which means the module housing is strong enough to withstand all worst case scenario forces that were applied to it. The following sections look in depth at the analysis of each part.

6.3.1 Outer Face

The first test applied to the outer face placed the 10lb force onto the major face while the two sides the screws mount into were fixed in place, as shown in Figure 59. This test shows that the max stress was located on the ends of the support running down the middle of the piece, though this max stress is only 0.9 MPa. The yield strength for 6061 aluminum is roughly 55 MPa, meaning that this piece has a safety factor of over 60 for this test.

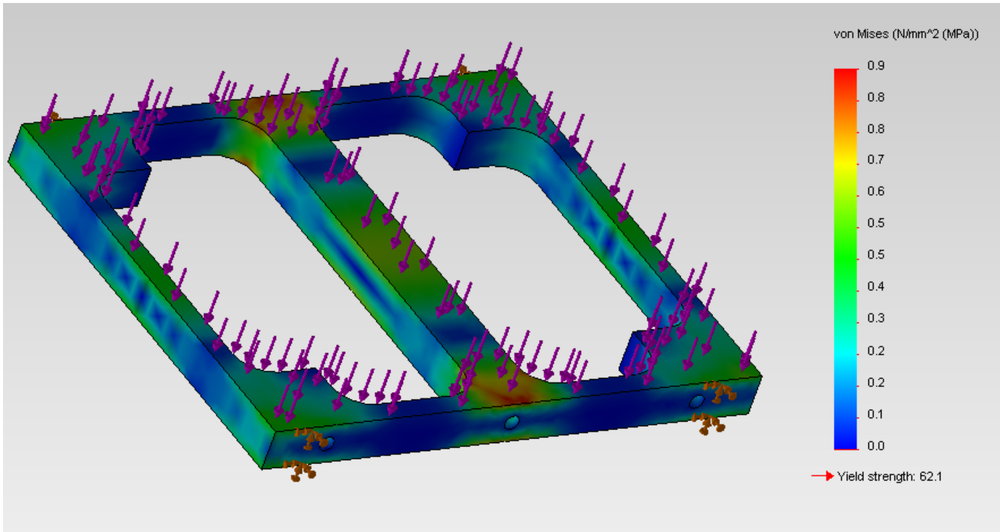


Figure 59: Outer Face Normal Test

For the second test, the force is applied to the side with the screw holes and pressed towards the center of the module, as seen in Figure 60. This test shows that the max stress is located along the skinny part of the beam. In this case the max measured stress is only 7.1 MPa, giving this face a safety factor of roughly 7.5

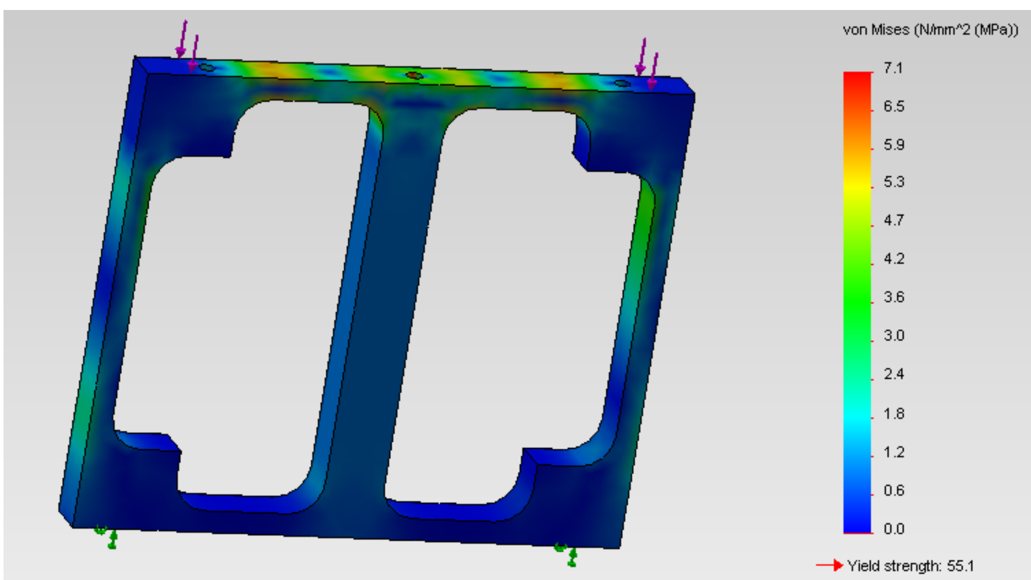


Figure 60: Outer Face Compression Test

6.3.2 Outer Side

The first test applied to the outer side placed the 10lb force onto the major face of the part while the opposite side was fixed, as shown in Figure 61. This test shows that the max stress was located at the junction of the shell feature and the outer frame, though this max stress is only 0.8 MPa. This gives this piece a safety factor of over 60, making this piece very robust in reference to a force applied in this direction.

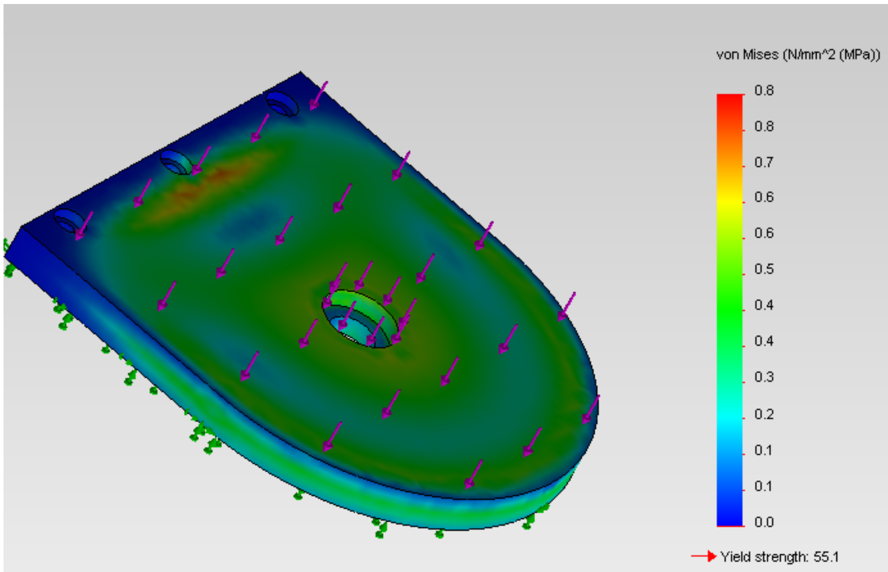


Figure 61: Outer Side Normal Test

For the second test, the force is applied to the flat bottom edge of the module, as seen in Figure 62. The fixed section in this test is the center hole of the module, which is to replicate that fact that while undergoing this force the piece would be mounted by a pin joint at that location. This test shows that the max stress is located around the center hole. In this case the max measured stress is 1.8 MPa, giving this face a safety factor of roughly 30.

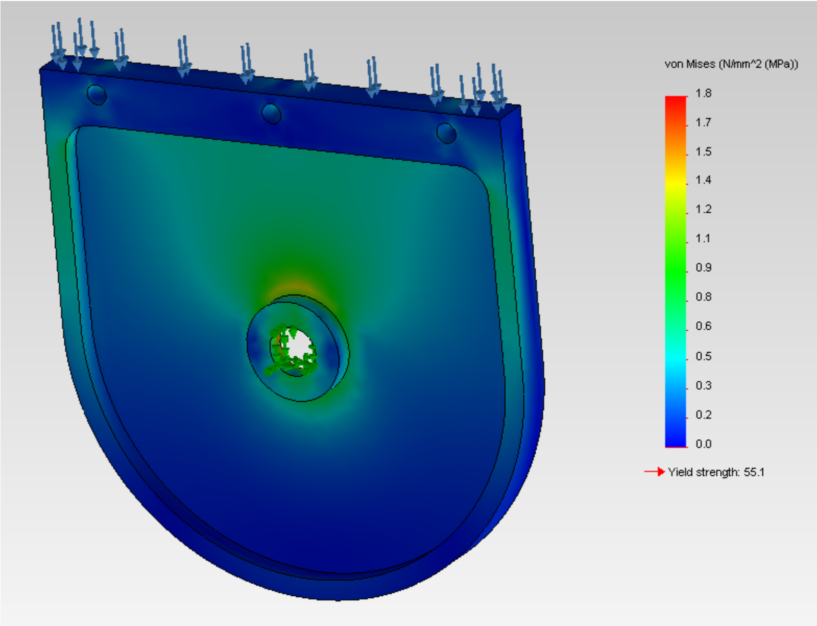


Figure 62: Outer Side Compression Test

6.3.3 Male Inner Face

The first test applied to the Male inner face placed the 10lb force onto the face where the trust bearing will be placed while the two sides the screws mount into were fixed, as shown in Figure 63. This test shows that the max stress was located on the edge where the weight reduction pockets meet up with the outer frame. There are also concentrations of stress located all around the surface where the bearings sit. The max stress for this situation is only 1.1 MPa, giving this piece a factor of safety of 50.

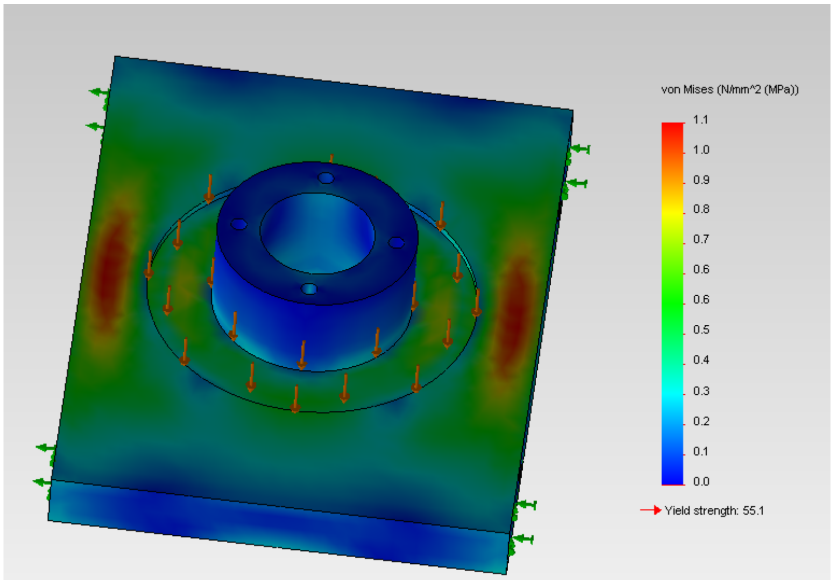


Figure 63: Male Inner Face Normal Test

For the second test, the force is applied to the side with the screw holes and pressed towards the center of the module, as seen in Figure 64. This test shows that the max stress is located where the frame separates the pockets created for weight reduction and in the pocket closest to the force. In this case the max measured stress is only 0.7 MPa, giving this face a safety factor of roughly 78.

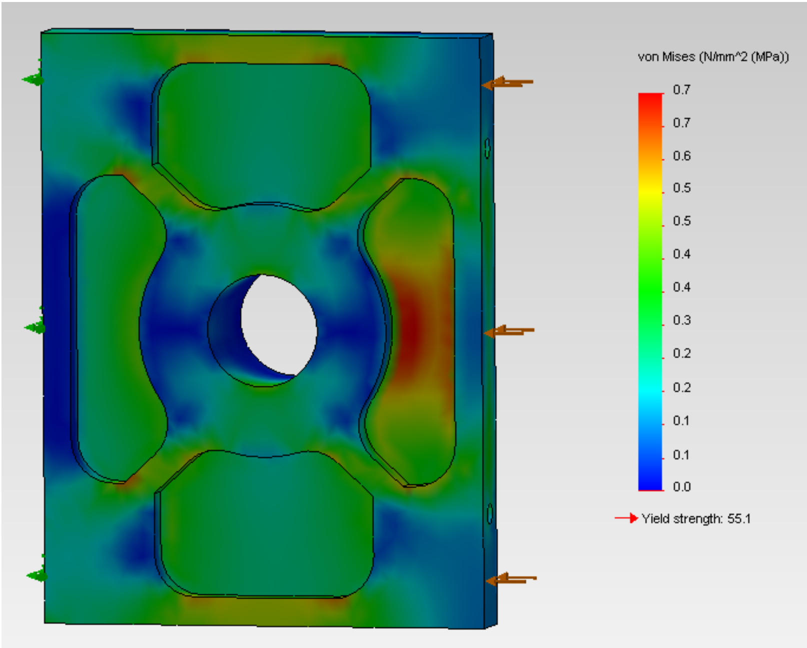


Figure 64: Male Inner Face Compression Test

6.3.4 Male Side 1

The first test applied to male side 1 placed the 10lb force onto the flat part of the joint pin while the opposite side was fixed, as shown in Figure 65. The force was applied in this location because it simulates the stresses incurred if the pin extended out past the outer face and the entire force was applied to it. This test shows that the max stress was located in a circle around the joint pin where the wall is the thinnest. The max measured stress is 20.1 MPa, giving this piece a factor of safety of over 2.5.

