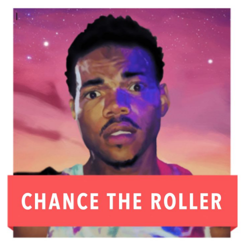
COLLEGE OF ENGINEERING
MECHANICAL ENGINEERING
UNIVERSITY OF MICHIGAN

ME 250 DESIGN AND MANUFACTURING I
Winter 2015

Design and Manufacturing of a Robotic Machine Player for the ME 250 Winter 2015 M-Ball Competition

April 21, 2015



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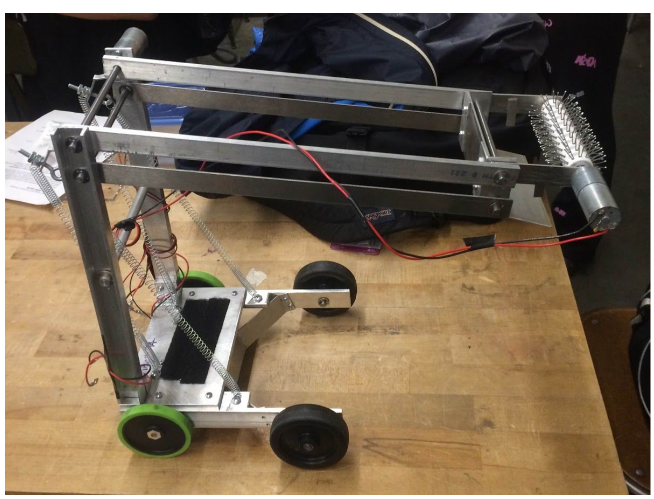

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1. ABSTRACT

Throughout the Winter 2015 semester, students in ME 250, a sophomore-level course offered at the University of Michigan, worked in teams to create a remote controlled machine, known as a Robotic Machine Player (RMP). In ME 250, the main goal of each team is to win a game designed by the instructors of the course, formally known as M-Ball. Each lab section works together and forms a "squad" consisting of four teams that collaborate on strategy, designating each RMP's roles in working for the squad's success.

This report serves as an overview of the design process our team underwent throughout the semester in order to design, analyze, and manufacture our RMP. The report begins with a summary of the constraints encountered this semester with a brief description of the M-Ball competition rules and the organization of the ME 250 course. A breakdown of the entire design process will be given, involving the development of team and squad strategies, collaboration, and selection. An analysis of the advantages and disadvantages of our squad's strategy will be stated, with our team's specific role accentuated.

After our design problem and constraints have been defined and the role of our RMP is understood, this report will describe the numerical and functional requirements our team assigned to our RMP. In addition, three preliminary concepts, illustrations, and detailed descriptions will be shown. Our team went through a significant process to choose a design that would meet our requirements. We extensively used computer-aided design (CAD) to show dimensions, functionality, and other important features while developing the final RMP design.

This report highlights specific analyses taken to confirm the functionality of our final conceptual design. We calculated a static analysis on components of our RMP, a motor analysis for all three motors used to power our RMP, and a torque-load analysis on our most critical module (MCM). The report will list modifications to our design made before manufacturing as a result of these calculations.

After the analysis portion, this report will discuss the issues, difficulties, and changes made during the manufacturing processes. To check functionality before the competition, preliminary tests were done, resulting changes to our design will be described in detail. Also included will be engineering drawings for every manufactured part of our RMP and a bill of materials. A summary of the entire design, build, and test processes for our RMP is highlighted in this report, along with a critique of our final design. An analysis of the advantages and disadvantages of the design, its performance in the M-Ball competition, the outcome of the competition, and an overview of the entire semester will also be emphasized.

2. INTRODUCTION

Design and Manufacturing I, or ME 250, is a required sophomore-level course for undergraduate Mechanical Engineering students at the University of Michigan. The course consists of designing, building, and manufacturing a remote controlled machine known as a Robotic Machine Player (RMP). Each lab section consists of a group of roughly 20 students who form four "teams" of 4-5 students, each team building their own RMP. The target of each RMP is to work with the other RMPs in the same lab section, together making a "squad" of four RMPs, to win an elimination-style game, suitably known as M-Ball. The RMPs in the squad heavily rely on each other throughout the semester from creating the final squad strategy together to assisting with manufacturing problems. Cooperation such as sharing and borrowing materials, ideas, and advice ensures a squad's best chance of victory.

M-Ball is a fast-paced competition set up on an arena the size of two ping-pong tables next two each other (see Figure 2-1 below). The primary goal of this game is to have more points than the opposing team at the end of the three-minute referee monitored time period. This is typically achieved with a combination of offensive roles, attempting to score as many points as possible, and defensive roles, which work to stop the opposing team from scoring.

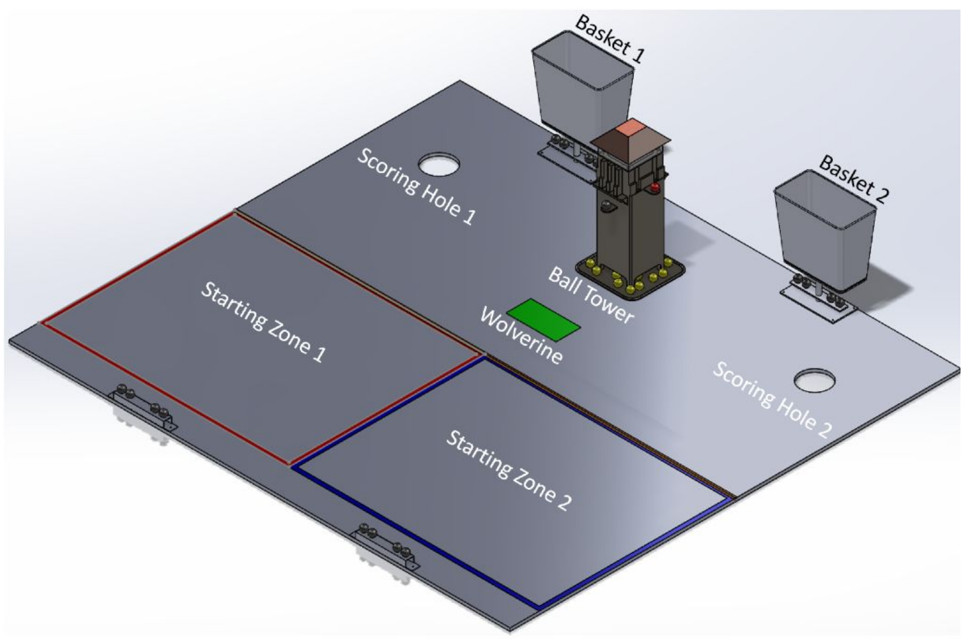


Figure 2-1: Winter 2015 M-Ball arena

The arena features several options to score and three differently weighted balls roughly the size of a ping-pong ball located in various locations and at varying heights, including on a tower in the middle of the arena. In order to score, balls must be retrieved from the arena and placed in a basket or scoring hole on the same side as the squad's starting zone. The amount of points scored depends on the weight of the ball, 2.5, 24, or 55 grams, and the height of the zone the ball is deposited in. When a ball is deposited in a tall basket at the back of the arena, the corresponding squad earns twice the ball's weight in points, while the shorter front baskets earn 1.5 times the weight in points, and the scoring hole cut out of the arena floor earns a point for each gram deposited in it. Additionally, a team can be awarded 75 points if the wolverine is over the opponent's hole at the end of the game.

At the end of the competition, whichever team has scored the most points wins and advances to the next round of the tournament, if applicable. There are also a strict set of guidelines that each RMP and squad must follow, including prohibited RMP materials, required starting dimensions and weight, and unacceptable game conduct. In order to ensure a victory, the four RMPs in each squad must be in constant communication and coordination.

The objective of this project was to create a RMP that can work with the rest of the squad to achieve victory while teaching students basic design and manufacture practices by providing hands-on experience. Our team was responsible for designing and building a RMP capable of collecting balls from any height and being able to deposit them into either basket, with a focus on the front perch balls and the front basket.

3. PROTOTYPE DESIGN

3.1 Squad Strategy Selection

The final strategy selected by our squad was a combination of each team's best ideas. After compiling the best strategies of our individual teams, our squad created two strategies. One strategy had a focus on controlling the tower with one RMP, while the other strategy had two RMPs scoring in both baskets. We discussed which strategy we thought would score us the most points while also providing the strongest defense for our team. We also took into consideration the flexibility of the strategies. After a thorough discussion with our individual teams, we each voted on the strategy we thought would be the most successful.

3.1.1 Team Strategy Selection

Before meeting with our squad to decide our final strategy, our team brainstormed our own individual ideas for the roles of each RMP in our squad. We each created three distinct strategies, relayed each of our our individual ideas to each other, and critiqued them. After our individual brainstorming, we had twelve different strategies to choose from. We selected and combined the best ideas from each strategy to form three strategies which we felt would give us the best chance at victory.

3.1.1.1 Strategy Concept 1 (see Appendix A.1)

The first strategy combines offense and defense, with two RMPs playing a primarily offensive role and two focused on a defensive role. RMP1 will be covering the scoring hole in order to ensure that the other squad does not block our hole or prohibit movement of the tower. RMP2 will focus on moving the tower towards our hole and ensuring that all of the ping-pong balls inside the tower fall into our hole. After the tower has been moved, RMP2 will gather the balls from the tower perches. RMP3 will be responsible for the movement of the wolverine and protecting the opposing squad's scoring hole, while RMP4 will be responsible for defending the opponent's baskets. RMP4's role will be versatile, and will be allowed to move freely around the arena and assist with scoring points or defense when necessary.

This strategy has several advantages, the primary one being the ability to score the maximum amount of points with both the Ping-Pong balls inside the tower and the balls on the perches. In addition, RMP3 and RMP4 have very versatile roles. This will allow our squad to respond very quickly to movements made by the other team. However, this strategy may be hard to implement since the majority of the action is taking place at the far end of the arena. It also may be difficult to defend against an offense-heavy team and control the wolverine for the duration of the game.

3.1.1.2 Strategy Concept 2 (see Appendix A.2)
Our second strategy also focuses on controlling the tower, but is more defensive in nature. RMP1 would be responsible for gaining control of the tower and moving it over our hole. RMP2 would be responsible for traveling to the opponent's two baskets and removing balls from the basket that have already been used to score, while RMP3 would be focused on covering the other team's scoring hole. RMP4 would play an offensive or defensive role to aid other RMPs in the squad, depending on the current situation of the game.

The main advantage of this team is its strong defensive strategy, which will ensure that the opposing squad will have trouble finding the opportunity to score any points. The versatile role of RMP4 is also a major asset to this strategy. This strategy does not account for the wolverine and only allots for one RMP to control the tower and move it over our hole. Unfortunately, if the opposing team is offense-heavy, they could score in the other two baskets that are not being covered by any of the squad's RMPs, making our defense strategies useless.

3.1.2 Squad Strategy
Our selected squad strategy incorporates a mixture of offensive and defensive RMPs. RMP1 and RMP2 will focus on scoring in both the front and rear baskets (see Figure 3-1). They will both have the ability to score in both baskets, but RMP1 will focus on the rear basket and RMP2 will focus on the front basket. These RMPs will pick up the red and black balls in order to score more points. RMP3 will be a versatile, defensive player that will prevent the opposing team from scoring points. RMP4 will focus on covering the enemy's hole. This will prevent the opposing team from moving the tower over the hole and scoring in the hole, preventing many easy scoring opportunities.

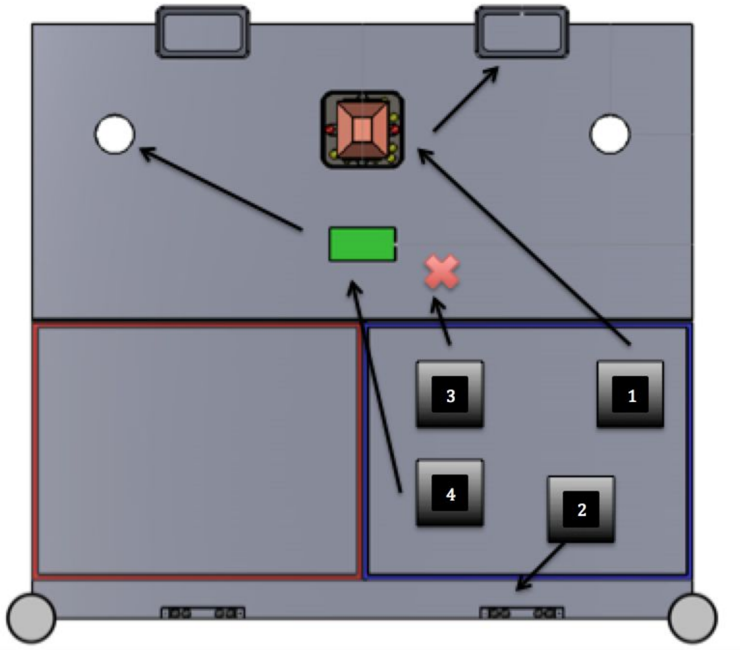


Figure 3-1: M-Ball arena showcasing chosen squad strategy

Our squad selected this strategy because it will allow us to score the maximum points throughout the duration of the game. Our strategy is a good mix of offense and defense, which enables significant flexibility for each RMP. This versatile ability of this strategy is critical to victory, ensuring that our squad can adapt to any changes in the opponent's strategy. With this strategy, our squad can defend against an offensive-heavy team and score easily against a defensive-heavy team.

