吴贤铭智能工程学院
SHIEN-MING WU SCHOOL OF
INTELLIGENT ENGINEERING

Final Report of Vm250 Course

Design and Manufacture of an Automatic Controlled Metal Trebuchet

Semester	Summer, 2022
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Contents

Abstract

In this project, we first did a concept design, then generated our initial design. Finally, we tested the prototype and improved some defective designs.

In the concept design, we made customer requirements (CRs), engineering characteristics (ECs), built up a house of quality (HOQ), and made product design specifications (PDS). We used software like Solidworks, AutoCAD for designing procedure.

In manufacturing, we focus on moving system, control system, reloading system and shooting system. As for the moving system, we used the Mecanum wheel to control prototype movement. As for the control system, we employed a PS2 controller and combined the Blue-tooth technique to control the trebuchet in a remote way. As for the reloading system, we de-signed a container track to store balls and implement a ferris wheel controlled by the steering engine to reload the balls. As for shooting system, we employed the friction wheels to shoot pin-pong balls and rocket balls. As for shooting tennis balls, we designed a catapult arm with a spring to control it. we also employed two steering engines, one steering engine is used to con-trol the elongation of the spring, and the other is used to control the timing of the launch of the catapult arm.

Our group accomplished the project within budget(￥2,500), and we did a cost estimation in the 4th part in this report. We also made a finite element analysis to prove the stability of our catapult for shooting tennis balls. Last but not least, we analyzed the advantages and disad-vantages of our project and made a further discussion.

1 Introduction

In the new era of rapid development of intelligent manufacturing industry, the design and manufacture of automatic server has become a topic of widespread concern. How to improve the accuracy of the serve and the feasibility of control has become the primary concern of the project engineers.

In our project, we need to design an automatic metal trebuchet under the given rules and scenes, and put all the given balls into a basket with a size of 20*20*20. We are given 10 ping-pong balls (Each one has 0.2 credits if shot into the basket), 5 rocket balls (Each one has 0.4 credits if shot into the basket), 2 tennis balls (Each one has 2 credits if shot into the basket). We need to get the highest score in 10 minutes.

The specific game set up is shown in figure 2-1. Our Catapult will depart from the Starting Zone. Then enter the shooting zone and assign three points in the shooting zone to cast. The trebuchet can only be controlled remotely once it enters the shooting zone, and we can't let it into the forbidden zone.

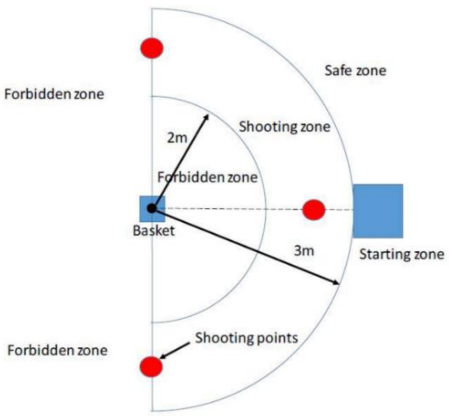


Figure 1 Game set up

There are four major requirements for the protype: movement, control, reloading, and size. For movement, the prototype must be powered by at least one DC motor with batteries. For control system, the prototype must be controlled by a remote controller for its movement. We also need to design a reloading system to reload at least one type of balls in a controlled way.

2 Concept Design

2.1 Problem Definition

2.1.1 Problem Statement

Here we would give a detailed statement of the introduction part and define our design goals through the concrete demands of customers. To dissect the problem, the basic rules of this game should be considered during the design procedure.

The aim of the game is to shoot three kinds of balls, which are ping-pong, rocket and tennis respectively, into the target with the distance of 2.5 meters in the specific game set up. To achieve that, the accuracy and power in ball shots should be determined by our metal treb-uchet. Meanwhile, reloading stability is of vital importance to ensure the automatic supply process of balls. Great mobility of device would assist the target of movement, such as going straight, turning and reverse, then shooting from three different position in game set up. So, the abilities of remote control and flexibility of movement are required.