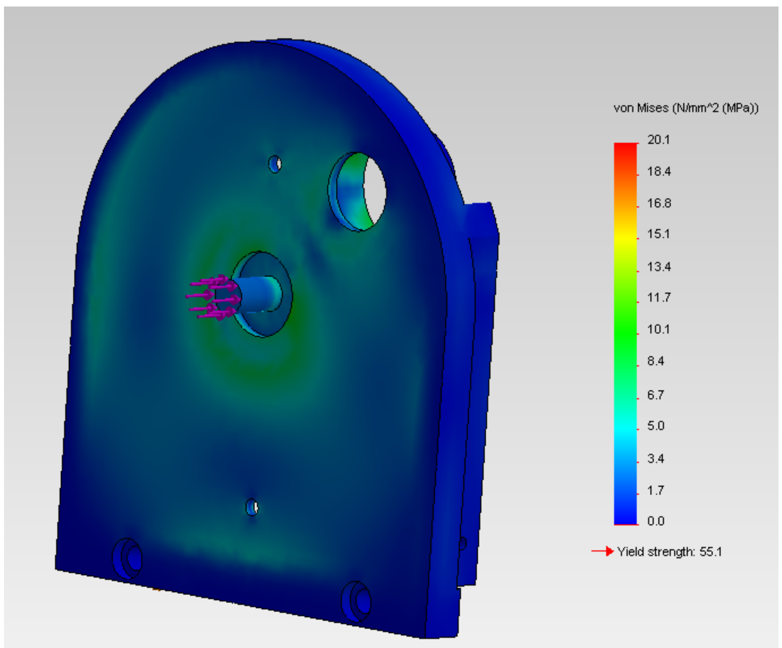


Figure 65: Male Side 1 Pin Test

For the second test, the force is applied to the flat bottom edge of the module, as seen in Figure 66. The fixed point in this test is the joint pin in the center of the face, simulating the fact that the rest of the module is mounted to that pin. This test shows that the max stress is located in the thin wall around the joint pin. In this case the max measured stress is 4.5 MPa, giving this face a safety factor of roughly 12.

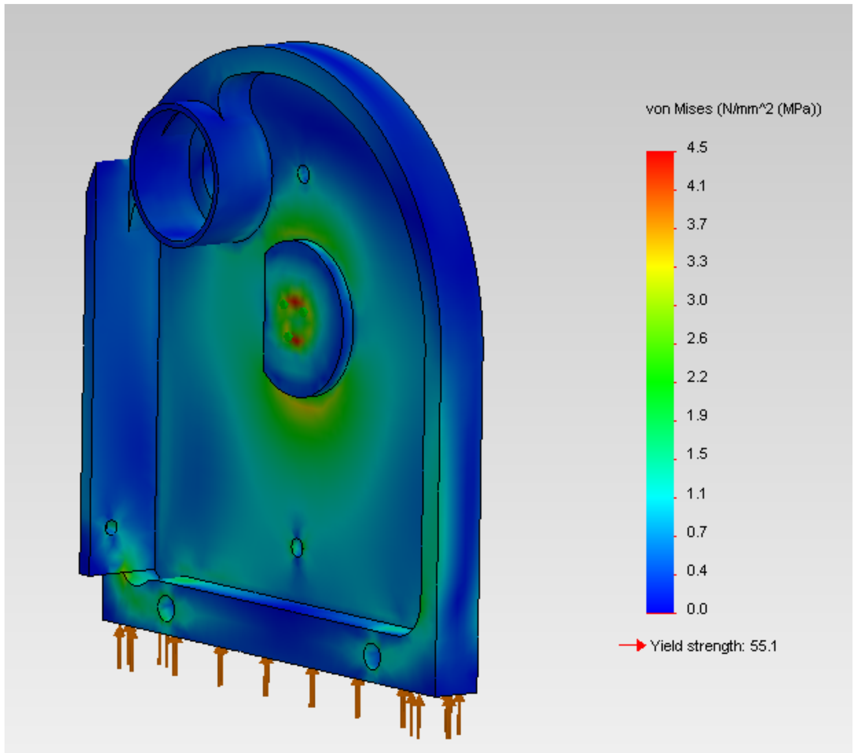


Figure 66: Male Face 1 Compression Test

6.3.5 Male Side 2

The first test applied to male side 2 placed the 10lb force onto the flat part of the joint pin while the opposite side was ground, as shown in Figure 67. The force was applied in this location because it simulates the stresses incurred if the pin extended out past the outer face and the entire force was applied to it. This test shows that the max stress was located in a circle around the joint pin where the side wall is the thinnest as well as along the slots cut into the outer frame. The max stress is 18.5 MPa, giving this piece a safety factor of just under 3.

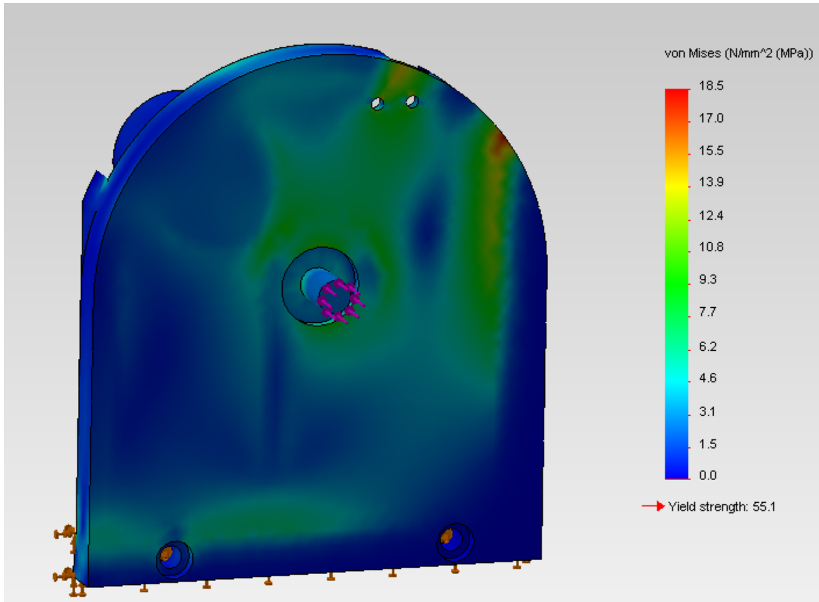


Figure 67: Male Side 2 Pin Test

For the second test, the force is applied to the flat bottom edge of the module, as seen in Figure 68. The fixed point in this test is the joint pin in the center of the face, simulating the fact that the rest of the module is mounted to that pin. This test shows that the max stress is located in the thin wall around the joint pin as well as next to the beam used to hold the battery in place. In this case the max measured stress is 4 MPa, giving this face a safety factor of roughly 13.5.

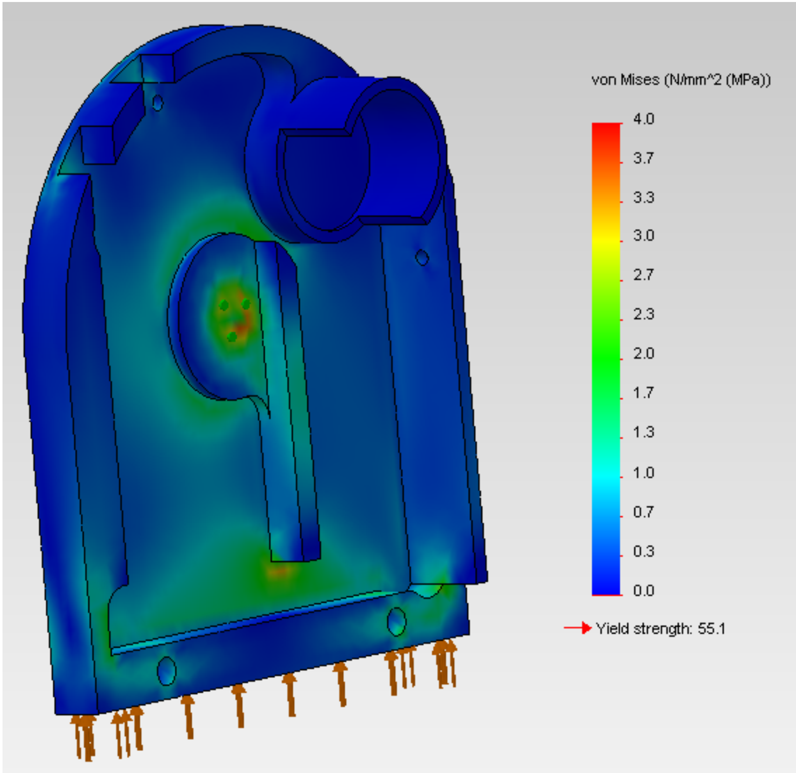


Figure 68: Male Side 2 Compression Test

6.3.6 Female Inner Face

The first test applied to the Female inner face placed the 10lb force onto the face where the trust bearing will be placed and fixed the two sides the screws mount into, as shown in Figure 69. This test shows that the max stress was located on the edges where the weight reduction pockets meet up with the surfaces the bearings sit on. There are also concentrations of stress located around the center joint motor shaft hole. The max stress in this test is only at 1.9 MPa, giving this piece a safety factor of 29.

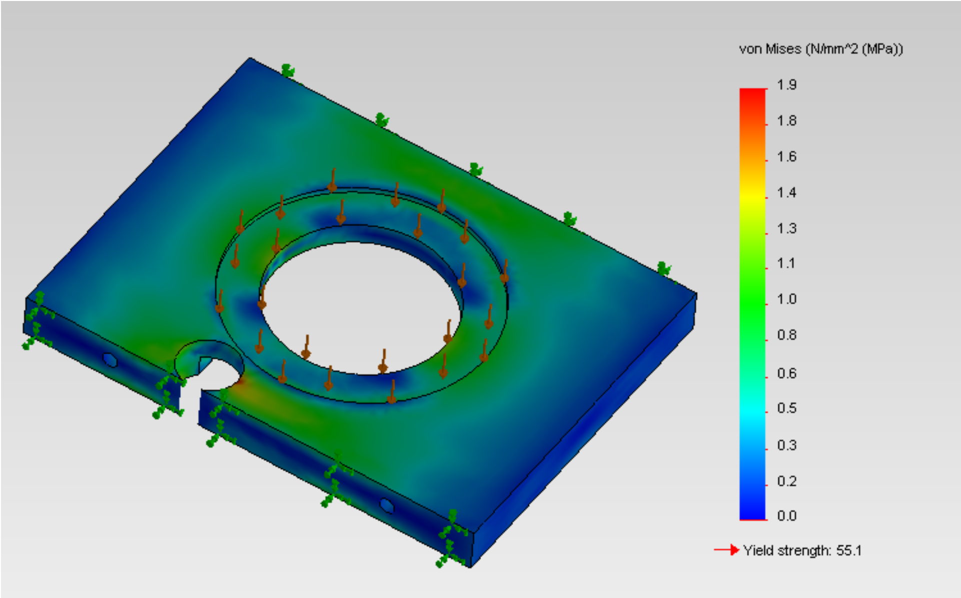


Figure 69: Female Inner Face Normal Test

For the second test, the force is applied to the side with the screw holes and pressed towards the center of the module, as seen in Figure 70. This test shows that the max stress is located were the frame separates the pockets created for weight reduction and bearing surface. There are also concentrations of stresses located on the edges of the hole created for the center joint gear. In this case the max measured stress is 3.4 MPa, giving this face a safety factor of 16.