In order to be prepared for the competition, our squad brainstormed several downfalls of our strategy and ways we could overcome them. Our squad strategy has two RMPs that are playing offensive positions. These RMPs would be the primary target of defensive attacks. Our strategy focuses on gathering the balls in the arena and placing them in the baskets, largely ignoring scoring in the hole. The opposing team could use this as an opportunity to block one (or both) of our baskets, which would force us to change our strategy mid-gameplay. If we were forced to score in the hole, our squad would score fewer points. We took this into consideration when designing our RMP. We designed our RMP to have the ability to score in both baskets, as well as a way to move around multiple defensive maneuvers if one or both of our baskets are blocked. Our opponent could also defend against us by removing balls from our baskets. In this case, we could quickly focus on gathering the balls back from our opponent and placing them back in our basket. For this reason, we chose to use a double gearbox motor to drive our RMP, with an appropriate gear ratio to ensure we could travel at the fastest speed possible.

Our squad also took into consideration the wide range of strategies our opponent could implement. If our opponent has an offense-heavy team, we could extend our RMP to its maximum height and get in the way of the opponent trying to remove our balls, cutting them off and ruining their strategy. In order to accomplish this, one RMP in our squad was designated as a defensive player. Its design focused on preventing our opponents from scoring both in the baskets and in the scoring hole. Furthermore, our strategy delegated one RMP to cover the other team's scoring hole. It would be easy for the other team to prevent us from covering their hole by blocking our path to their scoring hole. We overcame this by then delegating the RMP to other miscellaneous tasks such as sweeping loose balls on the arena floor into our scoring hole or getting in the way of the opponent's offensive RMPs. In order to be prepared to beat every possible strategy, we designed all of the RMPs on our squad to be versatile, with multiple defensive maneuvers and offensive mechanisms to ensure we can secure a win.

3.1.2.1 Squad RMP Roles

The roles of the four RMPs in our squad were designated after our final squad strategy was chosen. We needed two teams to design and manufacture RMPs to perform an offensive role, one team to create a defensive RMP, and another to build a RMP with the ability to cover the scoring hole. These roles stemmed from our final strategy requirements. The team leaders of our squad and the squad leader met at the end of one of our laboratory periods and chose our roles. Since one team wanted to design the defensive RMP and the other three teams did not have a preference, the other three roles were randomly assigned.

3.1.2.2 Our RMP Role

Our RMP was assigned one of the offensive roles. We were responsible for scoring points for our team, whether both in the hole or the two baskets (see Figure 3-2). It was necessary for our RMP to be very flexible with its design and be able to pick up, lift, and push balls. At the start of the game, our RMP was focused on gathering the black balls from the front of the arena and placing them in the front basket. Oppositely, the other offensive RMP was focused on the rear basket and other balls. We chose to score in the front basket since we predicted the rear basket to have lots of activity surrounding it, making it difficult to maneuver. Our machine had the capability to gather two balls at once, helping prevent our opponent from reaching some first. Our role included that if all of the balls had been gathered from the front perches, our RMP would changed its focus to whatever would help the most, depending on everything else that was happening on the area. Our RMP was also capable of getting the black balls from the rear perches and scoring with those, getting the heavier balls on the tower perches to score with, sweeping loose balls on the arena floor into our scoring hole, and assisting our squad's other RMPs in defending against the opposing squad.

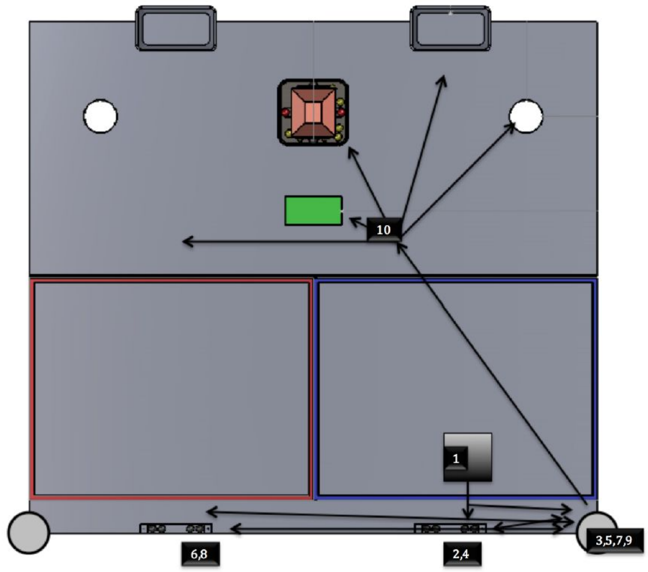


Figure 3-2: M-Ball arena showcasing RMP movement and interactions

3.2 RMP Requirements

In order to ensure that our RMP could perform an offensive role and score a maximum amount of points, we set three numerical and functional requirements for the entire RMP and subsystems. These requirements were decided based off the layout of the arena and our RMP's role in our squad's strategy. We also took the amount of points we would potentially be scoring into consideration, along with the wide range of possibilities for the opposing team's strategy. Another important factor when choosing our functional requirements was the difficulty of the task and time it would take to complete the task.

1. Can raise any type of ball 21" (above the height of the rear basket)
    a. This functional requirement is based off the height of the rear basket. Since the height of the rear basket is 20.5" we wanted to ensure that our RMP could reach the basket.We came up with this requirement so our team could score the most possible points, instead of only sweeping balls into the scoring hole and scoring in the 1.5X basket. This is important because we can score a lot of points for our team if we can fulfill this functional requirement.
2. Can retrieve and secure two balls of any weight
    a. Our team came up with this number based off the role of our RMP in the squad, and the number of balls underneath the 1.5X basket. Since there are four balls underneath the front baskets, we want to be able to secure two of them at once to ensure we can score the maximum amount of points. We also decided this requirement after we chose the dimensions of the roller system. Based off of the dimensions of the roller system and the diameter of the balls, we can only secure two balls at once. We wanted to minimize the weight on the arms and make the roller system as small as possible while still having the ability to score maximum points.
3. Can release two balls when necessary

a. We came up with this functional requirement from the functional requirement above. Since we can retrieve and secure a maximum of two balls at once with the roller system, we need to be able to release both of them to score the maximum amount of points. In order for our team to score any points, our roller system must be able to release both balls as well as collect them.

These functional requirements listed above were critical to ensure our RMP can perform an offensive role. Without the ability to raise the arms to the height of the rear basket and the front basket, our RMP would have been forced to deposit balls in the scoring hole, losing many potential points for our squad. In addition, it was necessary that our RMP could flawlessly retrieve, secure, and release balls of any size. If our RMP could not do any of the three items listed above, we could not score any points for our team using the roller system. If our roller system did work, we would have been forced to score with balls that were located on the floor of the arena. Our RMP would not perform an offensive role well if it could not score all of the balls in a variety of ways.

3.3 RMP Conceptual Design

After our functional and numerical requirements were defined, our team started to brainstorm conceptual designs for our RMP. In order to generate unique, efficient solutions our team members watched videos of previous M-Ball competitions and instead focused on the physical designs of the machines instead of strategy. We thought this was the best way to develop design solutions to see what previous designs worked well for an offensive machine. After we watched videos individually, our team came together, discussed our best ideas, and developed three designs that best fulfilled our functional requirements. We also used our requirements to help us conceptualize our designs.

3.3.1.1 Conceptual Design 1 “Roller with Shelf”

This RMP concept has arms that can bend so that the ends of the arms are raised, as shown below in Figure 3-3. The ends can reach high enough to deposit balls in both the front and rear baskets. The arms connect to a roller and another object. The roller pulls the balls in and the other object holds them while the RMP moves towards the destination basket. When above the basket, the balls are released from the object and the balls fall into the basket. This RMP design also has a curved shape in the front of it so the RMP is able to collect and concentrate balls on the arena floor to be able to push them into the scoring hole.

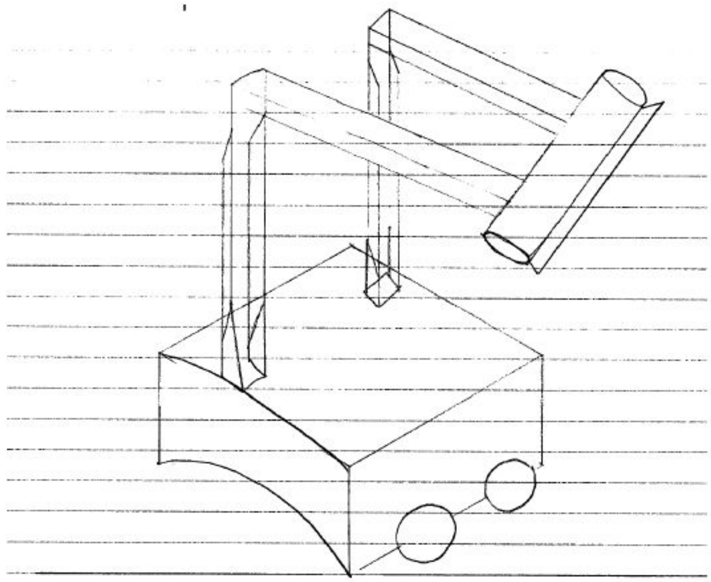


Figure 3-3: Hand Sketch of RMP Conceptual Design 1

3.3.1.2 Conceptual Design 2 "Bar with Container" (See Appendix B.1)

This concept has two bars that are connected to the base of the RMP and have the ability to extend and bend. The bending will allow the container to retrieve the balls located on the front perches. The bars are connected to a system that has a container and a rod that makes a loop about an inch above the container. The rod will push or pull the balls in the container as the RMP is skillfully maneuvered. The container can be raised to dump the balls into both baskets. A semicircle located on the front of the RMP will collect balls and allow them to be pushed into the scoring hole.

3.3.1.3 Conceptual Design 3 "Trap Door" (See Appendix B.2)

The floor at the top of this RMP will be able to slide away. It will have arms that can extend and bend to reach higher balls and baskets. The RMP can be strategically placed so that when the floor slides back to its normal place, balls can be trapped inside. When the extended arms place the trap door contraption over the basket, the floor can slide away again, releasing the balls in the basket for points. Like the other two concepts, this RMP will also have a curved face so that it can be used to push loose balls from the arena floor into the scoring hole.

3.3.2 Concept Selection

We used a Pugh Concept Selection Chart to compare the three RMP concepts that we had created. As seen below in Figure 3-4, Concept 1, the RMP with a roller and an object to hold the balls, received the highest net score at 41. Concept 2, the RMP with a bar and a container, got a score of 33 and Concept 3, the RMP with the trap door mechanism, only got a score of 19. These preliminary concepts were used, scored, and analyzed to help us choose our final design.

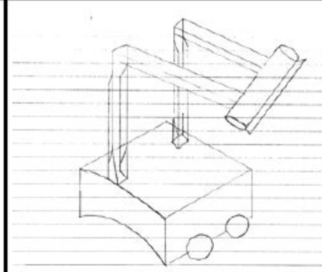
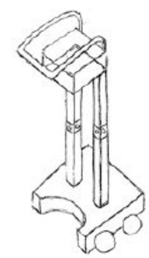
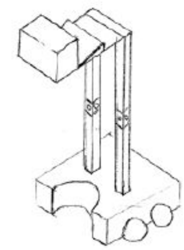
Description		Roller with Shelf	Bar with Container	Trap Door
Sketch				
Criteria	Weight	Concept 1	Concept 2	Concept 3
Ability to collect balls from the ground	4	+	0	+
Ability to collect balls from the shelf at the front of the arena	5	+	0	+
Ability to collect balls from the tower	2	+	+	-
Ability to push balls on the floor into the scoring hole	4	+	+	+
Versatility (ability to defend and achieve other goals)	3	+	0	0
Ease of driving and maneuvering	4	0	-	-
Ability to dispense balls into lower basket	5	+	+	+
Ability to dispense balls into higher basket	3	+	+	+
Reliability	5	+	+	-
Ability to withstand an opponent's attack	3	0	+	+
Speed	3	+	0	0
+		34	22	24
0		7	15	6
-		0	4	11
Net Score		41	33	19

Figure 3-4: Pugh concept selection chart

We decided that the most important things for our RMP are reliability, the ability to dispense balls into the front basket, and the ability to collect balls from the front perch. Therefore, each of these criteria were given a weight of 5. The RMP needed to be reliable so that it could perform well for the M-ball competition. The main goal of our RMP was to get the front perch balls and put them in the lower basket, which was the most important scoring technique offered. It was also extremely important that the RMP could collect balls from the arena floor and push them into our scoring hole. Our RMP needed to be easy to maneuver, so both of these criteria received a weight of 4. The ease of maneuvering helped us be more efficient, gave us more opportunities to score, allowed us to collect and push balls on the arena floor, which would have been important if we were prevented from scoring by the front perches from our opponent. The ability to collect balls from the tower perches was not crucial since our RMP has other ways it can score points, so this criteria only got a weight of 2. Speed, versatility, ability to withstand an attack, and the ability to deposit balls into the rear basket were all seen as mildly important, receiving weights of 3.

3.3.2.1 Final Concept

The three preliminary concepts in sections 3.3.1.1-3.3.1.3 were carefully analyzed using the Pugh Chart, their advantages, and their disadvantages. After a lengthy discussion, our team decided that Concept 1 would be the basis for our final design. We chose this concept because it will be the most successful and efficient at completing several functions, such as collecting balls, depositing balls into baskets, and pushing balls into the scoring hole. As can be seen by the conclusions of the Pugh Concept Selection Chart in Figure 3, Concept 1 is clearly the best choice. The roller is be able to get rid of the balls just as easily as it collects them, which is very important due to the way we scored points. Along with scoring, this concept is the most versatile because the roller's extending arm was able to defend when it was not scoring. Collecting balls with the roller would have been easier and more efficient than with the other two concepts. Getting balls from the tower perches would be difficult with the trap door, while the bar with container concept would have difficulty getting balls from the arena floor and from the front perches. The roller was able to easily retrieve any balls that were in the radius of the RMP's bendable arm and fulfill our RMP's assigned role.