In comprehensive analysis, the following detailed contents determined as design basics and customer requirements are clearly listed in the Table 2.1.1-1.

Table 2.1.1-1 Potential Customer Requirements

No.	Contents	No.	Contents
1	Control accuracy	11	High degree of freedoms
2	Remote control	12	Reloading stability
3	Automatic reloading	13	Compact size
4	High shooting accuracy	14	Low cost
5	Stable structure	15	Easy to control
6	Adaptive to three balls	16	Resistance to damage
7	High shooting power	17	Device safety
8	Adjustable structure	18	Ease of maintain
9	Flexibility of movement	19	Ease of programming
10	Working durability	20	Big ball storage

After given the potential customer requirements mentioned above, we use an affinity diagram to group them into functions, performance, durability and features in the Table 2.1.1-2.

Table 2.1.1-2 Affinity Diagram of Potential Customer Requirements

Class	Functions	Performance	Durability	Features
No.	2 3 6 19	1 4 7 10 12 15	16 18	5 8 9 11 13 14 17 20
Total	4	6	2	8

Analyzing from the table, the contents based on design rules are mostly divided as de-vice features requirement, inferring that the performances of them are of vital importance when cater to the demands of customers.

Without the need of analyzing the surveys to search for the potential effect of each contents, we regard all of the potential customer requirements in Table 2.1.1-1 as customer requirement in the following discussion.

2.1.2 Customer Requirements (CRs)

Inheriting the all the contents in Table 2.1.1-1, we divide customer requirements (CRs) into four parts: basic demand, desires, necessities and exciters, according to Kano Model [1-2] (see Figure 2.1.2-1)

In Table 2.1.2-1, we show the four classifications of contents. The category of basics is features that satisfied the basic requirement of the customers. The features the customers want in the device are shown in the desires. "Necessities" types are the baselines included in the necessary design demands of game. The exciter features will be the highlight characteristics that distinguish our device from others.

Table 2.1.2-1 Division of Customer Requirements

Class	Basics	Desires	Necessities	Exciters
No.	1 4 7 14	2 3 6	5 9 12 16 17 18 20	8 10 11 13 15 19
Total	4	3	7	6

According to the detailed definition above, each category can reflect the different design specialty in concept design, which means there exist priority among the listed contents. Actually our desired prioritized order is that necessities, basics, desires, exciters. The category of necessities is the given design rules of the game and should be satisfied firstly. Then the basic features that show basic customers' requirements are placed as the second. The spoken ideas are less needed and the exciters represent the uniqueness.

Referring to the Kano model shown in Figure 2.1.2-1, the curve of "attractive" are composed of desires, meanwhile the must-be curves are made up of necessities and basics.

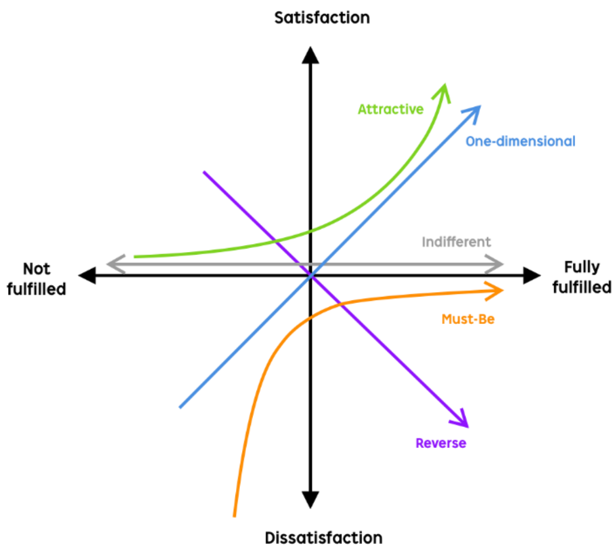


Figure 2.1.2-1 Kano Model

In the overall work, we classified the design contents into four classes and set them as the different inputs of Kano model. With the help of more comprehensive definition we can estimate the importance weight factor reasonably, while building the house of quality.