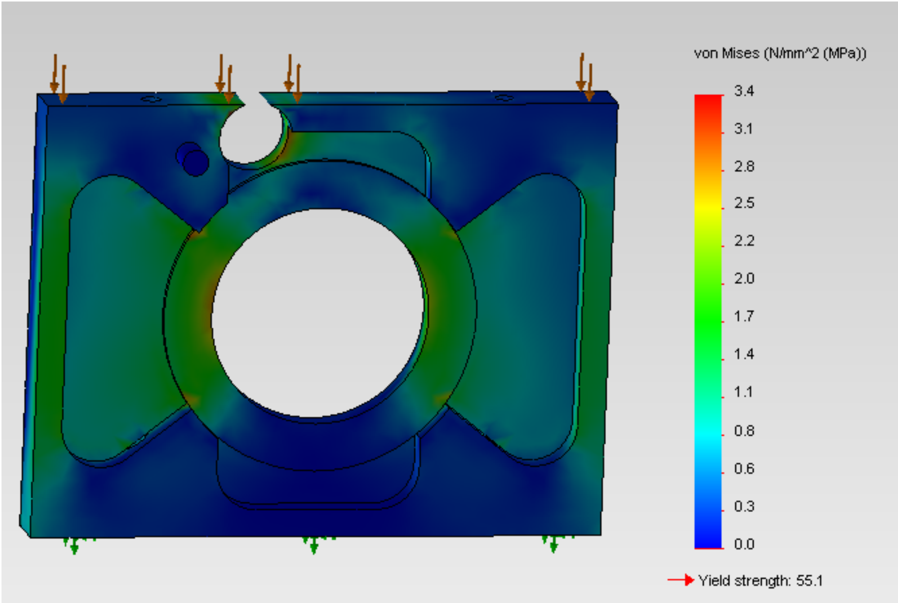


Figure 70: Female Inner Face Compression Test

6.3.7 Female Side 1

The first test applied to female side 1 placed the 10lb force onto the flat part of the joint pin while the opposite side was considered ground, as shown in Figure 71. The force was applied in this location because it simulates the stresses incurred if the pin extended out past the outer face and the entire force was applied to it. This test shows that the max stress was located in a circle around the joint pin where the side wall is the thinnest as well as in the thin walls of the motor mount. The max stress is 16.9 MPa giving this piece a safety factor of just over 3.

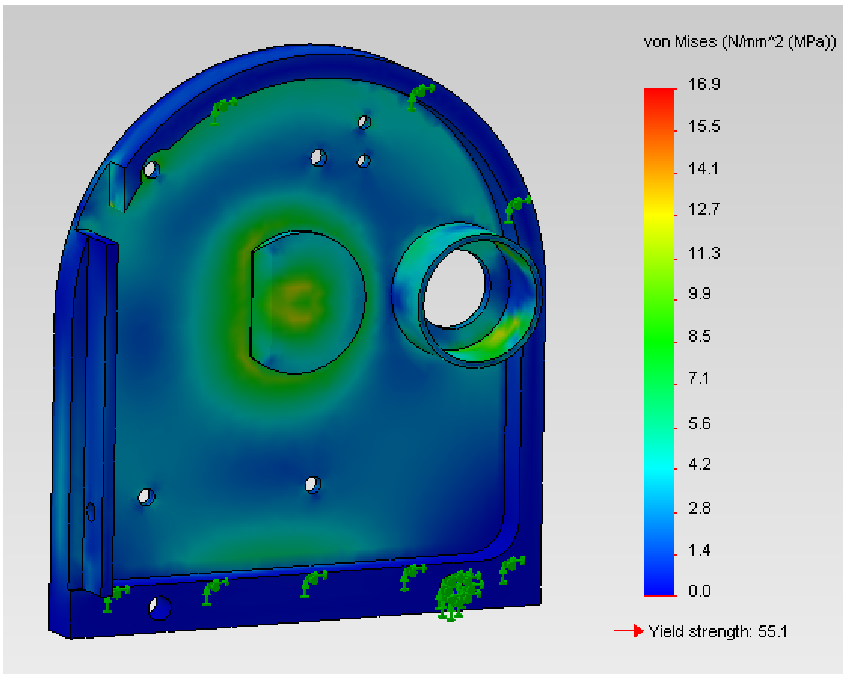


Figure 71: Female Side 1 Pin Test

For the second test, the force is applied to the flat bottom edge of the module, as seen in Figure 72. The fixed point in this test is the joint pin in the center of the face, simulating the fact that the rest of the module is mounted to that pin. This test shows that the max stress is located in the thin wall around the joint pin. In this case the max measured stress is 4.6 MPa, giving this face a safety factor of 12.

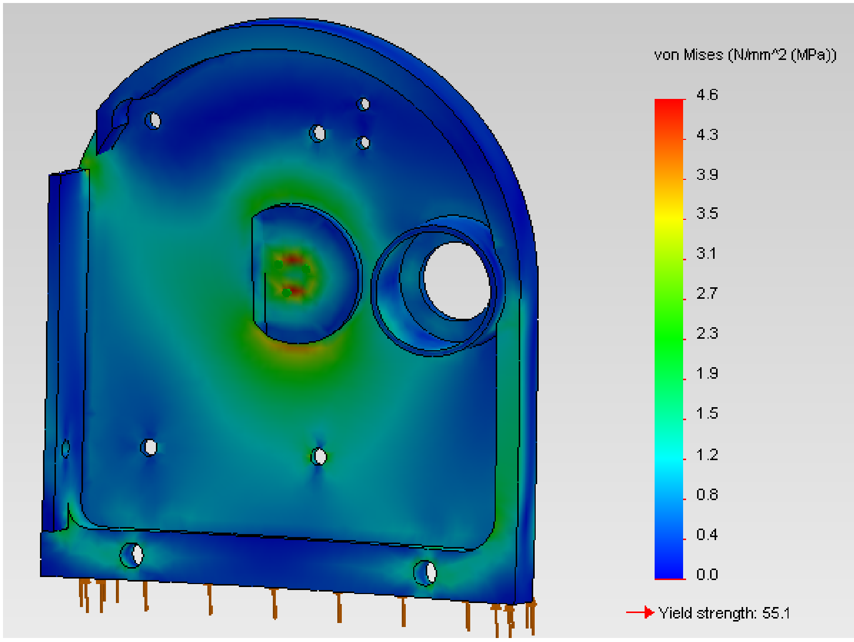


Figure 72: Female Side 1 Compression Test

6.3.8 Female Side 2

The first test applied to female side 2 placed the 10lb force onto the flat part of the joint pin while the opposite side was considered ground, as shown in Figure 73. The force was applied in this location because it simulates the stresses incurred if the pin extended out past the outer face and the entire force was applied to it. This test shows that the max stress was located in a circle around the joint pin where the side wall is the thinnest. The max stress is 13.8 MPa, giving this piece a factor of safety of 4.

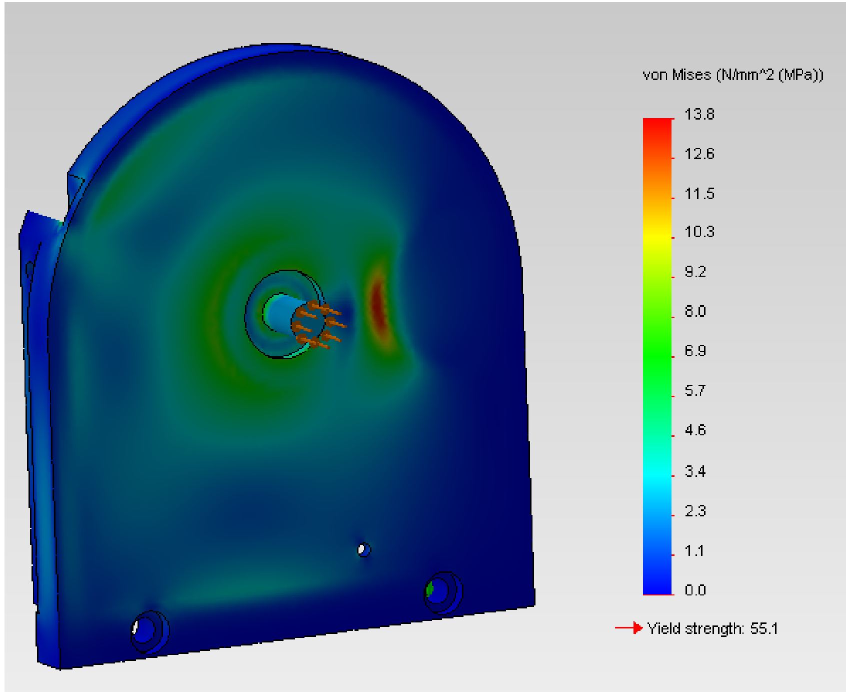


Figure 73: Female Side 2 Pin Test

For the second test, the force is applied to the flat bottom edge of the module, as seen in Figure 74. The fixed point in this test is the joint pin in the center of the face, simulating the fact that the rest of the module is mounted to that pin. This test shows that the max stress is located in the thin wall around the joint pin. In this case the max measured stress is 5.4 MPa, giving this face a safety factor of 10.

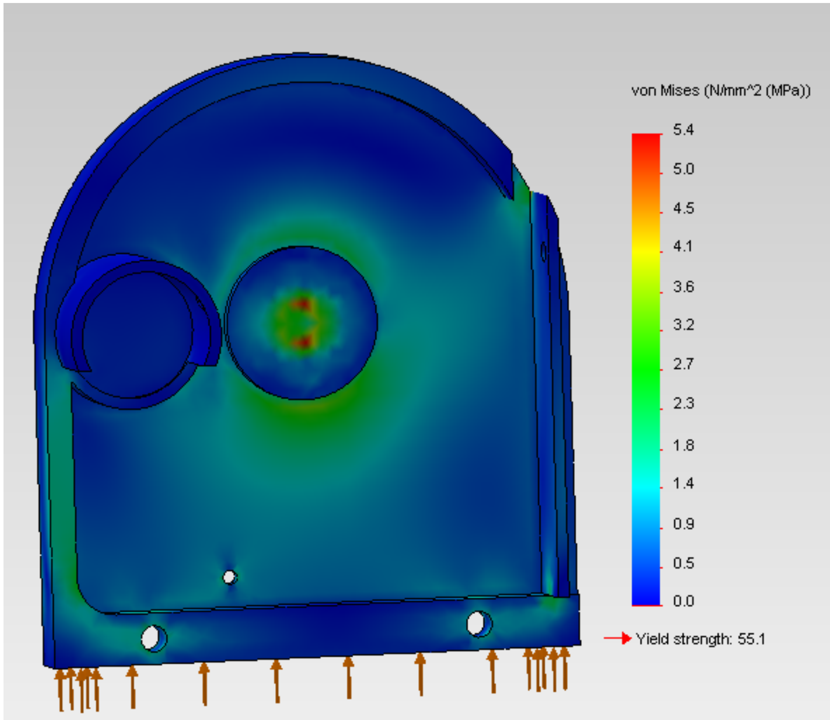


Figure 74: Female Side 2 Compression Test

6.3.9 Half Module

Stress tests were also done on assemblies of the module to see how the connected sides interacted with each other in terms of stress dispersion throughout the module.

The first test was applied to the male half of the module. This test measured the compressive stresses when the two sides were pressed together. As seen in Figure 75, one half has a 10lb force applied to it, representing the weight of five modules sitting on that face. The opposite side is considered fixed, representing the side of the module that would be sitting on the ground. This test shows that the stress gets transferred throughout the outer and inner face components. The maximum stress is located in the joint pin on the inner face of the module. The max measured stress on the pin is 11.7 MPa, giving the module half in this situation a safety factor of 4.7.