3.3.3 Final Concept Subsystems

After our final concept was selected, our team began to think of different designs for each of the three subsystems. The three subsystems for the RMP design we selected were the roller system, the arm of the RMP that connects the RMP base to the roller, and the plow that is at the front of the RMP to push objects on the arena floor. The roller system includes the roller and an object to secure the balls. The roller spins to collect the balls and helps secure them. The roller is able to spin in the opposite direction and deposit the balls in either basket and the object connected to the roller made sure the balls were secure on the way to the basket. The arm, which connects the roller system to the base of the RMP, will have a joint, or an elbow, to help move the roller up and down to its desired location. The plow could used to guide any loose balls on the arena floor into the scoring hole. The plow can also assist in defense by preventing the opponent's RMPs from scoring points and gathering balls.

3.3.3.1 Roller Subsystem

In order to function correctly for the duration of the game, the roller system must be able to collect and hold two balls at once, regardless of weight. It must be able to handle not only the heavier balls, but also the Ping-Pong balls, along with a mixture of both. With each red ball weighing 55 grams, the maximum weight the roller and object would have to hold at any given time is 110 grams. The maximum difference between two balls that can be picked up is 52.5 grams. We decided this requirement based on the size of the roller we want. We didn't want too big of a roller because we also needed to make sure that our RMP can quickly and easily maneuver around the arena. Since our RMP is limited in size and weight, more than two balls would be difficult for our RMP to hold onto and gather. This target value satisfies two of our RMP functional requirements, both of which were related to retrieving balls from the front perches. The roller body allowed us to gather balls from the front perches on our side of the arena and the opponent's side. The roller system was tested on picking up any combination of two balls at a time and holding the balls secure. The balls must also be held secure while the RMP is in motion, whether the RMP is moving horizontally on the arena floor or extending vertically to reach a ball or basket.

3.3.3.1.1 Roller System Concept 1 "One Roller with Shelf"

This system requires a shelf to be attached to the arms and located directly below the roller. This concept can be seen below in Figure 3-5. The roller and shelf combination system allows us to collect multiple balls at once and secure them into the shelf. The constantly spinning roller would hold the collected balls on the shelf until we can score with them, at which point the the roller would spin in the opposite direction depositing the balls into a basket. The shelf would be able to hold and collect two balls at a time regardless of the weight or original location of the balls.

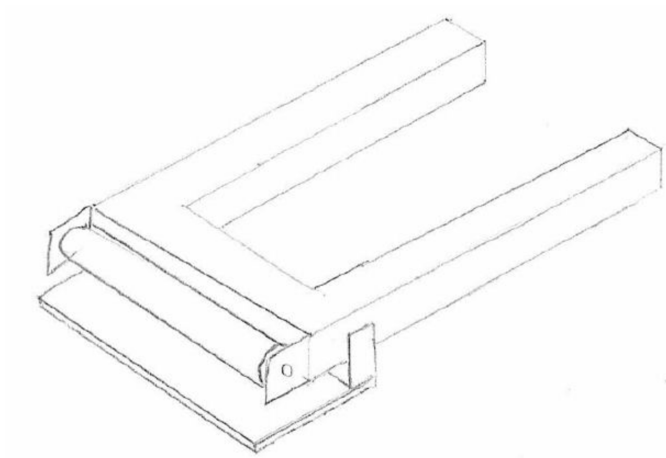


Figure 3-5: Hand Sketch of RMP Roller System Conceptual Design 1

3.3.3.1.2 Roller System Concept 2 "One Roller with Box" (See Appendix B.3)

The concept that has one roller with a box would require us to manufacture a box that would be attached to the arms and located underneath the roller. When put on the balls, the roller would propel them into the box. The box would be able to dump the balls out for when the system is located above the basket. If we chose to manufacture the roller system with a box for the collecting system, it would definitely ensure that any two balls collected would be secure during travel and movement. It may be difficult to position the box and dump the contents out, along with retrieving balls on the front perch and arena floor.

3.3.3.1.3 Roller System Concept 3 "Two Rollers and Shelf" (See Appendix B.4)

This concept would have two separate rollers. The original RMP concept would require redesign if this subsystem design is chosen due to physical constraints. Instead of having one roller connected at the end of the arm, this design would have an axle that has two separate rollers on it, shown below in Figure 9. This design also has a shelf contained in the roller system. By manufacturing the RMP with two rollers instead of one, we are ensuring that our machine will have at least one operational roller. If two rollers collect balls into one shelf instead of one, it will allow us to collect potentially more than two balls at once, increasing the number of points we can score. Just as in the design in Concept 1, the shelf will help secure the balls during motion as the rollers spin balls into it. The axle must be able to spin in both directions so the roller can deposit the balls. This system could easily retrieve balls of any weight and at any location.

3.3.3.2 Plow Subsystem

The plow on the front of the RMP must be able to collect at least six balls that are on the arena floor. Our team assumed that there is a small probability there will ever be more than six balls on the arena floor that are in close proximity that can be reached without obstruction. In addition, the plow must not be wider than seven inches in diameter. Since the scoring hole is seven inches in diameter, if our plow is smaller we will have the ability to ensure all balls we push over the scoring hole will fall in. The plow subsystem fulfils the functional requirement of being able to push loose balls on the arena floor into the scoring hole. The plow was tested by having six Ping-Pong sized balls on a flat surface near each other to see if the plow has the capacity to control all of the balls. The plow should also be capable of driving them over the scoring hole.

3.3.3.2.1 Plow Subsystem Concept 1 “Straight Edged Plow Carved into the Body of the RMP” (see Appendix B.5)

In this concept, the plow is carved into the body of the RMP and it has two straight edges. If we carve the plow into the RMP itself, it becomes easier to manufacture instead of attaching a separate plow. By carving a straight edged plow into the RMP, it would allow us to have very good control over the balls and ensure they do not roll away, as compared to the curved plow. If the carving is deep enough into the RMP and the width of the RMP is not more than seven inches, six balls can be easily collected, controlled, and pushed into the scoring hole.

3.3.3.2.2 Plow Subsystem Concept 2 “Curved Plow Carved into the Body of the RMP” (see Appendix B.6)

This concept is also carved directly into the base of the RMP, but the carving into the base is in the shape of an arc. This option would also allow us to collect several balls at once. The arc carving would be a deep enough cut in the RMP body so the volume of the plow can contain six balls. Since the plow spans the entire width of the RMP, the RMP must have a width of seven inches or smaller so the balls can be deposited in the scoring hole.

3.3.3.2.3 Plow Subsystem Concept 3 “Curved Plow Separate From the Body of the RMP”

This concept requires the manufacturing of a curved plow that is then attached to the front of the RMP, as shown below in Figure 3-6. Attaching a separate plow, as opposed to carving out of the RMP base, would take away any concern about cutting too much of the base away. While still within the maximum footprint dimensions (10” x 12”), the plow can be however big as needed to hold the six balls. Separately manufacturing the plow would make it easier to ensure that the diameter of the plow is 7 inches, confirming that the plow can get the balls it controls into the scoring hole. It would be similar to the design of the curved plow carving and be capable of collecting and controlling at least six balls at once.

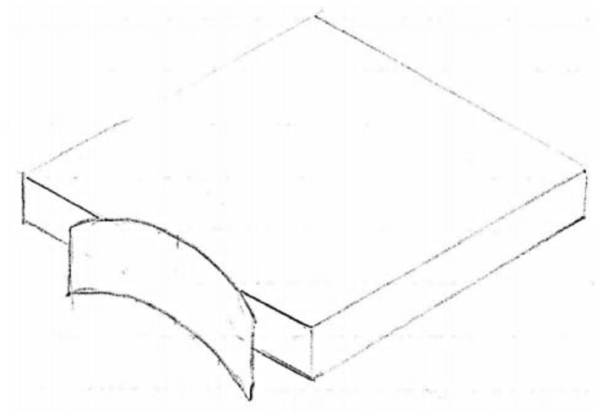


Figure 3-6: Hand Sketch of RMP Plow Conceptual Design 3

3.3.3.3 Arm Subsystem

The arm subsystem of the RMP includes an upper arm part, an elbow, and a forearm part. The upper arm is made up of the stationary poles perpendicular to the floor and connecting to the base which are shown as the supports in the detailed RMP sketch (see Figure 3-8 below). The forearm is the part that connects the roller system to the stationary poles and the elbow is the joint that allows the forearm to move up and down. The arm, which supports the roller, must be able to support the weight of the roller system and any balls it collects, with the maximum ball weight being 110 grams. It must have the ability to control the movement of the roller system accurately and quickly for the duration of the game. The arm must be able to raise and lower the roller so it can retrieve balls from the arena floor and deposit the balls in the rear basket (20.5”high) while fitting within the starting size requirements (10” x 12” for the base and less than 15” tall). To be able to deposit balls into a basket 20.5 inches off of the arena floor, we expect that the arm system must be able to raise the roller at least 21 inches above the arena floor.

3.3.3.3.1 Arm Subsystem Concept 1 “One Forearm” (see Appendix B.7)

The first arm concept is one forearm connecting the roller system to the elbow and upper arm supports. By manufacturing the machine with one elbow joint and one forearm, the overall weight of the RMP would be lower. However, since there is only one arm instead of two, it may be difficult to support the weight of the balls. The arm will be need to be very strong in order to support the weight of the balls. Although, it could potentially be easier for the one arm system to control the roller system. The joint would still be able to move the roller system from the ground to the higher perches.

3.3.3.3.2 Arm Subsystem Concept 2 “Two Forearms”

This concept closely aligns with the original RMP concept, having two forearms. If our RMP was manufactured with two arms, it would be much easier to ensure that the weight of the roller system and potential ball combinations are supported. With two arms, it would be simple to accurately and quickly control the roller system for the duration of the game, whether it is gathering balls from the floor or a higher perch. In Figure 3-7 below, the sketch exhibits the concept of two forearms, shown connecting to the elbow and top portion of the upper arms.

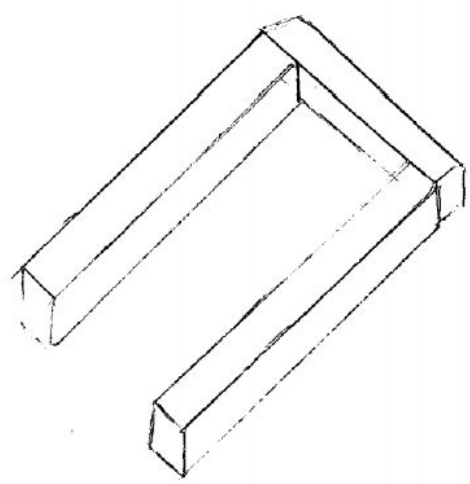


Figure 3-7: Hand Sketch of RMP Arm Conceptual Design 2

3.3.3.3.3 Arm Subsystem Concept 3 "Sheet as Forearm" (see Appendix B.8)

This arm concept uses a sheet of metal in place of forearms. If our RMP used a sheet as a singular forearm to control the movement of the roller system, the sheet would have to be a certain thickness to be able to support the weight of the roller system and collected balls. The weight of the sheet could put strain on the elbow and cause difficulty when changing the height of the roller system. It also might be difficult to attach the roller system to the end of the sheet. If the joint could support the weight of the sheet, the sheet would need to be able to support the weight of the roller system with balls and be able to move the roller between the arena floor and above the rear basket.

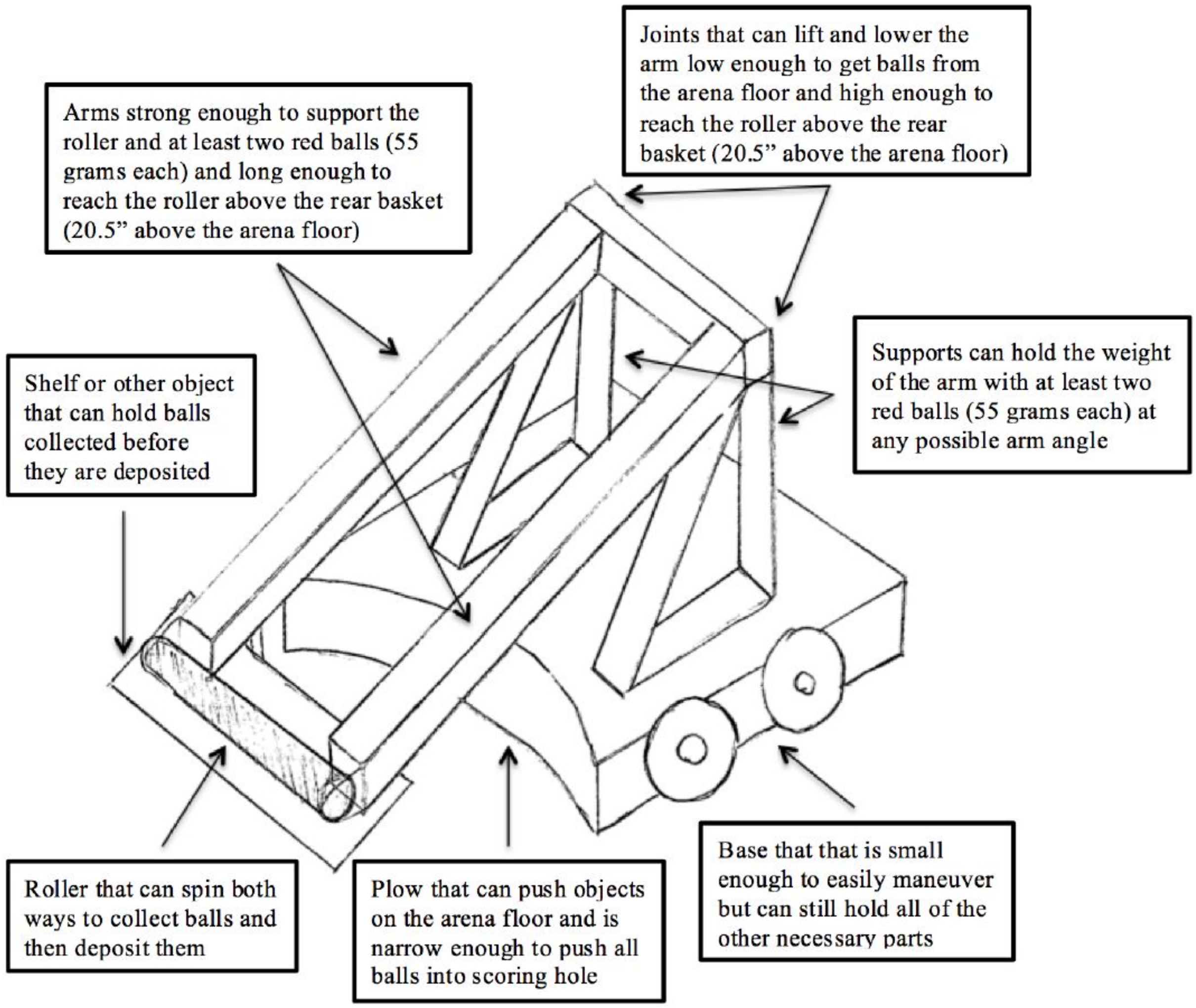


Figure 3-8: Detailed hand sketch of entire RMP, including subsystems

3.4 Detailed Design

3.4.1 Analysis Model

A significant amount of design parameters were chosen based off the physical requirements given to our RMP in the M-Ball rules. The maximum dimensions of our RMP had to be 10"X12"X15", with a maximum weight of 12 pounds. When designing our RMP, we had to take this into consideration during the entire design process, especially when choosing dimensions for our perpendicular arms, base, and slanted Aluminum arms. The base of our RMP was also modified several times to ensure it would not exceed the maximum width. We did not want our RMP to be disqualified because of its physical characteristics. Once we took into account unchangeable dimensions we had no control over, such as the radius of the wheels and the sizes of the control box and the motors, we started building the rest of our RMP around these dimensions.