2.1.3 Engineering Characteristics (ECs)

2.1.3.1 Benchmarking (on ECs)

By comparing with similar market devices, Benchmark is a significant part to search for engineering characteristics. We benchmarked on types of automatic pitching machine which are practical among the tennis players. After searching and reading lots of literature, four products with comparable characteristics and indicative functions are selected: OUKEI-787 [3], PT9001 [4], Nisplay N1 [5], FQ03 [6]. (Shown in the Figure 2.1.3.1)

(a) OUKEI-787

(b) PT9001

(c) Nisplay N1

(d) FQ03

Figure 2.1.3.1: Four products with comparable characteristics

The industrial designed devices dominate the great shooting accuracy and mobility performance. We choose the Nisplay N1 as compare device and do thorough investigation on manufacturing factors. We selected ten ECs that are of significant effects on targeted device performance. And compare these factors between our automatic metal trebuchet and on selected ECs.

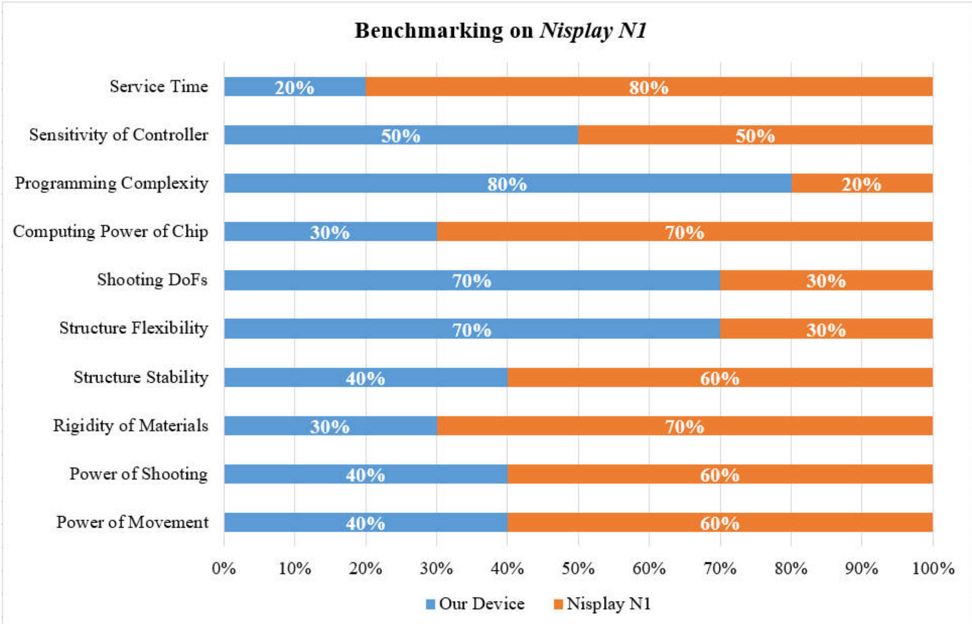


Figure 2.1.3.1-5 Benchmarking Result

As the Figure 2.1.3.1 shows the results of benchmarking, the industrial market device owns work duration estimated at 8 hours. The device represents the great characteristics in power of shooting and movement due to the stable structure and chips applied on it, ensuring the. In the comparison among remaining ECs, our device is supposed to performs better on shooting DOFs and structure stability. Moreover, with less complexity of programming, it enables us to DIY the remote controlled actions we desired.

2.1.3.2 Product Dissection

(a) (b)

Figure 1: Structure of Nisplay N1

The structure of Nisplay N1 is shown in the Figure 2.1.3.2. In the following statement, we do a product analysis on the Nisplay N1 to examine the reasonableness of ECs we picked up.