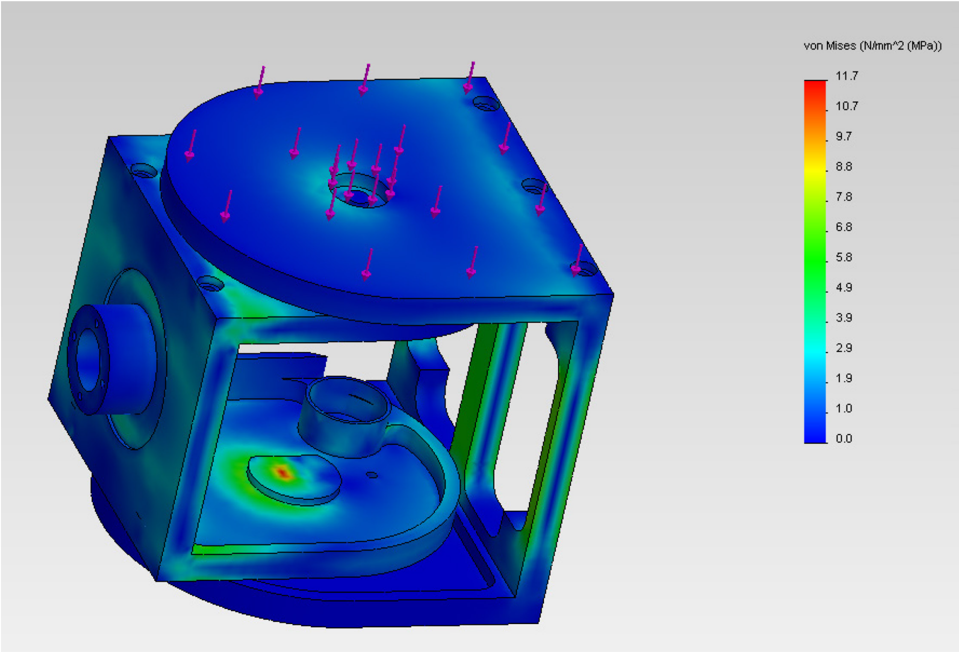


Figure 75: Male Half Side Load Test

The next test on the male half of the module was the compressive force that would be applied by the weight of five modules connected to the outer face, as seen in Figure 76. The inner face of the module was fixed so the effects of this force can be analyzed. Stresses were spread out over the outer face braces and concentrated at the pin joints. The maximum stress was measured at the pin joint, and was 3.4 MPa, giving a safety factor of roughly 16 for this test.

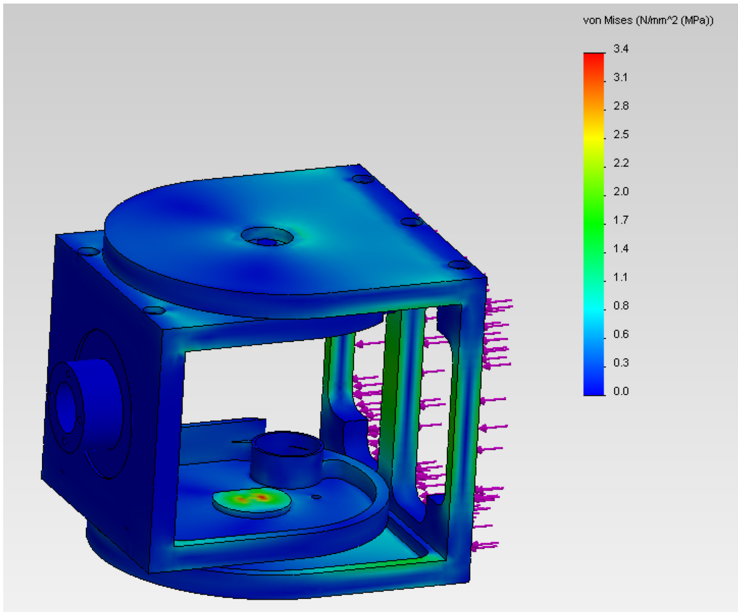


Figure 76: Male Half End Load Test

The third test preformed on the male half of the module measured the torque stresses that a module would experience when the main module is fixed on the edge of table and five modules are connected to it in a chain and hanging off the edge of the table, as shown in Figure 77. In order to simulate this test, a 150 in*lbs torque located on the outer face of the module was used. This simulation resulted in max stresses located on the top of the outer face (away from the fixed side) and at the joint pins, as shown in Figure 78. The max measured stress is 18 MPa, giving the half module a safety factor of 3 in this test.

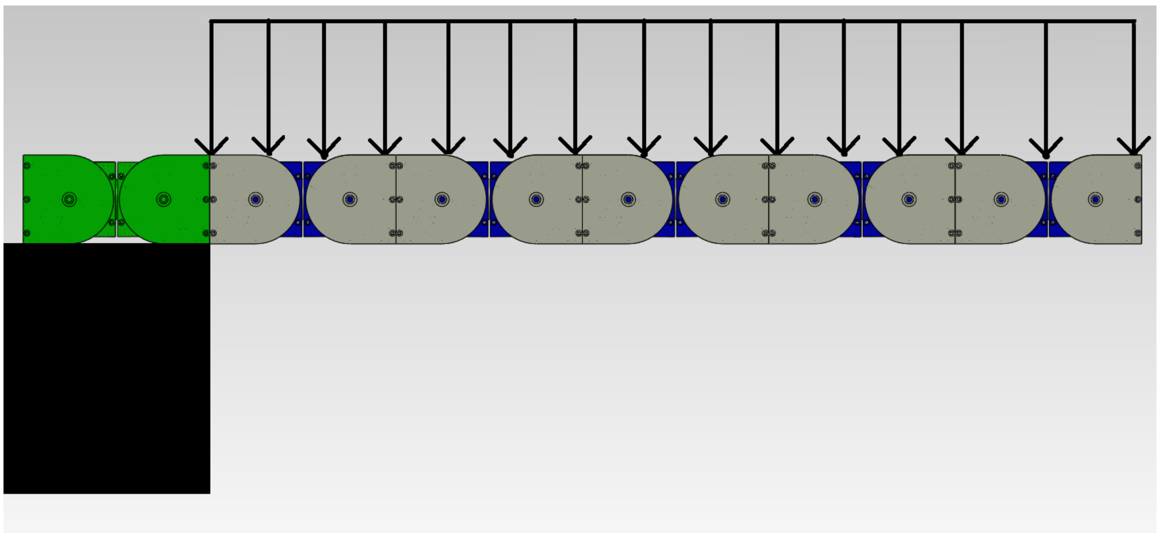


Figure 77. End Face Torque Test Visualization

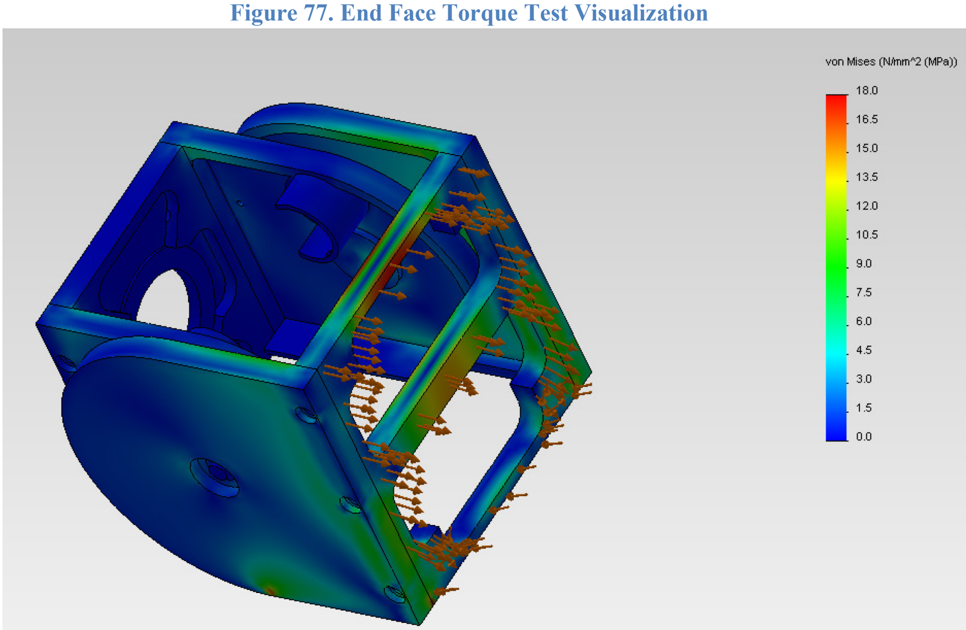


Figure 78: End Face Torque Test

6.3.10 Full Module

Finally, the strength of the entire module was tested. The scenario for this test is the module standing upright, with two additional modules stacked on top of it. The estimated force from the two modules is 10 lbf, which is applied to the top face. The maximum stress produced by this test is 3.2 MPa at the base of the joint pins, giving the module a safety factor of just over 17 for this loading scenario. This is very robust and this type of loading should not pose any problems for the module.

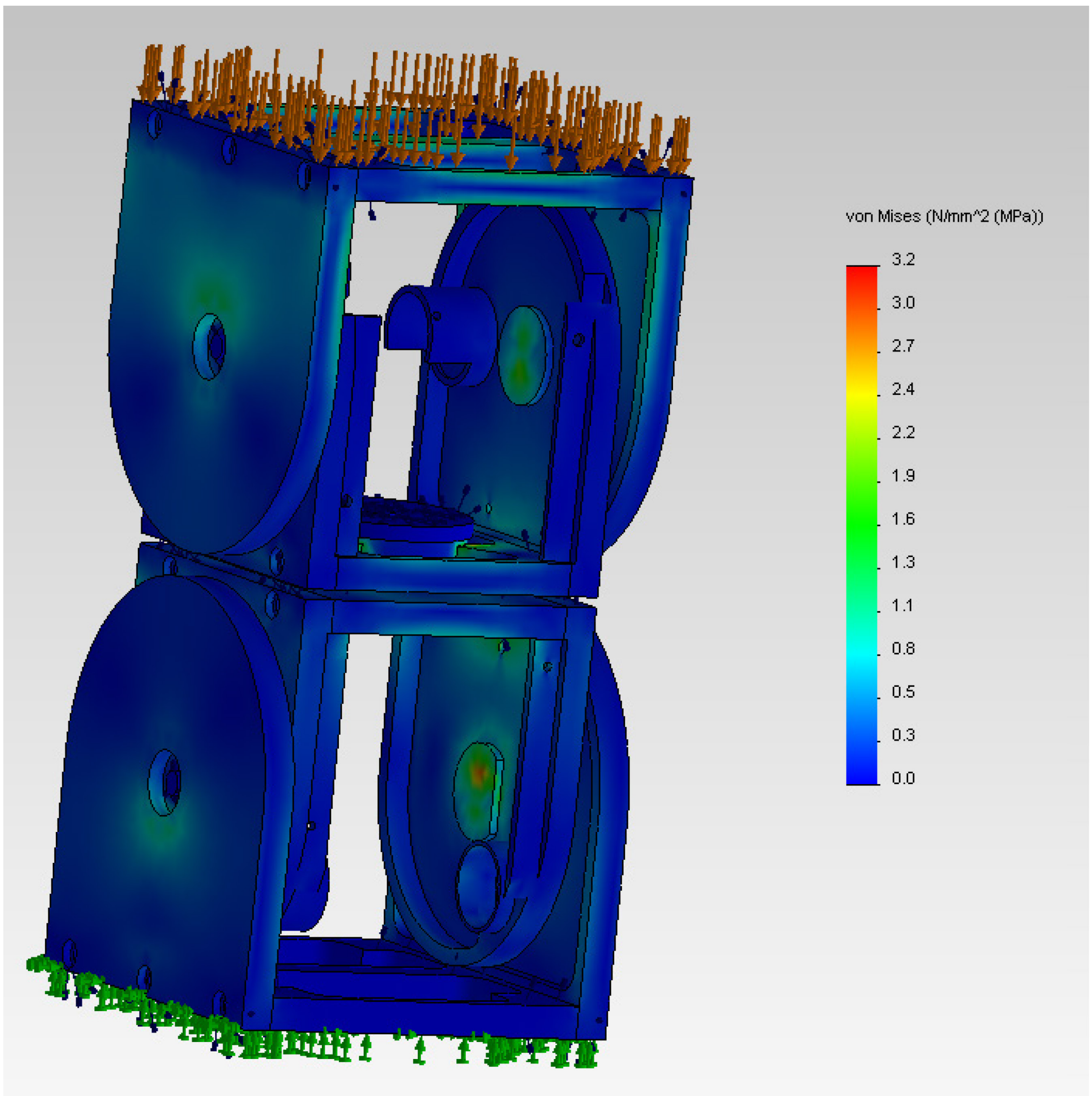


Figure 79. Full Module End Test

6.4 Connection Mechanism Analysis

Two different connection mechanisms were built by the end of the project. One was a mechanical connection mechanism and the other was an electrically switchable magnetic connector. Either of these designs can potentially be used with the final module, but would need some final tweaking before they can be used.

6.4.1 Mechanical Connector

Currently the mechanical connector is in the prototype stages. The connector was rapid prototyped in order to start the initial testing of its strengths and capabilities. But due to time constraints adequate testing could not be performed on the connection mechanism.