We also choose the dimensions and the weight of our RMP based on the amount of torque and speed that motors can provide and handle with the greatest amount of efficiency. In order to minimize the load on all three of our motors, we wanted to use as little material as possible. When it was viable, we chose to use the thinnest piece of metal or plastic available to us. We also tried to use materials such as the Delrin and Acrylic plates instead of steel, which has a much higher density and weight. Our number one priority was to have a working RMP that fulfilled all of our functional requirements, and we had to sacrifice some lightweight materials for this purpose.

In addition, we also choose a different set of wheels for the back wheels and the front wheels. We chose to use the newer, smaller wheels with the rubber tread. These wheels were chosen because of their greater ability for the RMP to turn, and their slight advantage in terms of the stability of the RMP. The back wheels also provided us with additional traction due to the rubber tread. We used the older Polypropylene wheels for the set of front wheels. The front wheels gave us more control over the movement of the RMP in terms of speed and allowed us to handle the weight of the roller system.

Another vital part in our RMP is our arms. The dimensions were chosen in a way that we would be able to reach our designated height of 21 inches, but also so our RMP would not tip under the weight of the roller system. We needed to have them done with the least amount of weight possible while also manufacturing them of a material that was strong enough to hold the MCM. The dimensions of many components of our RMP such as the plow and the slanted Aluminum arms, were chosen to make sure we would meet our functional requirements, while also staying under the maximum dimensions and weight.

3.4.1.1 Motor 1 Analysis - Wheel Control

The Pololu double gearbox motor is used to move the back wheels of our RMP. We chose the double gearbox motor because of its high no-load speed and wide range of available gear ratios. In addition, the double gearbox motor contains two motors inside it, and provides us greater control over the wheel axles and the driving as well as a balance between torque and speed. After looking at RMPs from last semester, we also noticed that the majority used double gearbox motors to operate their vehicle wheels. We determined that it would be inefficient to use the metal gearbox motor because of its low no-load speed (and therefore would not provide us with the required speed to reach our goal for the motor). This left us with the planetary motor and the double gearbox motor. Since the Pololu double gearbox motor can operate two axles simultaneously and the planetary motor can only operate one, we would require two planetary motors to move the wheels. We are only given three motors to use, which is why we chose the double gearbox motor to power the wheels.

Bane Bolts wheel radius (obtained from kit data sheet): 36.55mm = 0.03655m
Goal: Cover 3 meters of the arena in 15 seconds
Assumptions: the efficiency of the motor is 10-20%, as given in the lecture slides

Description of the gearbox (obtained from lecture slides):
Stall torque Ts = 0.0031 N*m,
No-load speed no = 11500 RPM

k (motor constant) = (Ts / no) = (0.0031/11500) = 2.696 * 10^(-7) N*m/RPM

Since the double gearbox has two motors, the stall torque needs to be multiplied by two.

Stall torque for both motors = 0.0062 N*m
Average rotational speed, n= ((60 * d)/(2 pi * t * r) = (60 * 3 / (2 pi * 15 * 0.03655) = 52.25 RPM
Operating speed, nr = (0.8*11500) = 9,200 RPM
M (gear ratio) = 9,200 / 52.25 = 176.065

The closest gear ratio available to fulfill this requirement is 344:1, which is the highest gear ratio for the double gearbox motor.

k (motor constant) = (Ts / no) = (0.0031*2*344*0.2) / (11500/344) = 0.012759 N*m/RPM
T = Ts - kn

Therefore T(344:1) = (0.42656) - (0.012759n), to find the torque at the average rotational speed that the motor will need to operate at, we plug in n = 52.25 RPM. This will give us a torque of 0.00617 N*m (see Figure 3-9).

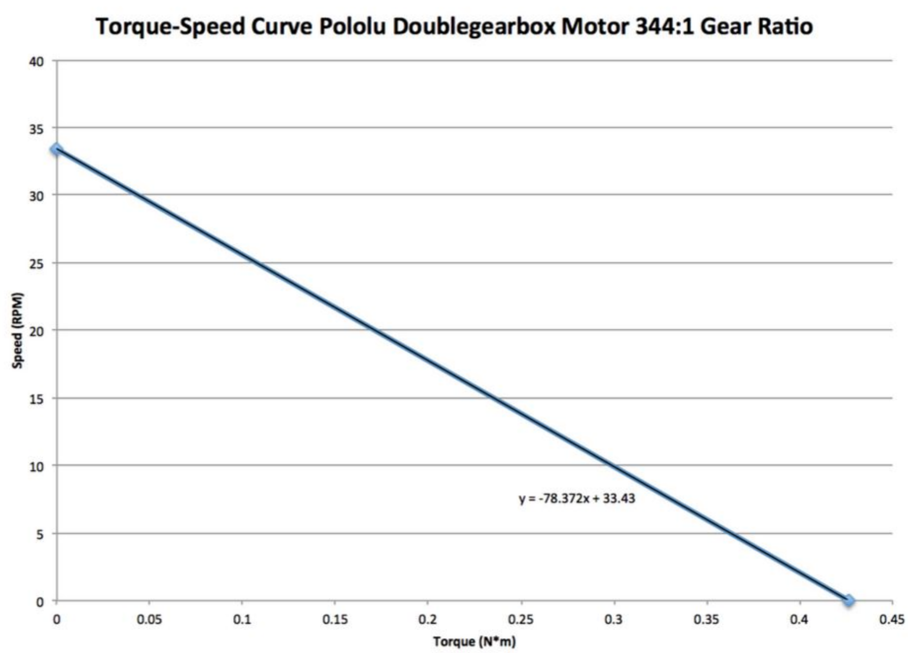


Figure 3-9: Torque-Speed curve for Double Gearbox Motor

3.4.1.2 Motor 2 Analysis - Arm Control

One motor will be allotted to lift the arms of our RMP. Since the arms of our RMP each weigh 192.88g and need to support the load of the roller system, we will need the motor that can supply us with the highest torque. Speed is not as important compared to torque, which is necessary to lift and support the roller system and the arms themselves. The metal motor provides us with the highest stall torque and the highest torque overall compared to the other two, which is necessary in order to ensure that the arms can control the roller system.

The description of the metal gearmotor:
Stall torque Ts = 1.13 N*m
No-load speed no = 100RPM
k (motor constant) = (Ts / no) = (1.13 / 100) = 0.0113 N*m/RPM
Assumptions: the efficiency of the motor is 10-20%, as given in the lecture slides

Using the Solidworks file of our RMP and 6061 Aluminum Alloy material properties, we obtained that both combined arms have a mass of 165.561g.

In order to calculate the total mass the motor must support, we must take into account the roller system. Using the Solidworks file, we obtained that the total mass of the roller system is 74.3383g + 110g from the two balls. When we take into account the mass of the metal gear motor and the weight of the balls the RMP must be able to hold, the total weight that must be supported is 515.937g.

After several methods of testing, we determined that the motor did not have the ability to lift the MCM to the desired height. In order to solve this problem, we added a spring system to reduce the amount of torque that is needed to be done by the metal motor.

There are now three forces acting on the slanted arms, the spring, the mass of the slanted arms, and the mass of the roller system and the metal motor combined.

To find spring constant, F = k*x, F and x were given for the maximum conditions that the 3” extension spring can handle without failure.

F = 9.875N, x = 0.1016m (data from McMaster website)

From the formula, we can find out that k = 97.195 N/m

Now, we will need to find the force done by the springs, which will help us find the torque. After finding the torque done by the springs, we will need to sum the moments around the pivot that is holding the slanted arms, the springs, and the roller system.

There were four springs that were used on the RMP to help reduce the torque required by the motor. There were two identical two each other that were 11” = 0.2794m in length when completely stretched (and in equilibrium) on the RMP, two additional springs that were 10.5” = 0.2667m in length when completely stretched (and in equilibrium) on the RMP. The value of x that we need to use in the formula is the stretched length. We know that the value of the unstretched spring is about 3” = 0.0762m.

For the two springs we get, $F_{spring1}$ = (97.195) * (0.2794 - 0.0762) = 13.918,
since we have two springs we times that number by two = 27.837N

The other two springs are (0.2667-0.0762)m = 0.1905 m. $F_{spring2}$ = (97.195 * 0.1905) = 18.516N, since we have two of those spring we will have a total force of 37.031N
Total force done by the spring $F_{springtotal} = F_{spring1} + F_{spring2}$ = 37.031 N + 27.837 N = 64.868N

The force acts exactly 1.5" = 0.0381m away from the pinned point on the slanted arms, therefore taking the moments at the pinned point (see Figure 3-10).

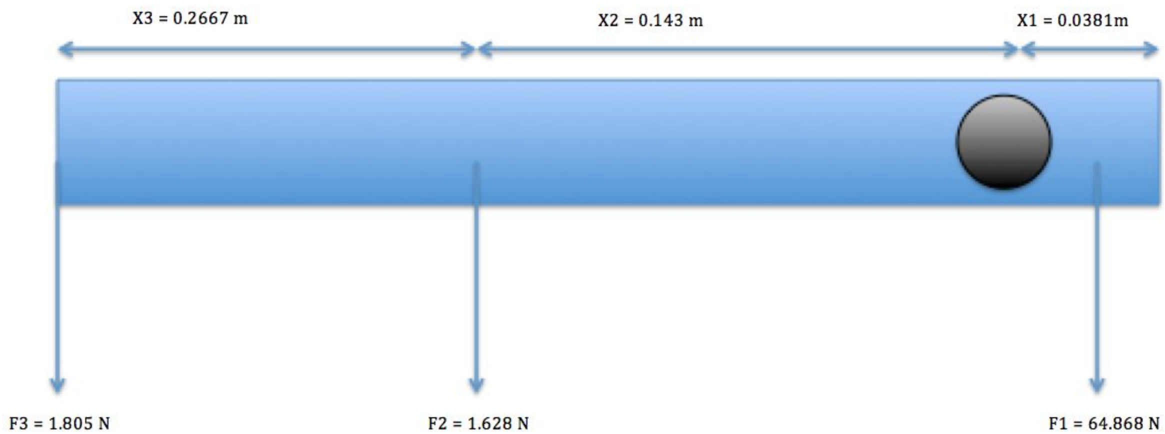


Figure 3-10: Free body diagram for motor 2

T_1 = 64.868N * 0.0381m = -2.4714 N*m (negative because it is acting clockwise).
T_2 = (0.143 m) * (0.165561 kg * 9.81m/s^2) = 0.2322 N*m
T_3 = (0.2667 m) * (0.184 kg * 9.81m/s^2) = 0.4814 N*m

Adding all of these moments together we end up with:
T_{net} = T1 + T2 + T3 = -2.4714 + 0.2322 + 0.4814 = -1.758 N*m.

This is the torque that is required to be done by the motor, however we acknowledge that the metal gear motor are only 10-15 % efficient. We are assuming that these motors run at their maximum efficiency which is 15%, given in lecture slides.

T_{motor} = (0.15 * -1.758) = -0.2637 Nm. This is the amount of torque that the metal gearbox motor needs to supply in order to rotate with the required speed to raise the motor.

Therefore T_{motor} is the torque done by the motor, plugging this value in the graph we will see that it does satisfy the graph and the motor would be operating at the speed given by the equation.

y = -442.48*x + 100 (Y-values are the speed and the X-values are the torque)
y = (-442.48 * -0.2637) + 100 = 216.682 RPM

We have found the speed and the torque that is required for the motor to lift the slanted arms. We also validated our answers based on the torque-speed graph of the motor (see Figure 3-11).

The speed that was calculated from the graph is slightly higher than the amount of speed that the motor can generate (no load speed = 100RPM). This could due to several reasons. First, there is an efficiency loss in the motor. We assumed that the motor runs at maximum efficiency, but we are unable to verify the exact efficiency of the motor. Second, the battery doesn't provide the maximum amount of voltage, which affects the speed the motor rotates at. Third, the spring isn't an actual plastic spring and isn't uniformly stretched when it is at equilibrium. We assumed that the spring constant was constant throughout the spring, which would not be the case of our RMP. There is also human experimental error and friction between the motor and the motor axle, which affects the final speed.