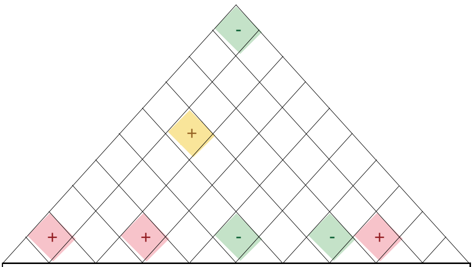
The Nisplay N1 is design as the similar shape with luggage, and the cuboid enclosed construction could protect customers from inside launch components. For shooting functions, it uses two friction wheels driven by industrial grade motor to launch the tennis balls, ensur-ing the precise accuracy and appreciable efficiency. Meanwhile, the flexible structure enables the users to adjust the launch angle from 0 to the maximum value of 60°, which satisfy the demands of various shooting displacement at the same position. As industrial product, Nisplay N1's aluminum alloy material assembly to ensure structural rigidity as the same time possesses capacity to contain 80 tennis balls.

Dissecting the specific features of Nisplay N1, we discover superiority of this product in design and manufacturing, and also explains the great performance in ECs. It's proved to be instructive to our automatic launch device.

2.1.4 Quality Functions Deployment(QFD)

2.1.4.1 House of Quality(HOQ)

As the core of QFD, House of quality(HOQ) is a graphical method of determining the correlation between customer requirements and the performance of the corresponding product.



			Engineering Characteristics									
	Improvement Direction		-	+	+	+	N/A	N/A	+	N/A	+	+
	Customer Requirements	Important Weight Factor	Power of Movement	Power of Shooting	Rigidity of Materials	Structure Stability	Structure Flexibility	Shooting DoFs	Computing Power of Chip	Programming Complexity	Sensitivity of Controller	Service Time
	Control accuracy	4	5	7		2	6	3	9	7	9	2
	Remote control	5	5	9				4	8	6	6	4
	Automatic reloading	3			7	9	4	9		6	3	
	High shooting accuracy	4	8	9	5	8	3	5	6	5	4	3
	Stable structure	3	9		9	9	7	3				
	Adaptive to three balls	5			3	3	6	9				
	High shooting power	3		9					6	3		7
	Adjustable structure	2			6	6	8	3			2	
	Flexibility of movement	4	7		2	8	5	6			5	
	Working Durability	2	4	4					7	2		8
	High degree of freedoms	1		5	3	6	8	9	4	6	3	
	Reloading stability	2			3	9	4	6				5
	Compact size	1					8	4				3
	Low cost	3	5	6	5	6		7	3	2		6
	Easy to control	3		3			3	6	4	8	3	
	Resistance to damage	1			9	8						
	Device safety	3	3	2	4	6	4					
	Ease of maintain	2				3	5	7	3	4	3	
	Ease of programming	2	3	3				5	5	9	5	
	Big ball storage	3				5	6					
	Raw Score		170	188	148	242	208	251	173	171	143	108
	Relative Weight %		9.4%	10.4%	8.2%	13.4%	11.5%	13.9%	9.6%	9.5%	7.9%	6.0%
	Rank Order		7	4	8	2	3	1	5	6	9	10
Technical Assessment	Our Device		4	4	3	3	2	2	2	3	3	2
	Market Device		5	5	4	4	3	3	4	3	5	4
Technical Difficulty			2	2	2	3	4	4	5	5	3	4
Target Value			4	4	3	3	3	3	3	3	4	3

Figure 2.1.4.1-1 House of Quality

We developed the diagram of House of Quality based on the CRs and ECs selected from above detailed analysis (refer to the Problem statement and ECs Part). In the following statement, the HOQ diagram would be analyzed from the ECs, relation matrix and target val-ue parts.

Since the ECs part is chosen as the first analysis segment, we select the ECs parts of the HOQ diagram in Figure 2.1.4.1-2.