6.4.2 Electrically Switchable Permanent Magnetic Connector

Each ESPM has an approximate pull force of 0.4kg on steel with it is activated. The approximate pull force between two ESPMs is 0.7kg. The attachment design incorporates four ESPMs on each face, resulting in a total pull force of 2.8kg between two modules. Since the faces were designed with interlocking bits, the connection strength is mainly based on the pull force, not the sheer force. This means that with a module weight of 1.02kg, the attachment mechanism has the pull force to lift at least one other module without disconnecting.

The ESPM parts will fit within the confines of two of the three faces on one half of the module. The third face, with the gears for the joints, does not have enough space to also fit the complete magnet system. While the circuitry was shrunk down in the design of the custom PCB, the major component to fit will be a capacitor with a voltage rating high enough to be used. These electronic components could fit into the module with better space management.

7 Project Accomplishments and Summary

7.1 Project Accomplishments

At the outset of this project, the project team was given the goal of designing and building three metal modules. The modules would be able to move, have functional attachment mechanisms and reconfigure on their own.

The module design went through numerous iterations and multiple prototypes before the final module was built. The final module design was able to meet our project goals in terms of size, weight and mobility. The module can move around untethered and is capable of lifting other modules to reconfigure. Based on analysis work, the module is very robust and more than capable of standing up to the demands of normal operation.

Along with the module, connection mechanisms were also developed. There were two types of connector, mechanical and magnetic. The mechanical connector went through multiple iterations before a final prototype was built. The magnetic connector changed between several different designs before settling on permanent switchable magnets. Several versions of the switchable magnet connector were made, ending with a viable prototype. Both types of connectors are available options for reconfiguration; though the magnetic connector is more compact and simpler then mechanical connector.

Throughout the project, a total of four module prototypes were built in order to better visualize the design. These prototypes started off very simple and became more and more complicated as the project went along. The final prototype was the RP module, which was a functional module and very close to the final design. These prototypes were critical to developing the design, since they exposed problems not found in the CAD models as well as some unforeseen problems. The final step of module realization was the final machined module. This module addressed all of the issues found on earlier prototypes and was fully functional while containing all the necessary components.

At the end of the project, the team had one fully functional metal module, with two different connection designs. The module also has programmable movement gaits, which allow the module to move in different ways. Even though the project did not meet all of its initial goals; the end product is a working module and two viable connector options. This is a good starting point for future projects which will benefit from having a working module and connection mechanism. With a relatively small amount of additional work, future teams will be able to have a fully functional self-reconfigurable robotic system.

7.2 Project Summary

This project has great potential to have a significant impact on a number of areas. There are numerous potential uses for this robot, owing to its small, modular design. The applications of the robot range from search and rescue, to mobile construction platforms and general multiuse systems, much like a Swiss army knife. These modules could be used in post-disaster scenarios to search in areas either too small or too dangerous for humans to enter. An example of this would be a collapsed building after an earthquake. Due to its reconfigurable nature, it could also be used to search more open areas, such as a forest or mountainous terrain. Another application could be surveillance or surveying work in almost any environment, including space and other planets, operating on its own or in conjunction with other robotic systems. In these situations, the ability to reconfigure and overcome unforeseen obstacles would be invaluable.

The final cost for a single prototyped module was about $2000 in its current state. For full production, changes such as cheaper electronic components have the potential to bring that price down. Additional work such as a streamlined production method and the economic benefit of large scale operations would also drive the price down.

Given the small size of the module, one module represents a very small hazard to people working around it. A larger system of modules could potentially be more hazardous to people. The most dangerous part of the robot would be power from the electronics or a breach in the battery pack. Both of these issues can be dealt with by using proper insulation and protection for the wires and battery. As far as the physical hazard from the modules, this is very small and the use of standard safety practices, such as standing away from the modules when in operation and proper use of the electrical system should be more than adequate.

Since the module uses off-the-shelf components, it is highly sustainable and can remain in service for a long time. Due to its small size and light weight, it uses very little power to operate and as a result has very little environmental impact.

7.3 Future Work

7.3.1 Modular Robot Design Size

For future versions of the module a decrease in overall module size should be looked into. In order to decrease the overall size of the module many of the internal components need to be smaller. Currently the parts limiting the size of the module are the motor controllers. In order to fix that custom made motor controls can be made or a new set of motors can be looked into to drive the module. These new motors would have smaller motor controllers or motors that do not require motor controllers.

The current housing for the module is robust. So in the future looking into the frame of the module is also a possibility. The non weight-bearing walls could be thinned or pocketed to reduce the overall weight. And new materials for the housing could also be looked into to replace the 6061 aluminum.

7.3.2 Integrate Connection Mechanism

One main need in future work is the integration of the attachment mechanism with the module as a whole. This would include both the mechanical integration of the attachment faces, as well as the circuitry and control of the mechanism. While there are concepts for the mechanical integration, actual mounting and testing will need to be done to determine complete feasibility.

The idea behind the mechanical connector was to have a low power draw mechanism that could be locked in the on or off state. There is currently one mechanical connection design that was prototyped, but never tested out. Future work can be done looking into the feasibility of this mechanical connector design.

The electrically switchable magnet connector has been prototyped and tested and is considered very feasible. More testing can be done with this mechanism, as well as further design of the actual mounting and control of the system.

Once both connection mechanisms are working, the two should be tested against one another to see which one performs better. They should be evaluated keeping in mind size, repeatability, functionality, and power usage. When the better connection mechanism is determined it should be implemented into the module and programmed to interact with other modules to allow autonomous connection and re-configurability.

7.3.3 Module Localization

Another important need in future work is the ability for a module to communicate with and find other modules. The project team looked at using the Wiimote IR camera as a possible solution to this problem, since it is able to output the location of four separate IR emitters at a time. If modules had the IR camera, it could be able to locate an IR emitter (attached to another module) and ideally move toward it. Once close to another module, the ability to recognize multiple IR sources can be used to accurately line up the two modules for connection.

Communication between modules is another important need for a useful modular robotic system. When disconnected, the modules will require wireless communication between each other to coordinate localizing and connection. Once connected, a faster and lower power wired connection can be implemented to allow communication between modules. This will increase the run time of the system, as well as allow faster data rates for higher level programming algorithms.

8 Conclusions

The goal of this project was to realize a self-reconfigurable modular robot for use in search and rescue operations. The module housing was designed, machined, assembled, and analyzed. The module itself included all the components required to move and operate, including the microcontroller, sensors, battery, motors, controllers, and all the integrating electronics. An extensible software framework was developed for modular robot control. Two viable connection mechanisms, one magnetic and one mechanical, were developed and prototyped to integrate into future iterations of the modular robot system.

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Appendix A: Design Metrics

Design Metrics

Design	Modular	Self-Contained[1]	Size	Individual Mobility	Group Mobility	Self-Reconfigurability	Localization[2]
M-Tran	10	10	8	2.5	10	10	7.5
Superbot	10	10	5	6.5	10	5	10
ATRON	10	10	7.5	0	10	10	5
Miche	10	5	8	0	0	0	5
Robot Pebbles	10	5	10	0	0	0	5
IMobot	10	10	5	10	10	0	5
Ckbot	10	10	3	4	7.5	10	10
Super-Tran	10	10	4	6.5	10	10	10
AM-Tran	10	10	6.5	10	10	10	10
Spaceframe	10	10	7.5	10	8	10	10

Note 1: 5 points for physical components, 5 points for computational components
Note 2: 5 points for localization while connected, 5 points for localization while disconnected

Individual mobility — **Group Mobility**

	Speed	Degrees of mobility[1]	Average			Speed	Degrees of mobility	Average
M-Tran	2	3	2.5		M-Tran	10	10	10
Superbot	7	6	6.5		Superbot	10	10	10
ATRON	0	0	0		ATRON	10	10	10
Miche	0	0	0		Miche	0	0	0
Robot Pebbles	0	0	0		Robot Pebbles	0	0	0
IMobot	10	10	10		IMobot	10	10	10
Ckbot	2	6	4		Ckbot	5	10	7.5
Super-Tran	7	6	6.5		Super-Tran	10	10	10
AM-Tran	10	10	10		AM-Tran	10	10	10
Spaceframe	10	10	10		Spaceframe	10	6	8

Note 1: 0 for 0, 3 for 1, 6 for 2, and 10 for 3

Appendix B: Microcontroller Decisions

Name	Processor	Memory	I/O	Peripherals	Supply Voltage	Output Power	Size	Price
mbed NXP LPC2368	32-bit ARM Cortex M3 at 96MHz	512kB flash & 64kB RAM	26 (6 PWM)	Ethernet, USB, CAN, 2 I2C, 2 SPI, 3 UART	3.3V (4.5-9V)	40mA per pin	2.20x1.14"	$60.00
Arduino Pro Mini	ATmega328 (8 or 16MHz)	32kB flash & 2kB SRAM	14 (6 PWM)	FTDI, I2C, SPI, UART	3.3V (3.3-7) or 5V (1.2-5)	40mA per pin	0.7x1.3"	$18.95
Arduino Nano	ATmega328P (16MHz)	32kB flash & 2kB SRAM	14 (6 PWM)	I2C, SPI, UART	5V (7-12)	40mA per pin	0.73x1.70"	$42.00
Arduino Fio	ATmega328P (8MHz)	32kB flash & 2kB SRAM	14 (6 PWM)	I2C, SPI, UART	3.3V (3.35-7)	40mA per pin	1.1x2.6"	$24.95
Maple Mini	32-bit ARM Cortex M3 at 72MHz	120kB flash & 20 KB SRAM	34 (12 PWM)	4 timers, USB, 2 I2C, 2 SPI, 3 USART	3.3V (3-12)	500mA @ 3.3V	2.02x0.72"	$34.99
Maple	32-bit ARM Cortex M3 at 72MHz	120kB flash & 20KB SRAM	43 (15 PWM)	4 timers, 2 I2Cs, 2 SPIs, 3 USART	3.3V (3-12)	500mA @ 3.3V	2.05×2.1"	$44.99
Baby Orangutan	ATmega328P (20MHz)	32kB flash & 2kB SRAM	18	2 Bidir Motor drivers	5-13.5V	40mA per pin & 1A on Motor	1.2" x 0.7"	$19.95
Orangutan SV-328	ATmega328P (20MHz)	32kB flash & 2kB SRAM	8	2 Bidir Motor drivers	5-13.5V	40mA per pin & 1A on Motor	2.15"x1.9"	$64.95
Overo Fire	ARM Cortex-A7 CPU	512MB flash & 512MB RAM	140 (6 PWM)	I2C, UART, SPI, Extra MMC lines			0.67x2.28"	$219.00
arbotiX Mini Robocontrollers	ATMEGA168 (16MHz)		20	2 Bidir Motor drivers, I2C	6-16V		2.4"x2.4"	$59.99

Appendix C: Electronics Decisions

Batteries

Name	Voltage	Capacity	Discharge	Size
PowerEdge LiPoly Pack	11.1V	450mAh	30C	15x25x50mm
PowerEdge LiPoly Pack	11.1V	850mAh	30C	19x25x50mm
Genesis Power LiPo Battery	11.1V	450mAh	25C	53x31x15mm
TP350-3SPL25J	11.1V	350mAh	25C	23x21x40mm
TP730-3SPL25J	11.1V	730mAh	25C	19x31x54mm
Venom 850mAh LiPo for Micro Jets	11.1V	850mAh	20C	54x30x22mm

Accelerometers

Sensor	Type	Vin	Power	Communication	Size	Price
MinIMU-9 (L3G4200D and LSM303DLM Carrier)	Accelerometer, Gyro, and Compass	2.5-5.5V	10mA	i2C	0.9×0.6×0.1"	$49.95
MMA7361L 3-Axis Accelerometer ±1.5/6g	Accelerometer	3.3V	0.5mA	Analog	0.5×0.4"	$11.95
Parallax Board Mount 3-Axis Module MMA7455	Accelerometer	3.3V		SPI or I2C	0.6x0.5"	$34.99
Grove - I2C 3-axis Accelerometer	Accelerometer	3-5V	47uA	I2C	2x2cm	
Analog Devices' ADXL335	Accelerometer	1.8-3.6	350μA	Analog	0.7x0.7"	
Triple Axis Accelerometer Breakout - ADXL345	Accelerometer	2.0-3.6	40μA	SPI or I2C	0.626x0.8"	