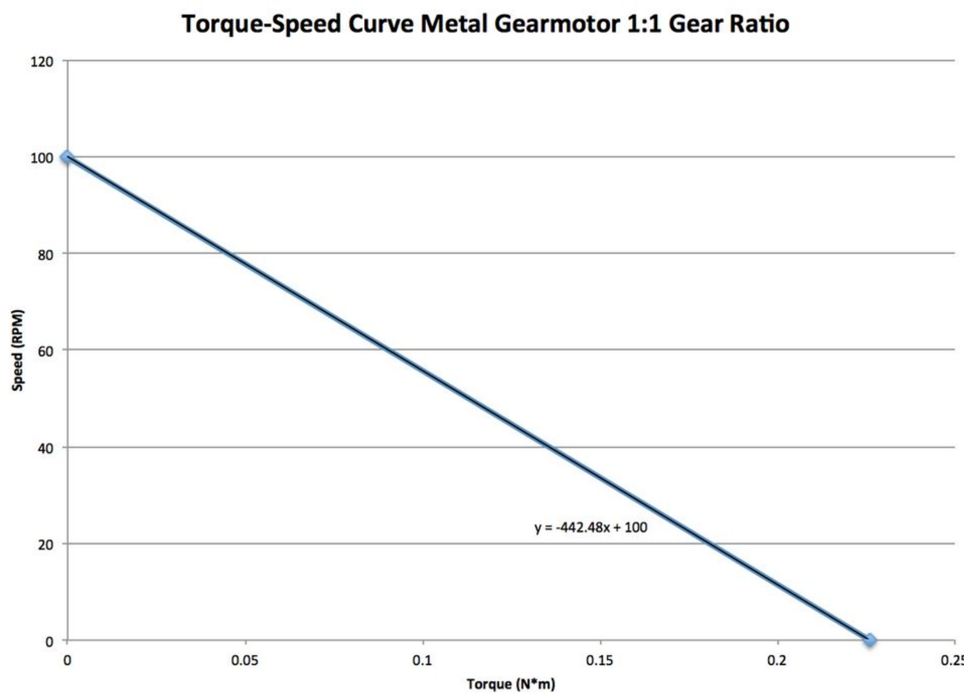


Figure 3-11: Torque-Speed curve for Metal Gearbox Motor

3.4.1.3 Motor 3 Analysis - Roller Control

We are going to use the metal gearbox motor to operate the roller system. This motor will be situated on top of the roller box and will need to be supported by the arms. Since we only need to support one axle, we choose between the Mabuchi planetary motor and the metal gearmotor. We chose the metal gear motor because of its design. The metal gearbox motor could be directly attached to the shaft of the roller system, which simplified our design and made it very easy to attach to the roller system. Attaching the planetary motor would require a system of gears, which would lead to a loss of speed due to the efficiency of the gears. Although the metal gear motor is heavier than the planetary, the metal gear motor would give the right amount of torque that we need.

We chose to operate the metal gear motor with the 1:1 gear ratio since the no-load speed (and the operating speed of the roller system) would be the highest value possible, allowing us to collect and dispense balls as quickly as possible.

The description of the metal gearmotor:
Stall torque Ts = 1.13 N*m
No-load speed no = 100 RPM
k (motor constant) = (Ts / n_o) = (1.13 / 100) = 0.0113 N*m/RPM
Assumptions: the efficiency of the motor is 10-20%, as given in the lecture slides

y = 100 - 442.48x = 100 - (442.48 * n)

There is not a certain speed that we need to accomplish or a certain weight to lift so we did not calculate any torque or speeds. However, by looking at the the torque-speed curve (see Figure 3-12) we can conclude that the speeds and torque that can be provided allow us to capture the balls at various time intervals.

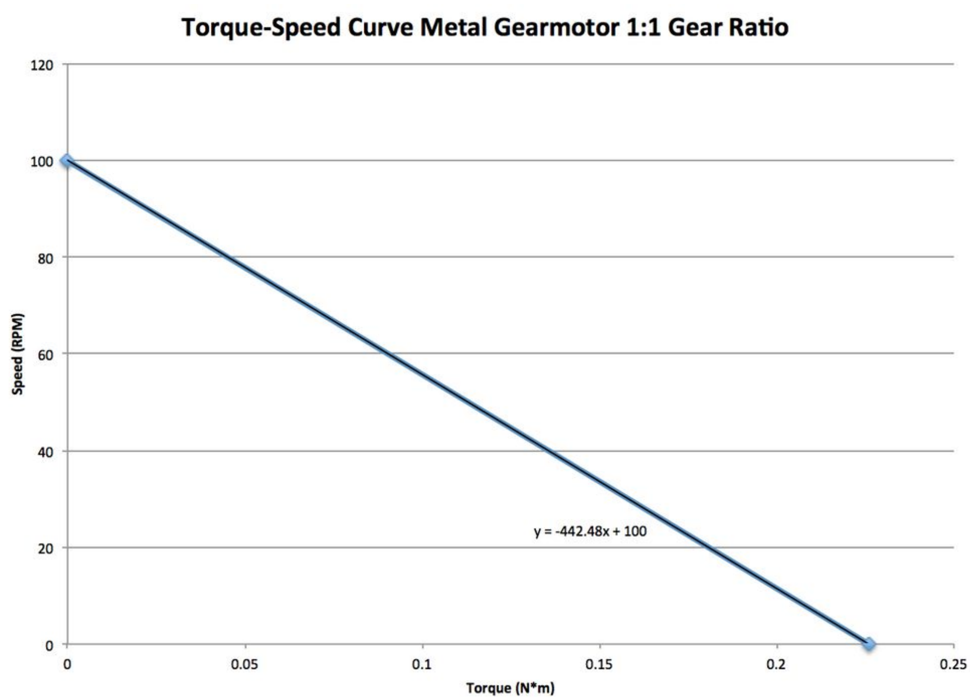


Figure 3-12: Torque-Speed curve for Metal Gearbox Motor

3.4.1.2 Static Analysis

In order to ensure that our RMP met our functional requirements and performed properly, we also performed two static analyses. The first static analysis focused on the tipping force of the RMP. Since the roller system and our MCM weighs ~510g when it contains two of the heaviest balls, we wanted to make sure that our RMP would not tip forward. In order to calculate this, we found the center of gravity of our RMP with the arms at a 90 degree angle (see Figure 3-13). When the arms are extended at a 90 degree angle, the RMP is most likely to tip. After we calculated the center of gravity of the RMP, we took the normal force of the front wheels to be zero and found the moment in the direction. In order to get the tipping force, we multiplied the moment we calculated by negative one. The moment we calculated ensured us that our RMP would not tip.

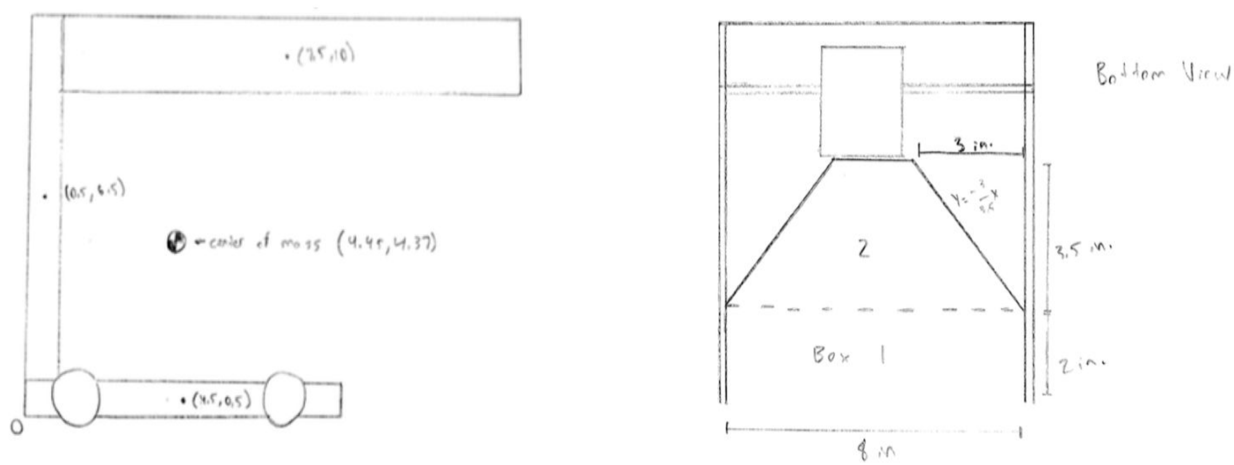


Figure 3-13: Hand sketch showing center of gravity and bottom of RMP

We also performed a static analysis on the plow on the bottom of the RMP. After we chose the dimensions of our RMP and the plow, we wanted to make sure that it could hold and control at least seven Ping-Pong balls. The dimensions of our plow and RMP are given in Figure 14. We obtained the diameter of each Ping-Pong ball, and found it to be 1.10 inches. We calculated the area the plow, and compared this to the diameter of seven Ping-Pong balls. After careful analysis, we obtained the result that the plow on the bottom of our RMP could actually hold eight Ping-Pong balls, surpassing our functional requirement.

3.2.1 Final Design and CAD Model

In order to visualize and properly design our RMP, we used SolidWorks, a CAD program, throughout the semester. SolidWorks helped us visualize potential issues with our RMP early on in the semester, which helped us greatly throughout the manufacturing process. We often tested dimensions of components out by creating them on CAD before physically manufacturing them. The CAD model we designed was highly detailed, and includes fasteners, holes, and other small manufacturing details (see Figure 3-14).

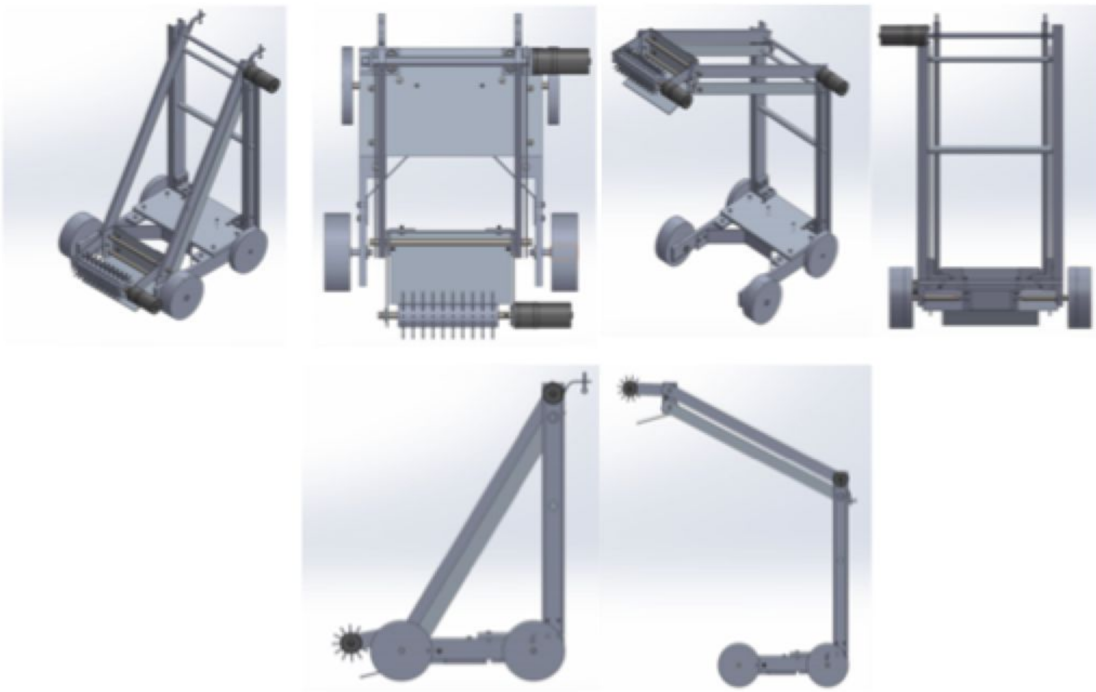


Figure 3-14: Detailed screenshotS of final CAD model, showing various angles of RMP

Our CAD model helped us greatly throughout the entire manufacturing process, and helped us spot potential issues with interference. For this reason, we continually kept it updated throughout the semester and we often turned to it as a guide for our manufacturing plans. In order to machine individual parts of our RMP, we created dimensioned engineering drawings and manufacturing plans directly from CAD (see Appendix C). These drawings and manufacturing plans had to go through an approval process before they could be manufactured.

The final design of our RMP was very different compared to our initial hand sketched design of our selected concept (see Figure 3-8). One of the major changes implemented in our final design was the addition of a spring system. Our initial design did not include a spring system because we thought that the torque of the metal gearbox motor would be enough to lift the weight of the arms and the MCM. We obtained these results from the analysis (see Section 3.4.1). After the majority of our RMP was completed, we had to design a spring system since our arms could not be lifted to the necessary height. We also completely redesigned the slanted arms. After further discussion, we concluded that one set of slanted arms may not have the ability to support the weight of the MCM. In order to avoid any functional problems with our RMP in the future and since we had excess Aluminum material, we chose to manufacture an additional set of arms connected to the roller system and remove the slanted arms connected to the base. In order to replace the slanted arms connected to the base, we decided to add two axles through the perpendicular arms for support. In addition, we decided to remove the rectangular joint at the top of the perpendicular arms and replace it with a circular axle. We decided to do this to account for the motor. Since we decided to use the metal gearbox motor, we needed a surface to attach to the shaft of the motor. Our design for the plow and the roller system remained similar to our hand sketched final concept, we just further developed the idea. The basic ideas of our initial prototype remained constant throughout the entire semester and were implemented in the final design of our RMP.