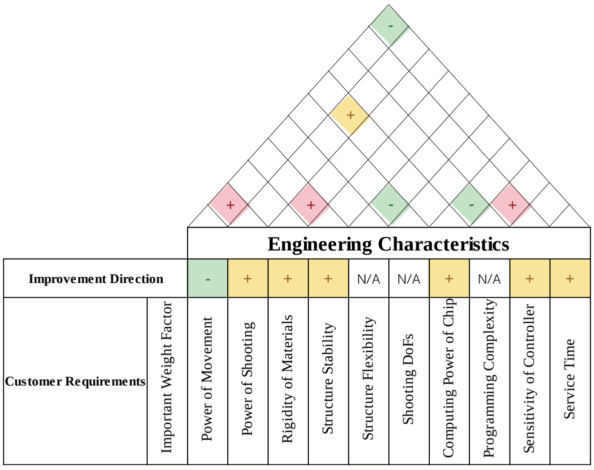


Figure 2.1.4.1-2 ECs of HOQ

The improvement direction is illustrated as while doing the specific changes on ECs, we could obtain better quality of our device performance. The correlation between different characteristics represents the variation trend. There are five types of relation in total: strong positive, positive, strong negative, negative and no correlation.

As shown in the figure, which infers that there exists strong positive correlation be-tween the structure stability and rigidity of materials. In manufacturing process, the selection of more rigid materials enhance the stability of device, which ensures that the impact of vibration on the accuracy of the launch process is reduced. Meanwhile, the negative correla-tion between power of movement and service time indicates that the moving process requires more power supply.

		Engineering Characteristics									
Improvement Direction		-	+	+	+	N/A	N/A	+	N/A	+	+
Customer Requirements	Important Weight Factor	Power of Movement	Power of Shooting	Rigidity of Materials	Structure Stability	Structure Flexibility	Shooting DoFs	Computing Power of Chip	Programming Complexity	Sensitivity of Controller	Service Time
Control accuracy	4	5	7		2	6	3	9	7	9	2
Remote control	5	5	9				4	8	6	6	4
Automatic reloading	3			7	9	4	9		6	3	
High shooting accuracy	4	8	9	5	8	3	5	6	5	4	3
Stable structure	3	9		9	9	7	3				
Adaptive to three balls	5			3	3	6	9				
High shooting power	3		9					6	3		7
Adjustable structure	2			6	6	8	3			2	
Flexibility of movement	4	7		2	8	5	6			5	
Working Durability	2	4	4					7	2		8
High degree of freedoms	1		5	3	6	8	9	4	6	3	
Reloading stability	2			3	9	4	6				5
Compact size	1					8	4				3
Low cost	3	5	6	5	6		7	3	2		6
Easy to control	3		3			3	6	4	8	3	
Resistance to damage	1			9	8						
Device safety	3	3	2	4	6	4					
Ease of maintain	2				3	5	7	3	4	3	
Ease of programming	2	3	3				5	5	9	5	
Big ball storage	3				5	6					

Figure 2.1.4.1-3 Relation Matrix of CRs & ECs

Then, we give a detailed consideration on the relationship matrix between CRs and ECs. As mentioned, we selected 20 CRs from brainstorm and discussion and 10 ECs while benchmarking. Here we form the relationship matrix of CRs and ECs, as a 20×10 table shown in the following table.

The relationship matrix constructs numerical linkage between 20 CRs and 10 ECs. As we mentioned, the CRs represent for customers abstract demands, ECs are hardware and software requirements encountered in industrial design and manufacturing. The values in the relationship matrix are corresponding coefficient between related CR and EC. The bigger value means the more relationship intensity.

	Raw Score	170	188	148	242	208	251	173	171	143	108
	Relative Weight %	9.4%	10.4%	8.2%	13.4%	11.5%	13.9%	9.6%	9.5%	7.9%	6.0%
	Rank Order	7	4	8	2	3	1	5	6	9	10
Technical Assessment	**Our Device**	4	4	3	3	2	2	2	3	3	2
	Market Device	5	5	4	4	3	3	4	3	5	4
Technical Difficulty		2	2	2	3	4	4	5	5	3	4
Target Value		4	4	3	3	3	3	3	3	4	3

Figure 2.1.4.1-4 Target Values of HOQ

In the target value part of HOQ, we determine the technical assessment and difficulty of devices, then set up target value as the trend in design quality.