Wireless Modules

Sensor	Wireless Type	Vin	Power	Wired Comms	Peripherals	Size	Price
RN-171	WiFi 802.11 b/g	3.3V	120-240mA (Tx); 40mA (Rx); 10mA (doze)	UART	10 digital and 8 analog	0.96X1.15"	
MOD-WiFi	WiFi 802.11 b/g/n	2.7-3.6V	154mA (Tx); 85mA (Rx); 250uA (sleep); .1uA (hib.)	UART, SPI		1.55×0.95"	$44.00
Digilent Pmod WiFi Expansion Module	WiFi 802.11 b/g/n	3.3V		SPI			$59.99
Microchip® MRF24WB0MA	WiFi 802.11 b/g/n		154mA (Tx); 85mA (Rx); 250uA (sleep); .1uA (hib.)	SPI, JTAG		21x31mm	$23.74
RedBack	WiFi 802.11 b/g/n				12 digital and 6 Analog		$75.00
WiFly GSX WiFi Breakout Board	WiFi 802.11 b/g	3.3V	210mA (Tx); 40mA (Rx); 4uA (sleep)	UART, SPI	10 digital and 8 analog	1.2x1.8"	$84.95
GainSpan Module	WiFi 802.11 b/g	3.3V	150mA (Tx); 140mA (Rx); 150uA (sleep); 7uA (hib.)		2 UART , I2C, 2 SPI, 2 ADC, & 3 PWM	1.25x0.8"	$33.95
XBee ZB S2	ZigBee	3-3.4v	35mA (Tx); 38mA (Rx); 15mA (idle); 1uA (sleep)	UART	10 digital and 4 analog	0.960×1.087"	$25.95
XBee 802.15.4 RF 2.4GHz Module	RF 2.4Ghz (802.15.4)	3-3.4V	1 mW; 35mA (Tx); 50mA (Rx); 10uA (sleep)	UART		0.960×1.087"	$23.95
Transceiver nRF2401A with Chip Antenna	RF 2.4GHz (802.15.4)	1.9-3.6V	10.5mA (Tx); 18mA (Rx);	SPI		0.5x0.675"	$24.95
Parani-ESD200/210	Bluetooth	3.3V	40mA	UART		0.7x0.78x0.47"	$55.00
Bluetooth SMD Module - RN-41	Bluetooth	3.3V	30mA	UART		13.4x25.8x2mm	$24.95
Bluetooth SMD Module - RN-42	Bluetooth	3.3V	26uA in sleep	UART		1.0x0.5"	$14.95
Bluetooth Modem - BluESPMiRF Silver	Bluetooth	3.3V-6				0.15x0.6x1.9"	$39.95

Appendix D. Final Module Component List

Component	Quantity
Maxon EC-Max Motors	x 3
Maxon Motor Controller	x 3
Mbed Microcontroller	x 1
Microcontroller Breakout Board	x 1
Battery Power Control Board	x 1
730 mAh Thunderpower Battery	x 1
Zigbee Wireless Transceiver	x 1
Limit Switch	x 2
Potentiometer	x 1
75 Tooth Center Gear	x 1
72 Tooth Side Gear	x 2
18 Tooth Side Motor Gear	x 2
16 Tooth Center Motor Gear	x 1
.875 ID Center Bearings	x 2
.875 ID Center Washers	x 4
Side Bushings	x 4
Side Lock Rings	x 4
Battery Mount	x 1
Motor Controller Mounts	x 2
Microcontroller Mounts	x 2
Motor Mounts	x 2
Pulleys	x 2
Pulley Mount	x 1
4-40 Screws	x 20
Metal 2-56 Screws	x 5
Plastic 2-56 Screws	x 20
2-56 Plastic Nuts	x 20
1.6 M Screws	x 3
22 Gauge Wire	

Appendix E. Printed Circuit Boards

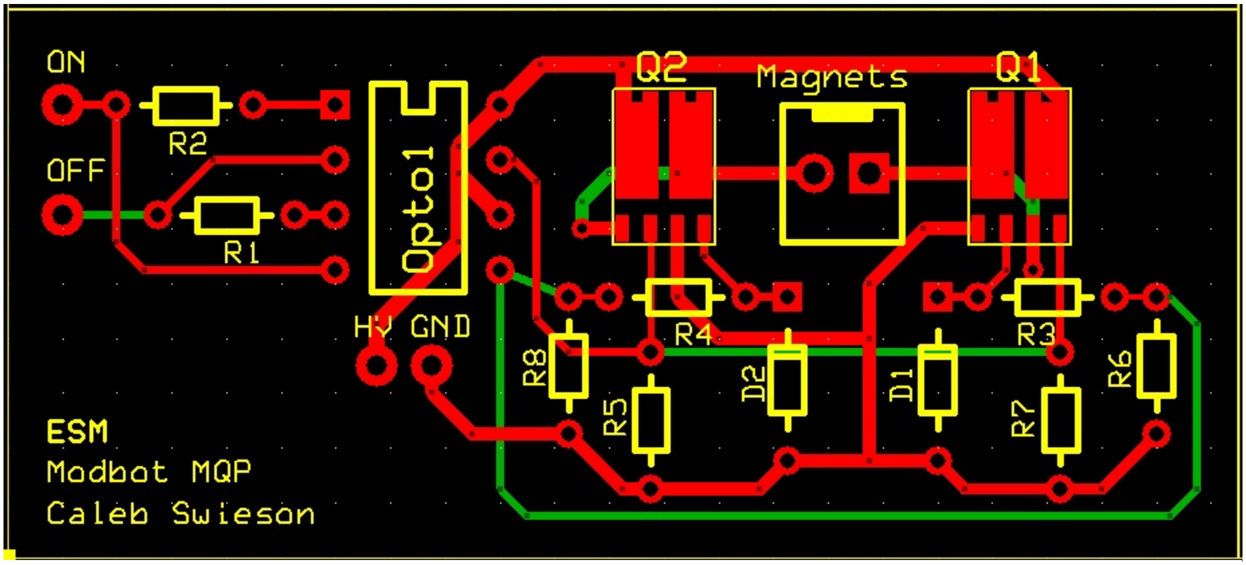


Figure 80. PCB switching circuit

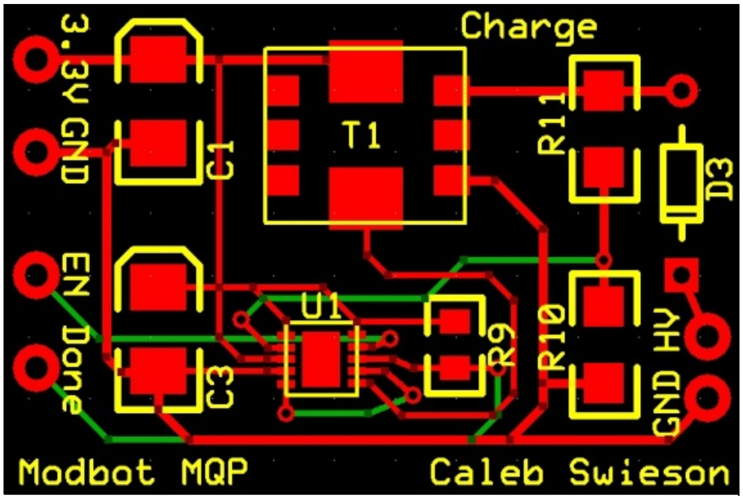


Figure 81. PCB Charging Circuit

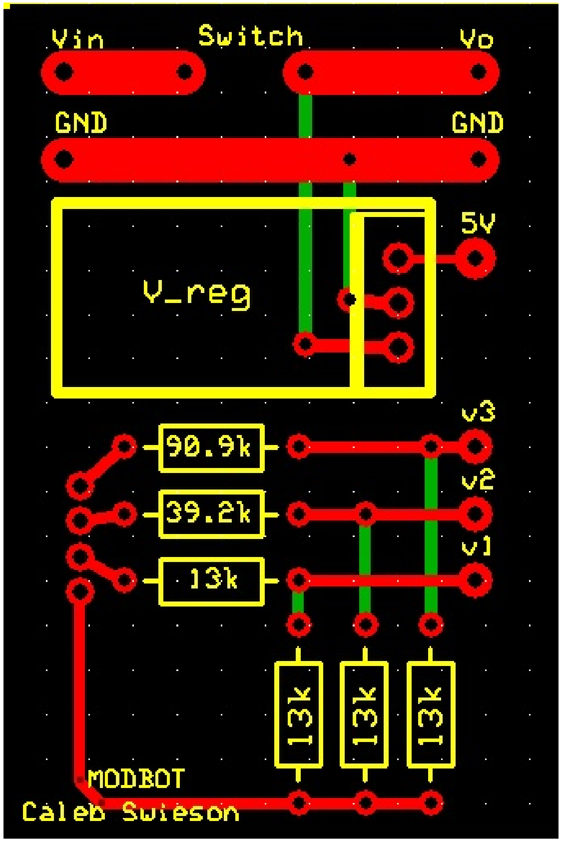


Figure 83. Power Management Board (PCB)

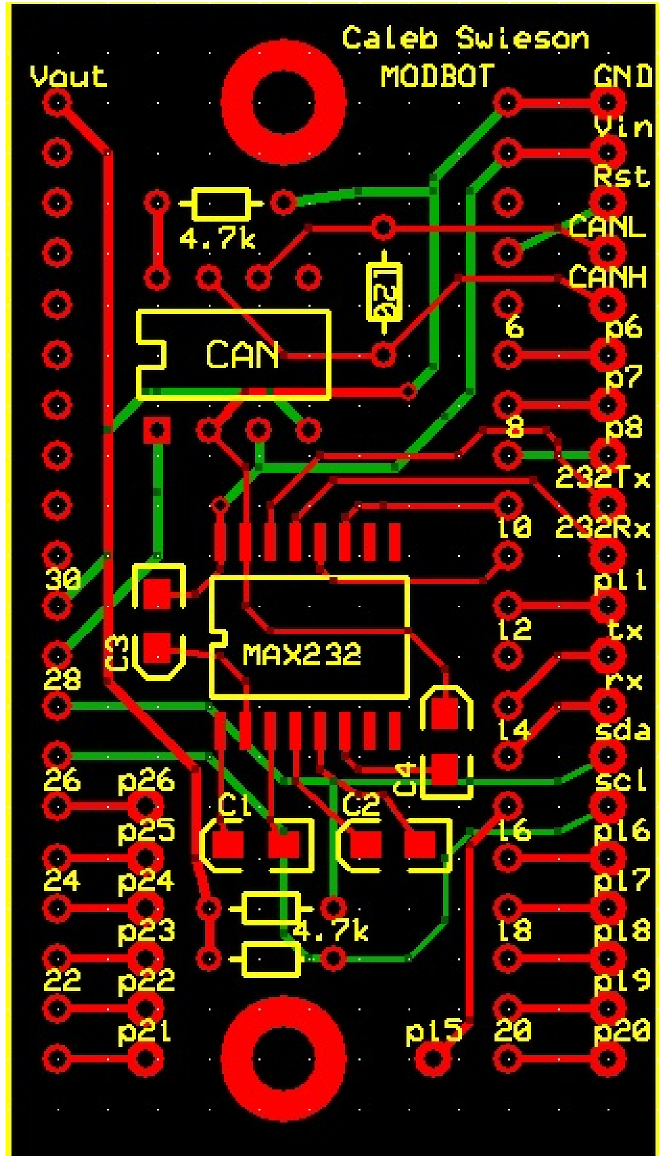
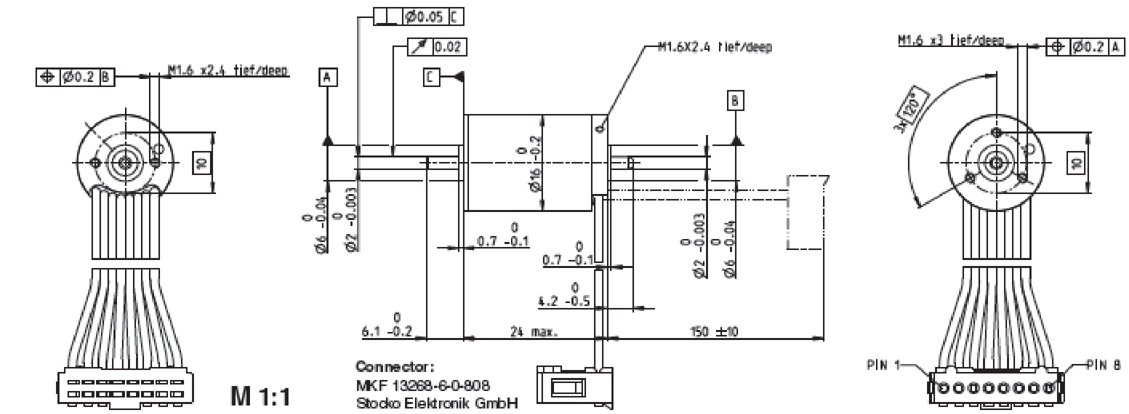