4 PROTOTYPE MANUFACTURING

4.1 Manufacturing Process

In order to manufacture our RMP we utilized a lathe, a mill, a vertical band saw, a drill press, and an arbor press for the majority of our manufacturing. We used several other machines including a shear, a bending machine, a horizontal band saw, and a water jet cutter. These machines had a minor role in the process of manufacturing our RMP, yet were vital to the overall final design. The majority of our time in the machine shop and in the ME 250 Lab was spent working on the lathe and the mill.

A lathe is a machine tool which rotates a given workpiece, such as an axle, on its axis to perform various operations such as cutting, facing, turning, and grooving with tools that are applied to the workpiece to create an object that has symmetry about an axis of rotation. We machined various pieces on the lathe that were round-shaped, including the axles in the MCM, the support axles for our arms, the hex pieces for our wheels, and the wheel shafts. Any object that needed to have a hole drilled through the center was machined on the lathe, along with any object that had a circular cross section. The most useful function on the lathe that we utilized was the grooving tool. The grooving tool allowed us to carve grooves in the axles so we could secure them with E-clips. Our time on the lathe was significantly less than our time spent on the mill, due to the simplicity of the operations we had to perform.

A mill uses the machining process of rotary cutters to remove material from a workpiece being fed in a direction at an angle with the axis of a tool. Milling can be used to perform a variety of functions, such as drilling, end-milling, and surface finishing. We frequently used the mills available to us in the machine shop for various functions. Any material that could not be placed on the lathe was milled. The mill gave us the opportunity to work with any material that did not have a circular cross section, which was vital to machining the majority of our RMP. All components of our RMP, regardless of volume, size, or material were able to be milled, providing we could hold it properly in the vise. The mill was primarily used to drill and chamfer holes and provide a smooth surface finish, along with end-milling pieces to a certain length. We used the mill in order to drill holes and cut to length with great accuracy and high tolerances. Due to the large amount of holes we had to drill, a significant amount of the time we spent manufacturing utilized milling machine.

Our design also featured several holes and dimensions that did not need to be produced with high accuracy and tolerances. For these pieces, we used the band saw and the drill press to save us time on the mill. The band saw was often used to cut stock pieces before they were end-milled to the correct length. We used the drill press as a substitute if we did not have milling time reserved, and if the desired holes on the workpiece were not critical. The drill press was used for the main component of our MCM, since its geometry prevented it from being held securely in the vise. The drill press was used for a number of pieces, such as the base and the roller support arms. The band saw and the drill press proved vital while manufacturing certain components of our RMP.

An arbor press is an operated hand-press that is used to perform press fitting of bushings, bearings, and axles. Towards the end of the semester, we made use of the arbor press to press fit several axles into the perpendicular arms, to ensure a tight fit for bushings in the wheels, and to secure pins to the perpendicular arm support axles.

In addition, we used several other machines to assist us with manufacturing such as a water jet cutter, a bending machine, and a shear. The water jet cutter enabled us to have an accurate cut for the dimensions of the 1/16" Aluminum slanted arms. However, we could not use the water jet cutter to place the holes in the arms. We also used the shear and the bending machine to produce parts. We used the bending machine for the plow and the MCM, while we used the shear for making accurate cuts in thin pieces of sheet metal.

The material resources in our RMP were primarily obtained from the kit provided, although we did have to make some minor trades and substitutions for materials in the crib. In order to ease manufacturing and increase the overall appearance of our RMP, we purchased several materials from other suppliers (see Table 4-1 for complete bill of materials). Fasteners, such as screws, washers, and E-clips were provided to us by the machine shop and the crib attendants.

Throughout the manufacturing process, there were several fabrication issues we faced. The first problem we faced was the bending of the sheet metal used in the roller system. Bending the sheet metal to line up perfectly for two axles to pass through it was very difficult, so we had to figure out another way to run the axles through. As recommended to us by the machine shop staff, we ended up making two 90 degree parts that would attach to a piece of sheet metal. These 90 degree parts were a replacement for the two bends we had to make before. We also faced manufacturing issues when cutting the sheet metal arms to be exactly the same size without bending them. To solve this problem, we decided to use the water jet cutter because of its extremely accuracy. The last fabrication issue we encountered was trying to press fit the arms to an axle and then press fit those to the perpendicular arms of our RMP. It was difficult for us to ensure the axles were the correct length to fit into the corresponding perpendicular arm. To solve this problem, we decided to simplify our RMP by putting pins through the arms and through the axle so the arms would move. After this, we press fit one end of the axle through the perpendicular arms, and connected the other end of the axle to the metal gearbox motor. We faced significant manufacturing issues when machining the slanted Aluminum arms and the perpendicular arms. At first, we attempted to manufacture the Aluminum slanted arms (14.5" in length) from Aluminum sheet metal. Since this piece of sheet metal was too large to fit securely in the vise, it could not be milled. Our only option was using the bandsaw to make an accurate cut. We faced a similar situation with the perpendicular arms (12" in length). In order to make sure we had an exact cut, we chose to buy stock metal from Alro Steel, as recommended to us by the machine shop staff. In addition, throughout the entire manufacturing process a major issue we faced was the time constraint. In order to counteract this, our team had to be very efficient while we had time in the machine shop and during class. To save time, we often chose to use the drill press instead of the mill when possible.

4.2 Bill of Materials (BOM)

Part #	Description	Material	Dimensions	Supplier	Total Quantity	Cost
1	Roller support system	Aluminum Sheet metal	18” length, 12” width, 1/16” height	kit	1	-
2	Roller support axles/Roller axle	12L14 Carbon Steel	Tight-Tolerance Rod 1/4” diameter, 12” length	kit	5	-
3	Roller	Plastic hairbrush	0.472” internal diameter, 3.75” length	Ulta Beauty Supply	1	$15.45
4	Metal gearbox motor	Stainless steel	2.13" length, 0.98" width, 0.98" height	crib	2	-
5	Roller support arms	Aluminum Sheet metal	18” length, 12” width, 1/16” height	kit	1	-
6	Ball Bearings	Stainless steel	1/4" internal diameter, 1/2" outer diameter, 1/8" thick	kit	5	-
7	Pin	Stainless steel	1/16” internal diameter	crib	2	-
8	Double universal joint (coupling)	Alloy steel	0.25” bore diameter, 2.016” length	crib	1	-
9	Spring pin	Alloy steel	3/8”	crib	4	-
10	E-clip retaining ring	Alloy steel	1/4” diameter	crib	16	-
11	E-clip retaining ring	Alloy Steel	3/8” diameter	crib	2	-
12	Perpendicular Arms	Aluminum Square Tube Stock	1” height, 0.5” width, 1/8” wall, 36” length	kit	1	$9.12
13	Base	Aluminum	1/4" thick, 18” length, 6”	kit	1	-

		Plate	width			
14	Plow	Aluminum Plate	1/16” thick, 18” length, 12” width	kit	1	-
15	Right 90 Degree Support	Aluminum Square Tube	1” width, 1” height, 1/16” wall, 24” length	machine shop	2	-
16	Wheels	BaneBolts	2 -7/8” X 0.4”, 1/2”	kit	2	-
17	Double Gearbox Motor	Tamiya 70168	-	kit	-	-
18	Support Axles	Aluminum rod	3/8” diameter	kit	1	-
19	Legs	Aluminum 90 Degree Angle Stock	18" length, 1” width, 1/4" thick	kit	1	-
20	Aluminum Slanted Support Arms	Aluminum plate	1/4” thickness, 18” length, 3/4” width	kit	2	$6.74
21	Bushings for wheel axle	Flanged Brass Bushings	1/4” inner diameter, 3/8” outer diameter	kit	4	-
22	Bushings inside wheel	Hex bushing	1/4” shaft, 1/2” hex	kit	4	-
23	Motor shafts (secure to axles)	Set screw	4-40 set screw, 1/2” length	crib	4	-
24	Screws (attaching various parts of RMP)	Phillips Head Machine Screw	6-32 Phillips Head Machine Screw, 1/2” length	crib	20	-
25	Screws (attaching various parts of RMP)	Phillips Head Machine Screw	4-40 Phillips Head Machine Screw, 1/2” length	crib	6	-

26	Washer (attaching various parts of RMP)	Washer	0.112” in diameter (fits 4-40 Phillips Head Machine Screw)	crib	6	-
27	3” Extension Springs	Spring	3” in length, unextended	kit	4	-
28	Ring screw	Ring Screw	4-40 Ring Screw, 1/2” length	machine shop	2	-
29	Polypropylene wheels	Back wheels	3" diameter, 1/4" bore	crib	2	-
Total Amount						**$31.31**

Table 4-1: Bill of Materials

5. PROTOTYPE TESTING

5.1.Preliminary Test and Scrimmages Results

In order to make sure our entire RMP functioned as desired, we performed several tests on our subsystems and the completed RMP as a whole. The first subsystem we tested was the MCM, since it was the first subsystem to be completely manufactured. We tested it by connecting the metal gearbox motor to a power supply and raising the roller to the correct height in order to collect balls from the front perches. Originally, we had the roller raised with two pins on each side, but when we were testing the roller system, we realized the pins were not strong enough. This made us realize that in order to reach our target value, we would have to use screws to stop the roller from falling down too far. After we changed our design to include screws instead of pins, our MCM worked perfectly. Solving this problem helped us fulfill our functional requirement of collecting two balls simultaneously. Before we added the screws it would have been difficult to collect one, but after adding the screws we could easily collect two balls from the front perches.

The next testing we performed was on the drivetrain. We connected our double gearbox motor powering the back wheels to the control box to test its functionality. The drivetrain plays a large part in our functional requirement of releasing balls into the basket, since our RMP has to move to the basket in order to score. At first, half of the drivetrain was not working well. We had trouble securing one of the set screws on half of the double gearbox. We decided to replace the set screw, which did not make a difference in the performance of the drivetrain. After more testing, including obtaining a new control box, we decided to replace half of the double gearbox. After this, the drivetrain worked well enough to move around the arena. We also put loctite on the screws in the drivetrain to ensure it worked as desired.

Our last test played an important role in the functional requirement of releasing the balls into the basket, and the functional requirement of reaching the height of 21” in order to score in the 2X basket. We attached our Aluminum slanted arms to our RMP and the MCM, and tested if they could raise to the desired height and dispense balls into the basket. The metal gearbox motor was not powerful enough, so we had to create a spring system in order to supply the system with enough torque to lift the MCM. After attaching two springs to each arm, the arms were able to raise and lower the MCM to the desired height. We ran into a few other problems while testing the Aluminum slanted arms. The two sets of arms were running into each other and preventing the RMP from raising and lowering the MCM. To solve this problem, we added more E-clips in order to make sure the arms would not shift back and forth. We also replaced the set screw through the metal gearbox motor with a pin, to ensure the axle and the motor would move together.

The biggest discrepancy between our actual RMP and the analysis was the ability of our arms to lift the MCM. In our analysis we calculated the metal gearbox would have enough torque to lift the MCM, but in reality it didn't. This may have been due to the weight of the MCM. We performed a torque analysis on the MCM with the planetary motor before we decided to use the metal gearbox motor instead. Since the weight of the metal gearbox motor is about 50g more than that of the planetary, this was most likely the reason behind the failure of our arms to lift the MCM. In addition, we may have underestimated the weight of the rest of the MCM in our analysis. The efficiency of the motor may have also been less than 20%, which is what we estimated in our analysis.

5.2.Redesign Based on Preliminary Tests and scrimmages

We made two major design changes to our RMP to solve issues we experienced during preliminary testing and in scrimmages. The first change we implemented was replacing the pins in our MCM that were used to prevent the arms connected to the roller from falling. At first, we used pins to prevent the arms from falling, but the roller and motor were too heavy so it made the pins slant downward. The pins weren't strong enough, and it didn't allow of roller to roll balls onto our shelf. After some brainstorming, we decided to change the pins to screws, which would provide more support for the roller arms. Once we added the screws, our roller could easily move balls onto the shelf. Re-designing and including the screws was simple, since we placed the new drilled holes in the same location as the previously drilled holes for the pin.

Our second major change required more work than the first. After extended testing and obtaining a new motor, we came to the conclusion that the metal gearbox motor we had was not powerful enough to lift the arms of the RMP to our desired height of 21 inches. In order to meet our functional requirement, we had to add a spring system to the arms of the RMP in order to provide more torque. This system involved springs that were connected to a small piece of metal at the top of the 1/4" thick slanted Aluminum arms. This spring system proved to be difficult to manufacture and design. The design of this spring system involved several iterations, some rough estimation, and some guessing and testing. At first, we added one spring to each side and connected those to the front of our base, but this wasn't enough torque. In order to add more torque to our system, we added another spring to each side. After adjusting the location of the spring a few times, we found a location that allowed our RMP to lower and raise the arms most easily. This design change allowed us to pick up balls and deposit them in the 2X basket, meeting our functional requirement. However, the motion of the arms was not extremely accurate since the torque of the system relied heavily on the torque provided by the springs. Nevertheless, this design change made the biggest difference in the performance of our RMP.

5.3.Discussion of Competition Results

In the M-Ball competition, our squad fell short and struggled to score in the baskets. A few of the RMPs from our squad had trouble moving, which crowded the starting area around the 1.5X basket. Our RMP managed to pick up five balls, but we only scored one. During the final competition, one of the opponent's RMP ran into us to knock our balls off of our RMP's shelf and off the arena. We didn't expect so much activity around the 1.5X basket, which led to us scoring fewer points than we hoped. As a squad, we didn't expect one of our RMPs to not be able to drive. After our inter-squad scrimmage, we made several last-minute changes to complete our RMP. We improved our wheel system, fixed our double gearbox motor, added the plow subsystem, added screws to the MCM to support the roller arms, and added a spring system to help raise our RMP's arms. We could've improved our RMP by figuring out a better way to make our vertical arm movement more accurate. This would allow us to pick up balls very quickly and control the roller system better. Our overall squad performance could have been improved by spreading our RMPs out at the beginning. We were all so close together and it made it easy for our opponent to defend against us.