The raw scores for each ECs are calculated by summing the products of the important weight factor and the corresponding coefficient in relationship matrix. Considering the effects of each CRs, the raw scores could demonstrate the all-round significance of each EC comprehensively. After obtaining the rank order of ECs, we make a technical appraisal and grade on each EC to evaluate technical distinction (1 for the poor performance, 5 for the pretty, comparatively). Since improving different characteristics attributes various difficulties, we set the target value for ECs based on the technical assessment and difficulty scores. The target values of characteristics indicate the trend in design quality.

We construct the design analysis based on the requirements of customers then combined with the detailed manufacturing characteristics. With the method of HOQ (house of quality) diagram, we dissect the design issues into comprehensive industrial scheme.

2.1.5 Product Design Specification (PDS)

A design specification is a detailed document providing a list of points regarding a product or process. The purpose of PDS is to ensure that the design quality and development of the product could satisfy the requirements of the customers.

In product design specification table, we prioritized the common features indicates the requirements of customers. The detailed special features are listed, which determine the high-lighted hardware and structures differential from other devices. There is few work we did on market research since this course project is far from industrial manufacture and market.

Table 2.1.5 Product Design Specification (PDS)

Product Identification		**Market identification**
➢ **Name:** Remote Controlled automatic metal trebuchet ➢ **Function:** Agilely moving and shooting ➢ **Special Features:** 1) Ps2 Bluetooth Control 2) Ardunio Single Chip 3) Mecanum Wheels 4) Trebuchet For Tennis Shooting	➢ **Common Features:** 1) Friction Wheels Shooting 2) Rolled plate loading 3) Power Supplies: 5V & 12V 4) Load Storage: 1tennis and 4 racket or 4 ping-pongs 5) Size Limit: 35*35*20 (cm, L*H*W)	➢ **Competing Products:** OUKEI-787, PT9001, Nisplay N1, FQ03 ➢ **Market Demand:** None
Key Project deadline:		
➢ Prototype Deadline: 2022.6		

2.2 Concept Generation

2.2.1 Shooting scheme1: Friction wheels

Considering the characteristics of light weight and small volume of ping-pong balls and rocket balls, this paper plans to use friction wheel[7] scheme to project them.

We collected a lot of information on the Internet, and found that the factors that determine the projection effect of friction wheel are mainly the following two factors: the material of friction wheel and the quality of the motor matching the friction wheel.

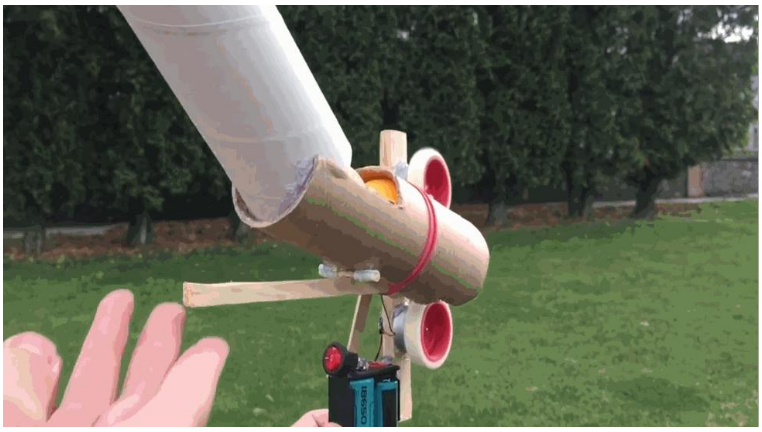


Figure 2.2.1-1 Friction wheel concept generation

On the material of friction wheel, we choose customized rubber friction wheel. In this way, we can not only facilitate the size of the motor, but also control the friction coefficient of the friction wheel, so that the feasibility of debugging is higher. For the motor, we choose MT4114 brushless motor, which has very large power and a wide range of adjustable speed, and is also convenient for us to select different speeds for debugging of Pin-Pong balls and Rocket balls and improve their stability.