Figure 82. Microcontroller Breakout Board (PCB)

Appendix F. Datasheets

EC-max 16 ∅16 mm, brushless, 5 Watt



Connector:
MKF 13268-6-0-808
Stocko Elektronik GmbH

Stock program
Standard program
Special program (on request)

Order Number

Motor Data		283825	283826	283827	283828
Values at nominal voltage					
1 Nominal voltage	V	4.5	6.0	9.0	12.0
2 No load speed	rpm	12800	13500	12600	13500
3 No load current	mA	148	120	72.4	60.2
4 Nominal speed	rpm	5230	5730	4930	5900
5 Nominal torque (max. continuous torque)	mNm	3.3	3.19	3.28	3.21
6 Nominal current (max. continuous current)	A	1.17	0.90	0.573	0.453
7 Stall torque	mNm	5.82	5.79	5.64	5.95
8 Starting current	A	1.89	1.49	0.901	0.762
9 Max. efficiency	%	53	53	53	53
Characteristics					
10 Terminal resistance phase to phase	Ω	2.38	4.04	9.99	15.7
11 Terminal inductance phase to phase	mH	0.0396	0.0634	0.163	0.254
12 Torque constant	mNm / A	3.08	3.9	6.26	7.8
13 Speed constant	rpm / V	3100	2450	1530	1220
14 Speed / torque gradient	rpm / mNm	2390	2540	2440	2470
15 Mechanical time constant	ms	10.7	11.4	10.9	11.1
16 Rotor inertia	gcm²	0.428	0.428	0.428	0.428

Specifications

Thermal data

17 Thermal resistance housing-ambient 23.5 K / W
18 Thermal resistance winding-housing 2.57 K / W
19 Thermal time constant winding 0.883 s
20 Thermal time constant motor 390 s
21 Ambient temperature -40 ... +100°C
22 Max. permissible winding temperature +155°C

Mechanical data (preloaded ball bearings)

23 Max. permissible speed 20000 rpm
24 Axial play at axial load < 2.0 N 0 mm
> 2.0 N 0.14 mm
25 Radial play preloaded
26 Max. axial load (dynamic) 1.5 N
27 Max. force for press fits (static) 18 N
(static, shaft supported) 600 N
28 Max. radial loading, 5 mm from flange 6 N

Other specifications

29 Number of pole pairs 1
30 Number of phases 3
31 Weight of motor 36 g

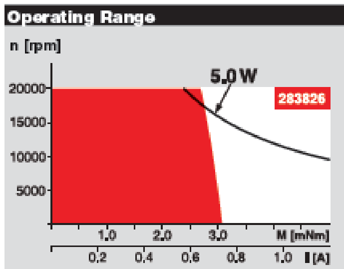
Values listed in the table are nominal.

Connection (Cable AWG 24)

brown	Motor winding 1	Pin 1
red	Motor winding 2	Pin 2
orange	Motor winding 3	Pin 3
yellow	V_{Hall} 3 ... 24 VDC	Pin 4
green	GND	Pin 5
blue	Hall sensor 1	Pin 6
violet	Hall sensor 2	Pin 7
grey	Hall sensor 3	Pin 8

Wiring diagram for Hall sensors see p. 27

Operating Range



Comments

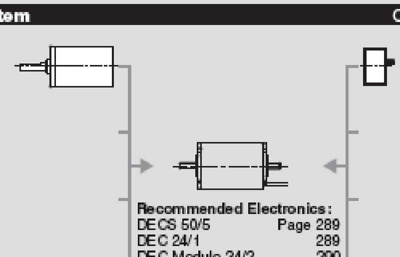
Continuous operation
In observation of above listed thermal resistance (lines 17 and 18) the maximum permissible winding temperature will be reached during continuous operation at 25°C ambient.
= Thermal limit.

Short term operation
The motor may be briefly overloaded (recurring).

Assigned power rating

maxon Modular System Overview on page 16 - 21

Planetary Gearhead
∅16 mm
0.1 - 0.3 Nm
Page 215



Encoder MR
128 / 256 / 512 CPT,
2 / 3 channels
Page 261

Recommended Electronics:

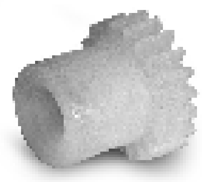
DECS 50/5	Page 289
DEC 24/1	289
DEC Module 24/2	290
DEC V 50/5	297
DES 50/5	298
EPOS2 Module 36/2	304
EPOS2 24/1	304
Notes	20

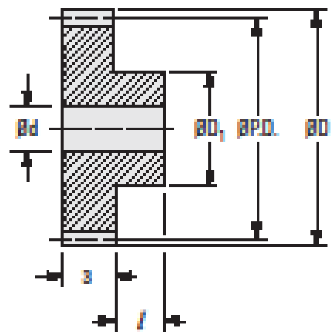
3 mm FACE WIDTH
20° PRESSURE ANGLE

PHONE: 516.328.3300 • FAX: 516.326.8827 • WWW.SDP-SI.COM

Metric
0 10

› **MATERIAL:**
Acetal





METRIC COMPONENT

Catalog Number	No. of Teeth	P.D.	D Dia.	d Bore Dia.	D_1 Hub Dia.	l Hub Proj.
A 1M 2MYZ05012	12	6	7	2	4	4
A 1M 2MYZ05013	13	6.5	7.5	2	4	4
A 1M 2MYZ05014	14	7	8	2	5	4
A 1M 2MYZ05015	15	7.5	8.5	3	6	7
A 1M 2MYZ05016	16	8	9	3	6	7
A 1M 2MYZ05017	17	8.5	9.5	3	6	7
A 1M 2MYZ05018	18	9	10	4	8	7
A 1M 2MYZ05019	19	9.5	10.5	4	8	7
A 1M 2MYZ05020A	20	10	11	3	8	7
A 1M 2MYZ05020	20	10	11	4	8	7
A 1M 2MYZ05021	21	10.5	11.5	4	8	7
A 1M 2MYZ05022	22	11	12	4	10	7
A 1M 2MYZ05023	23	11.5	12.5	4	10	7
A 1M 2MYZ05024	24	12	13	4	10	7
A 1M 2MYZ05025	25	12.5	13.5	4	10	7
A 1M 2MYZ05025A	25	12.5	13.5	6	10	7
A 1M 2MYZ05026	26	13	14	4	10	7
A 1M 2MYZ05026A	26	13	14	6	10	7
A 1M 2MYZ05027	27	13.5	14.5	4	10	7
A 1M 2MYZ05028	28	14	15	4	10	7
A 1M 2MYZ05030	30	15	16	4	12	7
A 1M 2MYZ05032	32	16	17	4	12	7
A 1M 2MYZ05035	35	17.5	18.5	4	12	7
A 1M 2MYZ05036	36	18	19	4	12	7
A 1M 2MYZ05038	38	19	20	4	12	7

Continued on the next page

NONMETALLIC MOLDED SPUR GEARS • MODULE 0.5

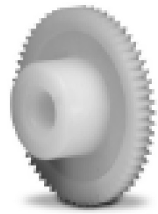
SDP/SI

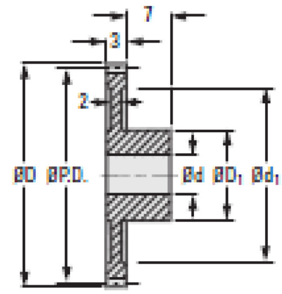
PHONE: 516.328.3300 • FAX: 516.326.8827 • WWW.SDP-SI.COM

3 mm FACE WIDTH
20° PRESSURE ANGLE

Metric
0 10

› **MATERIAL:**
Acetal





METRIC COMPONENT

Catalog Number	No. of Teeth	P.D.	D Dia.	d Bore Dia.	D_1 Hub Dia.	d_1 Dia.
* A 1M 2MYZ05040	40	20	21	4	12	14.5
A 1M 2MYZ05042	42	21	22	4	12	16
A 1M 2MYZ05045	45	22.5	23.5	4	12	18.5
A 1M 2MYZ05048	48	24	25	6	15	19
A 1M 2MYZ05050	50	25	26	6	15	20
A 1M 2MYZ05052	52	26	27	6	15	21
A 1M 2MYZ05054	54	27	28	6	15	22
A 1M 2MYZ05055	55	27.5	28.5	6	15	23
A 1M 2MYZ05056	56	28	29	6	15	23
A 1M 2MYZ05060	60	30	31	6	15	24
A 1M 2MYZ05064	64	32	33	6	15	25
A 1M 2MYZ05065	65	32.5	33.5	6	15	27
A 1M 2MYZ05070	70	35	36	6	15	29
A 1M 2MYZ05072	72	36	37	6	15	30
A 1M 2MYZ05075	75	37.5	38.5	6	15	33
A 1M 2MYZ05080	80	40	41	6	15	36
A 1M 2MYZ05090	90	45	46	6	15	39
A 1M 2MYZ05096	96	48	49	6	15	42
A 1M 2MYZ05100	100	50	51	6	15	44
A 1M 2MYZ05120	120	60	61	6	15	54

* Coring opposite hub only.

Continued from the previous page

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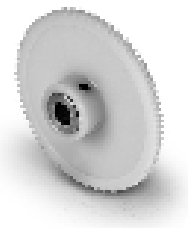
NONMETALLIC MOLDED SPUR GEARS • MODULE 0.5

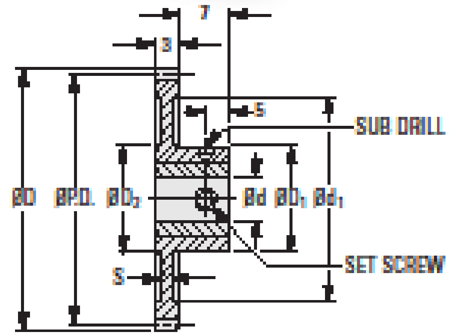
SDP/SI
PHONE: 516.328.3300 • FAX: 516.326.8827 • WWW.SDP-SI.COM

3 mm FACE WIDTH
20° PRESSURE ANGLE

MATERIAL:
Gear – Acetal
Insert – Brass

Metric
0 10





METRIC COMPONENT

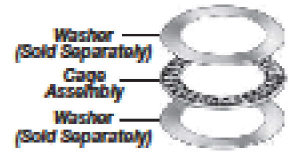
Catalog Number	No. of Teeth	P.D.	D Dia.	d Bore +0.025 0	D_1 Hub Dia.	S	d_1 Dia.	D_2 Dia.	Set Screw
A 1Z 2MYZ0501803	18	9	10	3	8	–	–	–	M2.5
A 1Z 2MYZ0501903	19	9.5	10.5	3	8	–	–	–	M2.5
A 1Z 2MYZ0502003	20	10	11	3	8	–	–	–	M2.5
A 1Z 2MYZ0502103	21	10.5	11.5	3	8	–	–	–	M2.5
A 1Z 2MYZ0502204	22	11	12	4	10	–	–	–	M2.5
A 1Z 2MYZ0502304	23	11.5	12.5	4	10	–	–	–	M2.5
A 1Z 2MYZ0502404	24	12	13	4	10	–	–	–	M2.5
A 1Z 2MYZ0502504	25	12.5	13.5	4	10	–	–	–	M2.5
A 1Z 2MYZ0502604	26	13	14	4	10	–	–	–	M2.5
A 1Z 2MYZ0502704	27	13.5	14.5	4	10	–	–	–	M2.5
A 1Z 2MYZ0502804	28	14	15	4	10	–	–	–	M2.5
A 1Z 2MYZ0503004	30	15	16	4	12	–	–	–	M2.5
A 1Z 2MYZ0503204	32	16	17	4	12	–	–	–	M2.5
A 1Z 2MYZ0503504	35	17.5	18.5	4	12	–	–	–	M2.5
A 1Z 2MYZ0503604	36	18	19	4	12	–	–	–	M2.5
A 1Z 2MYZ0503804	38	19	20	4	12	–	–	–	M2.5
A 1Z 2MYZ0504004	40	20	21	4	12	2	14	12	M2.5
A 1Z 2MYZ0504204	42	21	22	4	12	2	16	12	M2.5
A 1Z 2MYZ0504504	45	22.5	23.5	4	12	2	18.5	12	M2.5
A 1Z 2MYZ0504806	48	24	25	6	15	2	19	15	M3
A 1Z 2MYZ0505006	50	25	26	6	15	2	20	15	M3
A 1Z 2MYZ0505206	52	26	27	6	15	2	21	15	M3
A 1Z 2MYZ0505406	54	27	28	6	15	2	22	15	M3
A 1Z 2MYZ0505506	55	27.5	28.5	6	15	2	23	15	M3
A 1Z 2MYZ0505606	56	28	29	6	15	2	23	15	M3
A 1Z 2MYZ0506006	60	30	31	6	15	2	24	15	M3
A 1Z 2MYZ0506406	64	32	33	6	15	2	25	15	M3
A 1Z 2MYZ0506506	65	32.5	33.5	6	15	2	27	15	M3
A 1Z 2MYZ0507006	70	35	36	6	15	2	29	15	M3
A 1Z 2MYZ0507206	72	36	37	6	15	2	30	15	M3
A 1Z 2MYZ0507506	75	37.5	38.5	6	15	2	33	15	M3
A 1Z 2MYZ0508006	80	40	41	6	15	2	36	15	M3
A 1Z 2MYZ0509006	90	45	46	6	15	2	39	15	M3
A 1Z 2MYZ0509606	96	48	49	6	15	2	42	15	M3
A 1Z 2MYZ0510006	100	50	51	6	15	2	44	15	M3
A 1Z 2MYZ0512006	120	60	61	6	15	2	54	15	M3