6. DISCUSSION AND RECOMMENDATIONS

6.1. Project summary

Our roller system and the four arms that kept it steady ended up being significantly more heavy than we expected. The metal gearbox motor was not able to lift it by itself, so the strongest critique of our design would be to have planned for this from the start. The spring system we added counteracted the weight the perfect amount so that the roller system was able to reach balls on the arena floor and go high enough to deposit balls into the rear basket. Something we could have done differently would be to have another motor attached to the top axle which would probably be strong enough to raise the roller system. We also could have tried using the planetary gearbox and try to find a gear system that would help the single motor lift the weight. Lastly, we could have designed a necessary spring system or a counterweight into the initial design that would help lessen the amount of force the motor would have to turn.

One good part of our design was the MCM (roller system), which worked really well with the metal gearbox motor and successfully was able to collect two balls, hold them securely, and despot them on command. Other good parts were the legs, holding the wheels well and were long enough to make sure the RMP stood securely and the base which held all other parts of the RMP together while being short enough so the roller system could be lowered all the way to the arena floor.

Bad points of our design include a possibly crooked attachment of the arms holding the roller system to the perpendicular arms that connected to the base. As previously mentioned, this attachment also did not have a motor or other system that was strong enough to lift the necessary weight.

6.2. Future project idea

A different competition the RMPs could participate in would be a game similar to capture the flag. The RMPs would be lined up on opposite sides of an arena, and they would have to capture the other team's flag. It could be combined with M-Ball, so each team would earn points from placing balls into baskets and into the hole, but capturing the other teams flag would earn the most points. This is more of a modification that could change the M-Ball competition, or it could be a separate competition we could do after M-Ball that is similar to capture the flag, but doesn't involve scoring in baskets or the hole like M-Ball does.

7. REFERENCES

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8. ACKNOWLEDGEMENTS

To conclude this report, we would like to deeply thank all of the instructors that helped us with this class including professors and GSIs. This class required a lot of thinking and covered a very large amount of material. A big thanks to David for helping us make many changes to our RMP when we ran into problems and for supporting us throughout the entire semester, and a special thanks to Xu, Jean, Sky, and Tony for helping us during office hours with a variety of problems and decisions we ran into, helping us get items from the crib, and giving us advice throughout the semester on manufacturing.

In addition, we would like to thank Professor Umbriac and Professor Saitou for instructing this course, teaching us the information and providing the necessary resources to create a successful RMP ,while also teaching us about various different manufacturing methods used in mechanical engineering, statistical analysis, and machining tolerances. The tools we learned through the instruction in this course provided us with knowledge that we will carry with us throughout our entire mechanical engineering career.

Furthermore, we would like to thank the professionals in the machine shop. In particular, we would like to thank John and Charlie, as they have been really patient in helping with our understanding of the machines and the tools that were available for us. We would also like to thank the shop staff that helped us produce pieces with the water jet cutter.

John, along with all of the other machine shop staff, have been very committed to help us learn how to comfortably and correctly use the machines. The machine shop, especially John, saved us a lot of time and frustration, especially when dealing with broken taps, broken drill bits, and re-designing essentially our entire RMP. Their advice, expertise, and knowledge helped us manufacture efficiently and to the best of our ability. We could not have manufactured a working RMP without their help.

NOTES:

1) 5 points will be assigned to the overall quality of this report.

2) Ensure that following items are also complete and correct:
   - Project title page
   - Table of contents
   - Page numbers
   - Figure/Table numbers
   - Figure/Table titles
   - Referencing of all tables and Figures in your text
   - Appendices
3) Use this document as your report template. Delete all the unneeded text. For example, you should delete all the “Note:” sections, before submitting the final report.

APPENDICES

A. STRATEGIES

A.1 Strategy Idea 1

RMP1's main task is to cover our scoring hole while RMP2 moves the tower towards our hole. This is to prevent the other team from blocking our hole once they notice that we are trying to score by moving the tower. This would allow us to move the tower towards our hole and ensure that we will score points without interference. Depending on how long it takes RMP2 to move the tower over our hole, RMP1 and RMP2 may have extra time to remove the heavier balls from the top of the tower and place them in our basket. At the start of the game, RMP3 will be responsible for the wolverine. RMP3 could either hold onto the wolverine for the duration of the game and place it over the opponent's hole at the end while focusing on scoring points, or protect the wolverine over their hole for the duration of the game to prevent them from scoring there (see Figure A-1). RMP4's responsibility is defending the opponent's baskets, preferably the higher basket on the far end of the arena. RMP4 will be allowed to move freely and will have to ensure the baskets are blocked. However, and if the other team appears to be attempting to score the majority of their points in the lower basket, RMP4 will have to maneuver to that basket to prevent them from placing the balls in.

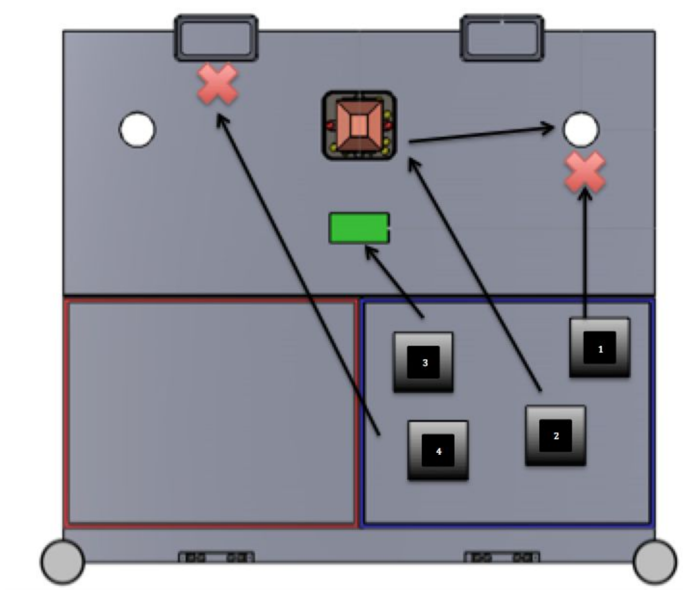

Figure A-1: M-Ball arena showcasing strategy idea 1

Advantages

1. RMP4 has the possibility of defending both baskets and preventing the opponents from scoring any points in the baskets at all. Its use is extremely versatile and is major defensive player.
2. RMP1 and RMP2 will work together to ensure that we score all of the points on the tower, both the Ping-Pong balls when we place it over the hole and the heavier balls on the perches. This will allow us to score as many points as possible.
3. RMP3's use is also extremely versatile, and will allow us to move it where needed. It can either be used as a defensive player by blocking the opponent's hole with the wolverine or offensive by scoring points. Either way, the wolverine will be accounted for.

Disadvantages

1. Since most of the action is taking place at the far end of the arena, it may be difficult to maneuver the machines around the crowded area. It may be difficult for RMP2 to move the tower while at the same time RMP1 is blocking the hole.
2. RMP4 is responsible for defending both baskets on opposite ends of the arena. If the opponent has an offense-heavy team, then they may be using both baskets simultaneously to score, defeating the purpose of RMP4.
3. It may be difficult for RMP3 to keep control of the wolverine throughout the game. The other team might reach it first or take control of it during the game.

	Possible outcomes	**Score**	**Probability**	**Exp-score**
1	<u>Move wolverine completely over opponent hole</u>		0.4	
	Keep opponent from taking tower	0		0
	Scoring from wolverine	75		30
				30
2	<u>Move wolverine over opponent hole</u>		0.2	

	Move tower to our hole	175		35
	Scoring from wolverine	75		15
				50
3	Unable to capture wolverine		0.4	
	Keep opponent from taking tower	0		0
	Scoring from wolverine	0		0
				0
	Total			**80**

Table A-1: Outcome analysis for strategy 1

- Outcome 1 – Since we would have one machine focusing on controlling the wolverine and another machine focused on moving the tower, it is highly likely that we can successfully score with the wolverine and control the tower. If we can control the wolverine at the end of the game, we can earn 75 points.
- Outcome 2 – It may be difficult to move the tower to our hole and score points from the wolverine even if we have two machines specifically designated to doing those two tasks. Our opponents may make this impossible, but if we score this way, we would earn points from the wolverine at the end of the game and most of the points from the balls in the tower.
- Outcome 3 – Depending on the other team's strategy and the level of activity on the far end of the arena, it may be impossible to capture the wolverine. In a worst-case scenario, we would score zero points from the wolverine and the tower.

A.2 Strategy Idea 2

RMP1 would focus on gaining control of the tower and moving it over our hole. The Ping-Pong balls inside the tower would then be released, allowing us to score. RMP2 would focus on the other team's side of the arena, specifically the two baskets. RMP2 would travel to the baskets where the other team has scored points, preferably with the heavier balls and remove them from the basket. RMP2 could then take the balls removed from the opponent's basket and place them in ours, allowing the other team to lose points and our team to score (see Figure A-2). RMP3 would be responsible for covering the opponent's hole. The other team would be forced to score using the baskets, thus allowing RMP2 to remove the balls and take away their points. RMP2 and RMP3 ensure that the opponent scores as little as possible. RMP4 would act as needed. RMP4 could either play an offensive or defensive position depending on the current situation of the game. This would allow R4 to come to the aid of any machine and ensure the game runs smoothly, with us scoring as many points possible.

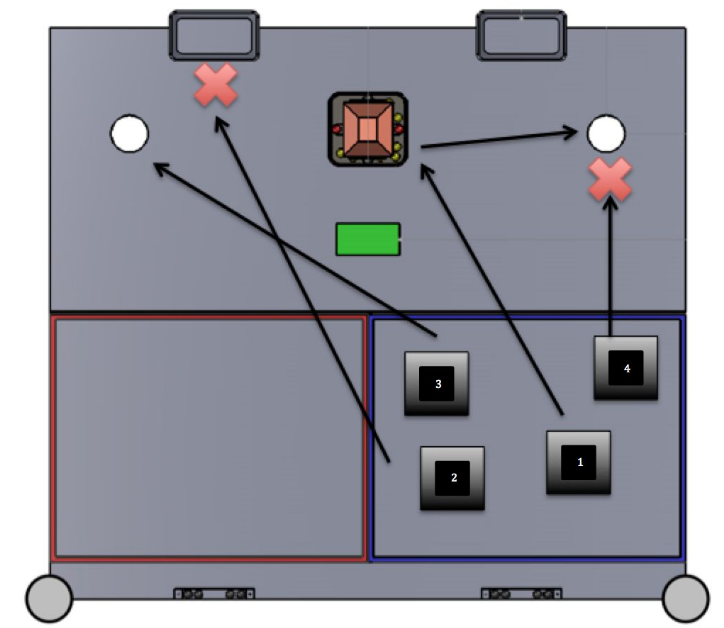

Figure A-2: M-Ball arena showcasing strategy idea 2

Advantages

1. RMP3 would provide defense over the opponent's hole to ensure they cannot score there. This may be a good idea and prevent the team from scoring at all if their machines cannot reach the baskets.
2. RMP4 would move freely and assist where needed. This will allow the other machines to focus on scoring as many points as possible without worrying about things such as dropping balls on the arena.
3. RMP2 would remove balls from the opponent's baskets and place them into our baskets, preventing them from scoring the maximum amount of points.

Disadvantages

1. RMP3 is not being used to score points and is instead preventing the other team from scoring. The other team has two other baskets they can score in, which would make covering the hole pointless

2. With four other machines on the opposing team, it may be difficult for one machine to keep control of the tower and move it over our hole. The other team can gain control of the tower very easy.
3. The wolverine is not accounted for in this strategy. Ignoring the wolverine may cost us 75 points and a loss. In addition, the machines are mostly concentrated on the farther end of the court, which may be too crowded for the machines to work effectively.

	Possible outcomes	**Score**	**Probability**	**Exp-score**
1	Move tower completely over our hole		0.5	
	Balls in our hole at first	250		125
	Balls swept into hole	12.5		6.25
				131.25
2	Tower doesn't make it all the way to our hole		0.25	
	Balls into our hole at first	75		18.75
	Balls swept into our hole	37.5		9.375
				28.125
3	Opponent gains control of tower		0.25	
	Balls into our hole at first	0		0
	Balls swept into hole	50		12.5
				12.5

Total			**171.875**

Table A-2: Outcome analysis for strategy 2

- Outcome 1 – Since our strategy focuses on moving the tower over our hole, as out main way of scoring points, it is highly likely we will be able to complete this task. If we move the tower, we can assume most of the balls inside will go into our hole, as well as several balls around the tower that will be swept inside.
- Outcome 2 – It is possible that we are not successful in moving our tower all the way to our hole due to the design of our machines, or interference from the opposing team. Since this is one of our main ways of scoring, it is not very likely. Since the tower could be partially over our hole, some balls inside could fall and allow us to score, in addition to those around the tower that fall and are swept in during movement of the tower.
- Outcome 3 – It is also possible that the opponent gains control of the tower before our machine has the chance. Our opponent may also have controlling the tower as their primary goal and may have a machine better equipped at doing this than ours. However, the chances of this are slim since we have several machines that could assist with moving the tower. If we cannot gain control of the tower, we could also sweep several balls into our hole that are on the arena.

A.3 Strategy Idea 3

RMP1 is capable of grabbing the balls from both upper parts of the tower and depositing them into both types of baskets. Because it can extend, it can also be used as a defender when the opposing squad is trying to get balls into their baskets. RMP2 is designed to control the tower (see Figure A-3). It is supposed to grab the tower and move it over our hole to get all of the Ping-Pong balls into our hole. If the other squad has control of the tower, it can be used to block the other squad's hole so they can't get the Ping-Pong balls and possibly take the tower away from it. RMP3 can achieve multiple tasks by being able to push anything on the table. It can push the opposing squad's RMPs to disrupt their plans, can push the wolverine away from our hole if it was put there, can push the wolverine over the other hole to get those points, and can push loose balls that are on the table to our hole to get extra points. RMP4 specializes in defense. It can block the opposing squad from scoring balls into their baskets, but if there is no threat of that, it can be used to block holes and push loose balls into our hole. RMP4 should be able to get the balls from the side of the table with the shorter baskets.