We designed a track to carry the ball out of the reloading device and into the friction wheel device through 3D modeling. The inclination of the track should not be too high. If the initial velocity of the ball is too high, it will increase the complexity of debugging. As for the friction wheel, we choose an adjustable angle support to hold it in place. In this way, we can easily give the ball an initial launch angle and make its fall more stable. At the same time, we can adjust the fixed distance of the friction wheel to improve the accuracy of launching. The whole design of friction wheel is shown in below figure. In the following chapters, we will further elaborate on the methodology and manufacture of this design.

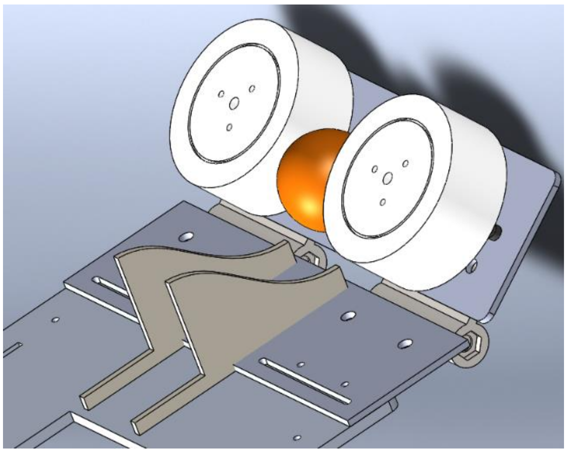


Figure 2.2.1-2 The whole design of friction wheel

2.2.2 Shooting scheme2: Stone catapult controlled by the steering engine and spring

Given the heavy weight of the tennis balls, the friction wheel may not be the best choice for shooting tennis balls. We're going to design another way to launch tennis balls. We took inspiration from the ancient catapults [8-9], which have the advantages of being stable in structure and being able to throw heavy objects, perfect for our tennis ball shooting needs.

Figure 2.2.2-1 Stone catapult concept generation

We designed a moment arm for throwing tennis balls and connected it to a spring. In the stone throwing structure, we use two steering gears, the first gear is used to control the elongation of the spring, the second gear blocking the moment arm, control the timing of the launch. We put the arm back in place, use the first actuator to block the arm, then control the second actuator to stretch the spring, and then control the first actuator so that it does not block the arm. Because the spring needs to return to its original length, the casting stone arm will project the tennis ball. The whole design of stone catapult is shown in below figure. In the following chapters, we will further elaborate on the methodology and manufacture of this design.

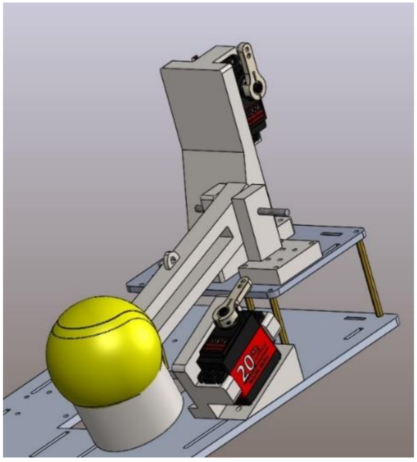


Figure 2.2.2-2 The whole design of stone catapult

One of the highlights of our catapult stone is that we have this dual steering structure. The steering gear can control the precise rotation aspect, but cannot achieve fast reset and high-speed rotation. If a Stone Catapult uses just one steering engine to stretch the spring, it is unrealistic to rely on the same steering engine to restore the spring to its original length. So, we use the structure of the double steering gear, not only to stretch the spring of the steering gear sufficient operation time, and do not need it reset.

2.2.3 Reloading scheme: A container track and a ferris wheel controlled by the steering engine

The design of loading ball is mainly composed of container track and ferris wheel. A container track is a track that can hold four or five balls. In the starting zone, we put ping-pong balls and rocket balls into container rails. The container track has a certain angle to facilitate the ball to fall smoothly into the ferris wheel.