Steel Thrust Needle-Roller Bearings

Because of the large contact area between the rollers and washers, these bearings are great for medium to heavy duty, low-friction jobs. Their compact, low-profile design works well in narrow spaces. A complete bearing consists of one cage assembly and two washers (sold separately). For an even lower profile, you can use cage assemblies without washers on material that is hardened to Rockwell C58-C64 with a surface finish of 16 microns.

All components are made of steel. Temperature range is –40° to +248° F for inch sizes; –4° to +248° F for metric sizes. Note: Dynamic load capacities listed are for thrust (parallel to shaft) loads.

Cage Assembly



Inch

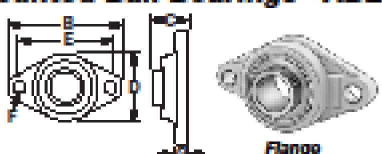
For Shaft Dia.	OD	CAGE ASSEMBLIES Thick.	Dynamic Load Cap., lbs.	Max. rpm		Each	WASHERS 0.032" Thick	Each	0.126" Thick	Each
1/2"	15/16"	5/64"	1,920	13,000	5909K31	$2.91	5909K44	$0.98		
5/8"	1 1/8"	5/64"	2,170	11,000	5909K32	2.91	5909K45	1.05		
3/4"	1 1/4"	5/64"	2,410	9,500	5909K33	2.97	5909K46	1.10	5909K59	$2.52
7/8"	1 7/16"	5/64"	2,900	8,000	5909K34	2.97	5909K47	1.10	5909K61	3.13
7/8"	1 11/16"	5/64"	4,400	7,500	5909K35	4.04	5909K48	2.15	5909K62	4.41
1"	1 9/16"	5/64"	3,150	7,500	5909K36	2.97	5909K49	1.10	5909K63	4.66
1 1/8"	1 3/4"	5/64"	3,850	6,500	5909K37	2.97	5909K51	1.47	5909K64	5.39
1 1/4"	1 15/16"	5/64"	4,500	6,000	5909K38	3.02	5909K52	1.47	5909K65	3.81
1 3/8"	2 1/16"	5/64"	4,600	5,500	5909K39	3.81	5909K53	1.47	5909K66	8.93
1 1/2"	2 9/16"	5/64"	4,850	5,000	5909K41	4.03	5909K54	1.81	5909K67	5.58
1 3/4"	2 1/2"	5/64"	5,600	4,400	5909K42	4.28	5909K55	1.98		
2"	2 3/4"	5/64"	5,800	4,000	5909K43	4.56	5909K56	2.31	5909K69	12.13

Metric

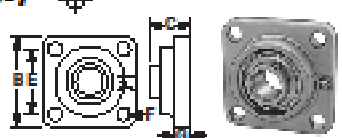
For Shaft Dia., mm	OD, mm	CAGE ASSEMBLIES Thick., mm	Dynamic Load Cap., lbs.	Max. rpm		Each	WASHERS Thick., mm		Each	Thick., mm		Each
10	24	2	2,070	17,000	5909K11	$3.48	1	5909K71	$1.18	2.75	5909K83	$8.12
12	26	2	2,230	15,000	5909K12	3.95	1	5909K72	1.23	2.75	5909K84	8.32
15	28	2	2,550	13,000	5909K13	3.82	1	5909K73	1.23	2.75	5909K85	8.32
17	30	2	2,700	12,000	5909K14	3.82	1	5909K74	1.23	2.75	5909K86	9.00
20	35	2	2,950	10,000	5909K15	4.41	1	5909K75	1.23	2.75	5909K87	9.80
25	42	2	3,300	8,500	5909K16	4.41	1	5909K76	1.38	3	5909K88	11.93
30	47	2	3,650	7,500	5909K17	5.06	1	5909K77	1.60	3	5909K89	13.43
35	52	2	4,000	6,500	5909K18	5.55	1	5909K78	1.93	3.5	5909K91	15.03
45	65	3	6,700	5,000	5909K19	9.41	1	5909K79	3.01	4	5909K92	17.38
50	70	3	7,200	4,800	5909K21	10.15	1	5909K81	3.38	4	5909K93	19.88
55	78	3	8,500	4,300	5909K22	12.30	1	5909K82	3.77	5	5909K94	22.21

Food-Grade Stainless Steel Mounted Ball Bearings—ABEC-1

Base Mount



Flange Mount



Square-Flange Mount

With their corrosion-resistant stainless steel construction and smooth surfaces that won't trap debris, these are the ultimate bearings for use in food-handling equipment that is frequently washed down. Bases are solid cast 300 series stainless steel. Ball bearings are deep grooved and made of Type 420C stainless steel. They're permanently lubricated with USDA-approved grease and double shielded—so they're virtually maintenance free. Shields block out dirt and are made of Type 304 stainless steel.

All bearings are made to ABEC-1 dimensional tolerance standards. Temperature range is –30° to +160° F. Furnished with two stainless steel set screws to secure the bearing to the shaft.

Base Mount

For Shaft Dia.	Center Ht. (A)	Dynamic Load Cap., lbs.	Max. rpm	O'all Lg. (B)	O'all Ht. (C)	Base Wd. (D)	Ctr.-to-Ctr. (E) Min.	Max.	Bolt Slot (F), Lg. × Wd.		Each
3/4"	1 5/16"	2,430	1,120	5"	2 1/2"	1 1/4"	3 7/16"	4 9/16"	13/16" × 29/64"	3749T1	$201.78
1"	1 7/16"	2,670	935	5 1/8"	2 3/4"	1 7/16"	3 11/16"	4 9/16"	3/4" × 29/64"	3749T2	229.20
1 1/4"	1 11/16"	3,660	795	6"	3 15/64"	1 9/16"	4 1/4"	5"	15/16" × 9/16"	3749T4	279.87
1 1/2"	1 15/16"	5,550	610	6 7/8"	3 29/32"	1 7/8"	4 15/16"	5 3/4"	31/32" × 9/16"	3749T7	371.95

Flange Mount

For Shaft Dia.	Dynamic Load Cap., lbs.	Max. rpm	O'all Lg. (B)	O'all Ht. (C)	O'all Wd. (D)	Ctr.-to-Ctr. (E)	Bolt Hole Size (F)	Thick. (G)		Each
3/4"	2,430	1,120	4 13/32"	1 9/32"	2 3/8"	3 17/32"	7/16"	7/16"	3756T1	$201.78
1"	2,670	935	4 7/8"	1 7/16"	2 3/4"	3 57/64"	1/2"	17/32"	3756T2	229.20
1 1/4"	3,660	795	5 9/16"	1 21/32"	3 1/8"	4 19/32"	1/2"	17/32"	3756T4	279.87
1 1/2"	5,550	610	6 3/8"	2 3/32"	4"	5 21/32"	9/16"	9/16"	3756T7	371.95

Square-Flange Mount

For Shaft Dia.	Dynamic Load Cap., lbs.	Max. rpm	Square Size (B)	O'all Ht. (C)	Ctr.-to-Ctr. (E)	Bolt Hole Size (F)	Thick. (G)		Each
3/4"	2,430	1,120	3 3/8"	1 15/32"	2 1/2"	7/16"	7/16"	3756T11	$201.78
1"	2,670	935	3 3/4"	1 17/32"	2 3/4"	29/64"	17/32"	3756T12	229.20
1 1/4"	3,660	795	4 1/4"	1 21/32"	3 1/4"	1/2"	17/32"	3756T14	279.87
1 1/2"	5,550	610	5 1/8"	2 3/32"	4"	9/16"	9/16"	3756T17	371.95

Self-Locking External Retaining Rings

No groove required for installation. Rings dig in to the shaft material, so expect minor scratching. Use with an unhardened shaft. They're tougher to remove compared to standard retaining rings.

Black-finish steel rings have a minimum Rockwell hardness of C47 for shaft diameters 1/4" and larger (3/32"- 3/16" shaft diameters are not rated).

Stainless steel rings are made of Type 15-7 or 17-7 PH stainless steel, which is magnetic. Minimum Rockwell hardness is C44 for shaft diameters 1/4" and larger (3/32"- 3/16" shaft diameters are not rated).

CAD For technical drawings and 3-D models, click on a part number.

			Black-Finish Steel			Stainless Steel		
For Shaft Dia.	OD	O'all Height	Pkg. Qty.		Per Pkg.	Pkg. Qty.		Per Pkg.
3/32"	0.326"	0.029"	100	98430A114	$4.76	5	97622A101	$4.43
1/8"	0.366"	0.029"	100	98430A116	4.52	5	97622A102	3.35
5/32"	0.397"	0.029"	100	98430A119	5.23	5	97622A104	4.59
3/16"	0.444"	0.031"	100	**98430A118**	5.12	5	97622A107	3.48

CAD | Catalog Page | Bookmark

External Self-Locking Retaining Ring Black-Finish Steel, for 3/16" Shaft Diameter

Packs of 100

ADD TO ORDER

Plastic Flanged Sleeve Bearings

Nylon—A reasonably slippery, rigid, and abrasion-resistant material that handles light jobs without the need for lubrication.

MDS-Filled Nylon—The same qualities as nylon combined with wear-resistant molybdenum disulfide (MDS).

UHMW—Ultra-high molecular weight (UHMW) polyethylene is USDA approved and FDA compliant. It withstands wet, corrosive environments.

Acetal—An economical alternative to PTFE, this material is not only strong, but also resistant to chemicals and moisture.

PTFE—Has the lowest coefficient of friction of all our materials, so it's ultra-slippery. It also offers excellent chemical resistance and performs well at extreme temperatures.

View tolerance information for these bearings.

Bearing Material	Temperature Range	P max	V max	PV max
Nylon	-20° F to 250° F	400	360	3,000
MDS-Filled Nylon	-40° F to 176° F	2,901	118	3,400
UHMW	-200° F to 180° F	1,000	100	2,000
Acetal	-20° F to 180° F	1,000	1,000	2,700
PTFE	-350° F to 500° F	500	100	1,000

			Flange		Nylon			MDS-Filled Nylon		UHMW		Acetal	
For Shaft Dia.	OD	Lg.	OD	Thick.			Pkg.		Each		Each		Each
3/16"	5/16"	1/4"	3/8"	3/64"	1	6389K401	$4.11	6294K432	$1.07	57785K201	$7.16	___	__
3/16"	5/16"	1/4"	7/16"	1/16"	1	6389K402	3.46	**6294K201***	3.59	57785K108	7.19	2705T11	$3.58

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MDS-FILLED Nylon Bearing Flanged, for 3/16" Shaft Dia, 5/16" OD, 1/4" Length

Tolerances for Bearings

Each

ADD TO ORDER