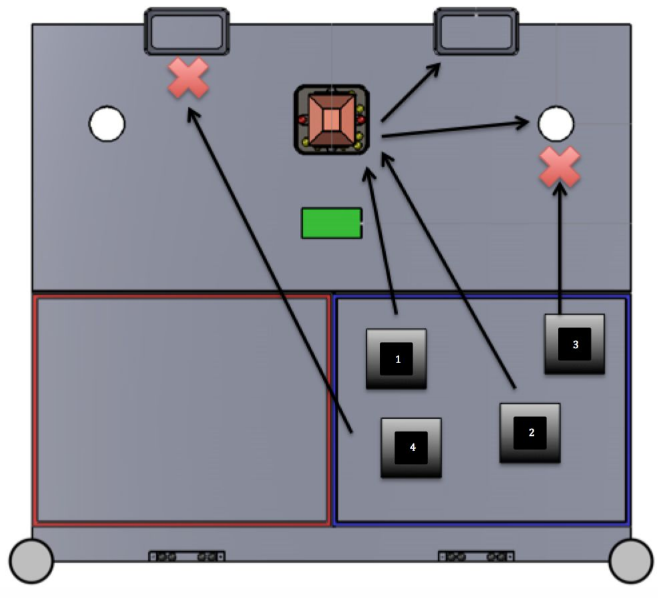

Figure A-3: M-Ball arena showcasing strategy idea 3

Advantages

1. By having each RMP able to achieve multiple tasks, it covers almost all of the important tasks that can possibly be achieved during gameplay.
2. The mix of offense and defense ensures that the other squad shouldn't be able to score too many points while we should have the capability of scoring a lot ourselves.
3. This solves the unknown factor, because no matter what the other squad does, this strategy should have another way to score and defend in return.

Disadvantages

1. This strategy does not include a way to get the balls out of the opposing squad's baskets if they are able to get them in there, meaning that those points are final.
2. By having so many tasks responsible to each RMP, an RMP may focus on certain responsibilities and miss out on crucial tasks that result in us missing points or the other squad getting many points.
3. If RMP1 is not able to achieve its duties because of something the other squad did, it is essentially useless and being wasted. Additionally, we would miss out on all basket point opportunities just because this one RMP is not being used.

Possible outcomes	Score	Probability	Exp-score

1	Can get balls from the top of tower and put in baskets		0.7	
	Balls put in higher basket	302		211.4
	Balls put in lower basket	72		50.4
	Balls swept into our hole by another RMP	48		33.6
				295.4
2	Can move tower over our hole		0.2	
	Balls in our hole from tower	250		50
	Loose balls from tower swept into hole	12.5		2.5
				52.5
3	Can control wolverine		0.1	
	Wolverine is over opponent’s hole at the end	75		7.5
	Wolverine is over our hole or over neither hole	0		0
	Wolverine is over neither hole	0		0
				7.5
	Total			**355.4**

Table A-3: Outcome analysis for strategy 3

- Option 1 – Since we have multiple machines focused specifically on getting the heavier balls on the perches and getting them into baskets, it is highly likely that we will be able to score points from the four black balls and one red ball, either in the higher or lower baskets or a combination of both. Additional balls could be swept into our hole by one of our machines.
- Option 2 – The tower and the Ping-Pong balls inside is a main source for gaining points, it is likely the opponents are going to try to take control of it also. It may be difficult to control the tower with one RMP without the other team interfering. Some of the loose balls from around the tower could be also swept into our hole.
- Option 3 – Our Strategy makes one machine in charge of controlling the wolverine, along with playing offensive and defensive positions. Since only one machine is responsible for the wolverine, it is highly unlikely that we will be able to have it over our opponent's hole at the end. If we were able to do this, it would allow us to gain 75 points.

B. CONCEPT SKETCHES

B.1 Concept Sketch 2 "Bar with Container"

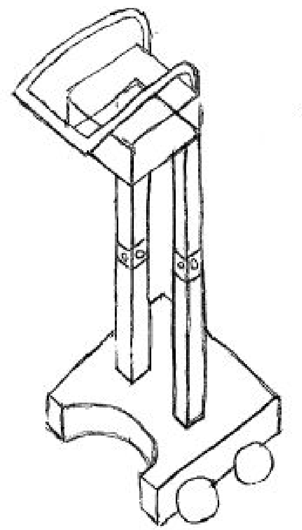

Figure B-1: Hand Sketch of RMP Conceptual Design 2

B.2 Concept Sketch 3 "Trap Door"

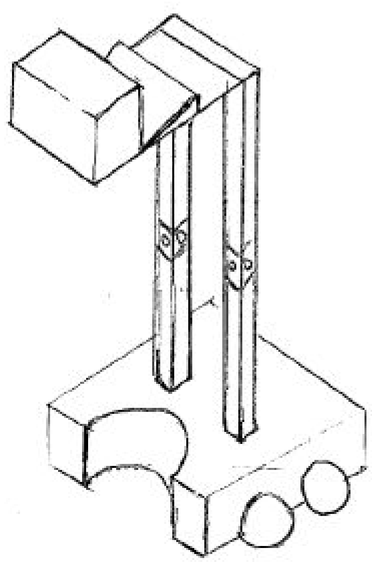

Figure B-2: Hand Sketch of RMP Conceptual Design 3

B.3 Roller System Concept Sketch 2 "One Roller with Box"

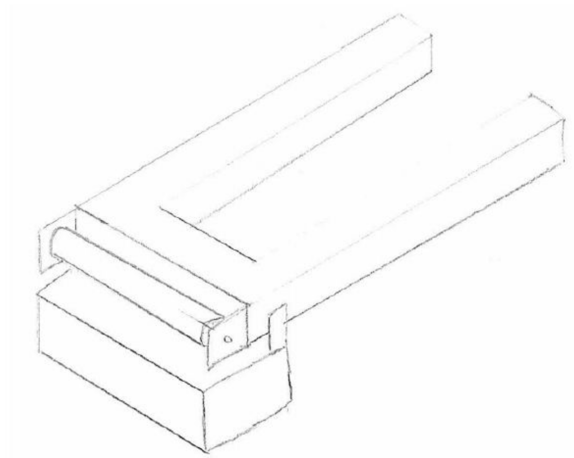

Figure B-3: Hand Sketch of RMP Roller System Conceptual Design 2

B.4 Roller System Concept Sketch 3 "Two Rollers with Shelf"

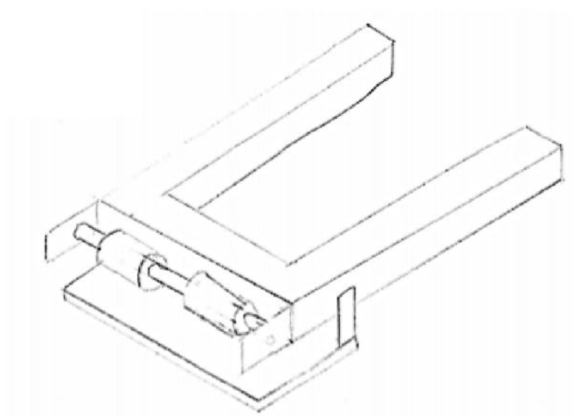

Figure B-4: Hand Sketch of RMP Roller System Conceptual Design 3

B.5 Plow Concept Sketch 1 "Straight Edged Plow Carved into the Body of the RMP"

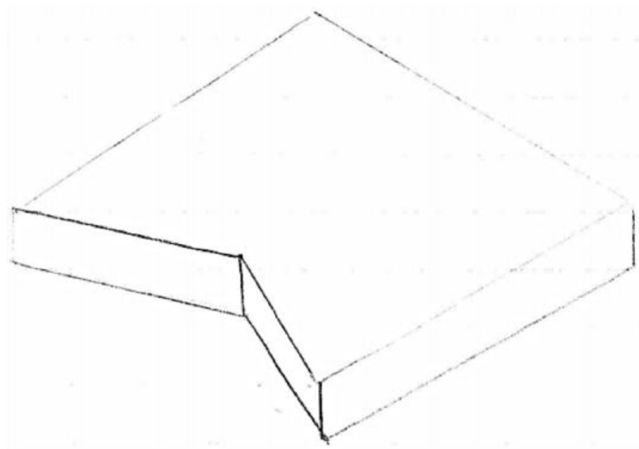

Figure B-5: Hand Sketch of RMP Plow Conceptual Design 1

B.6 Plow Concept Sketch 2 “Curved Plow Carved into the Body of the RMP”

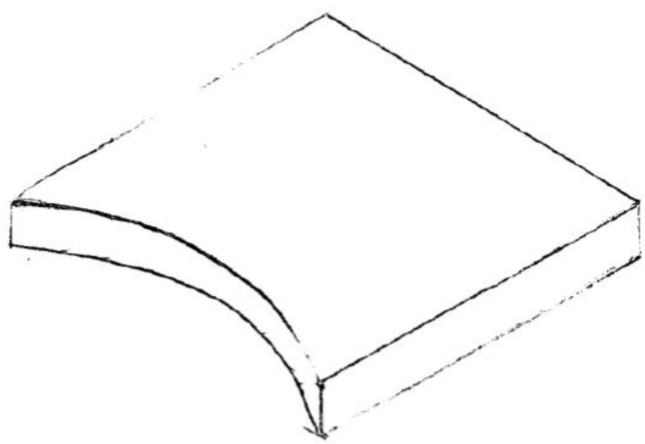

Figure B-6: Hand Sketch of RMP Plow Conceptual Design 2

B.7 Arm Concept Sketch 1 “One Forearm”

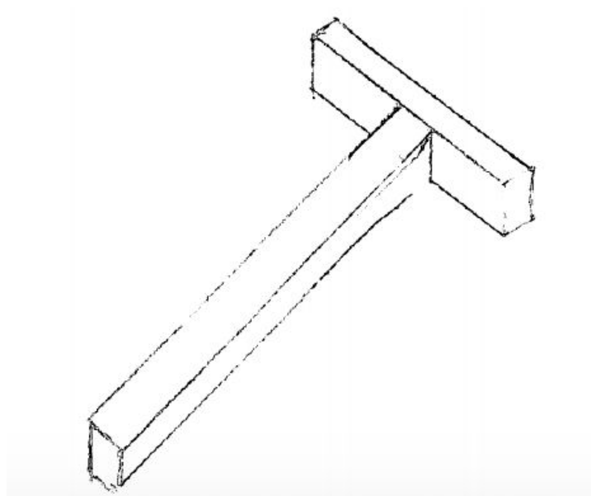

Figure B-7: Hand Sketch of RMP Arm Conceptual Design 2

B.8 Arm Concept Sketch 3 "Sheet as Forearm"

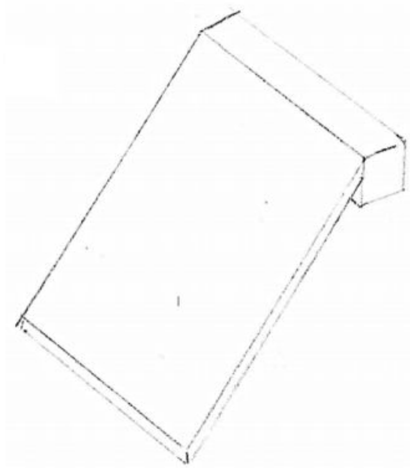

Figure B-8: Hand Sketch of RMP Arm Conceptual Design 3

C. Dimensioned Drawings and manufacturing plans (4 points)

C.1. Dimensioned Drawings of Individual Parts

Part #	Part Name	Module
1	Perpendicular Arms Right Side	Arm System
2	Elbow Axle	Arm System
3	Motor Holding Roller Support Axle	Roller
4	Roller Body	Roller
5	90 Degree Part Left Side	Roller
6	90 Degree Part Right Side	Roller
7	Perpendicular Arm Support	Arm System
8	Rear Wheel Axles	Drivetrain
9	Double Gearbox Buffer	Drivetrain
10	Right Leg	Base

11	Left Leg	Base
12	Front Axles	Drivetrain
13	Plow	Base
14	Unbent Plow	Base
15	Aluminum Slanted Support Arm	Arm System
16	Aluminum Slanted Support Arm 0.25”	Arm System
17	Spring Connector	Arm System
18	Left Perpendicular Arm	Arm System
19	Base	Base
20	Roller	Roller
21	Roller Support Arm (without motor)	Roller
22	Roller Support Arm (with motor)	Roller
23	Quarter Inch Roller Axle	Roller
24	Lower Arm Axle	Arm System
25	Support Axle	Arm System

Table C-1: List of all components used to manufacture RMP

D. PURCHASED AND TRADED ITEMS

D.1 Purchased materials

Supplier	Part name/number	Dimensions	Total quantity	Price	Description
Alro Steel	Aluminum Square Tube Stock	1” height, 0.5” width, 1/8” wall, 36” length	1	$9.12	Used for the perpendicular arms
Alro Steel	Aluminum Flat Bar Stock	0.75” width, 0.25” height, 36” length	1	$6.74	Used for the slanted Aluminum support arms
Ulta Beauty Supply	Plastic Hairbrush	0.472” internal diameter, 3.75” length	1	$15.45	Used as the roller for the roller system
Total Amount				**$31.31**	

Table D-1: Complete list of purchased materials

D.2 Traded items (inter-squad)

Trade-in part	Trade-out part(s)	From	Positive Trade Deficits	Description
N/A	N/A	N/A	N/A	N/A

Table D-2: Complete list of traded items (inter-squad)