The main function of the ferris wheel is to make the ball one by one to fall into the orbit to undertake the wheel. We use the steering gear to control the rotation of the ferris wheel through the PS2 controller and Bluetooth remote technology. The design of the entire load is shown below:

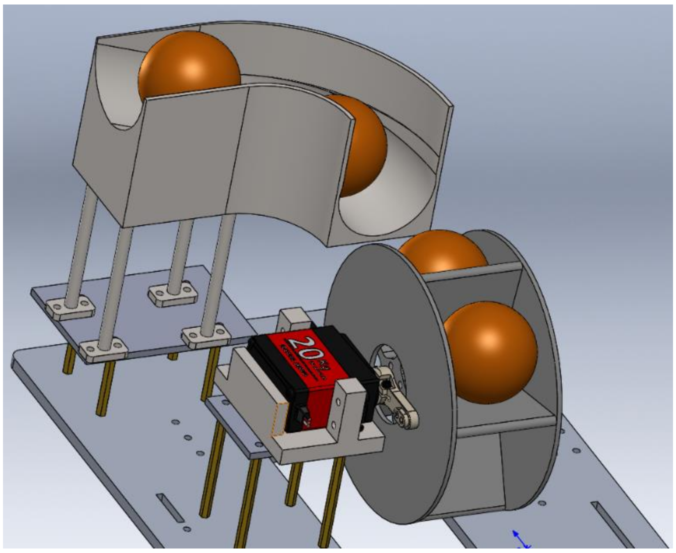


Figure 2.2.2-3 The whole design of reloading system

2.3 Material selection

Actually, the selection of materials is a very important part of this project, so we will make important explanations on the selection of materials below. In the process of material selection, the main problem we encounter is how to balance the quality and price of materials. Generally, good materials are more expensive. On the one hand, we consider the limit of the project cost. On the other hand, the durability and stability of the material directly affect the performance of prototype. Therefore, in order to make the right material choice, we listed the characteristics of each material.

In the prototype design process, we were mainly faced with material selection issues: material selection of two-layer car body board, friction wheel. Firstly, we will talk about the material selection of the two-layer car board. The specific characteristics of each material are shown in the next table.

Table 2.3 The material selection of the two-layer car board

Materials	Thickness	Cost	crushing resistance	Flexibility
Wood Plate	5mm	Low	Low	High
Acrylic plate(3mm)	3mm	Low	Moderate	High
Acrylic plate(5mm)	5mm	Moderate	High	High
Metal plate	5mm	High	Extremely High	Low

As we can observe from the table above, metal plate is the most pressure-resistant material, but it is more expensive and less feasible (difficult to make modifications). Wood plate is cheaper, but it does not withstand pressure, which makes trebuchet prone to jitters during projection. Compared with other materials, 5mm thick acrylic plate is the best choice. It not only has high compressive resistance and is not easy to trebuchet deformation, but also has lower price and high feasibility. Therefore, we choose acrylic plate as the manufacturing material of our base plate and upper plate.

Next, we will discuss the material selection of friction wheel. In the selection of friction wheels we mainly consider the following two kinds of friction wheel, rubber friction wheel [10] and silica gel friction wheel [11], as shown in the figure below:

(a) Rubber friction wheel

(b) Silica gel friction wheel

Figure 2.3: The material selection of friction wheel

The advantage of rubber friction wheel is that it is cheap, but compared with silica gel friction wheel, its dynamic friction factors are more difficult to control, indicating that its projection effect is not good, which will lead to different results of each projection and poor stability. The silica gel friction wheel is a good solution to these problems, silica gel friction wheel shows a smoother, better control of dynamic friction factors, and more stable pitching results. Therefore, even though the silica gel friction wheel is more expensive, we still choose it because the material of the friction wheel is crucial to our final result of projection.

2.4 CAD & Solidworks Work

In the Concept Design part, we used AutoCAD to sketch the base plate and other plates, and Solidworks to draw all the 3D models. After drawing on the computer, we used laser cutting and 3D printing to make the plates and 3D models respectively. In the design process, we fully considered the interplay between the components and set the form and dimensional tolerances to help improve the accuracy and feasibility of the modeling.

For example, we set bilateral dimensional tolerances to fix the bearings and rotating rods when designing the stone catapult structure. The details will be shown in the solidworks engineering drawings.

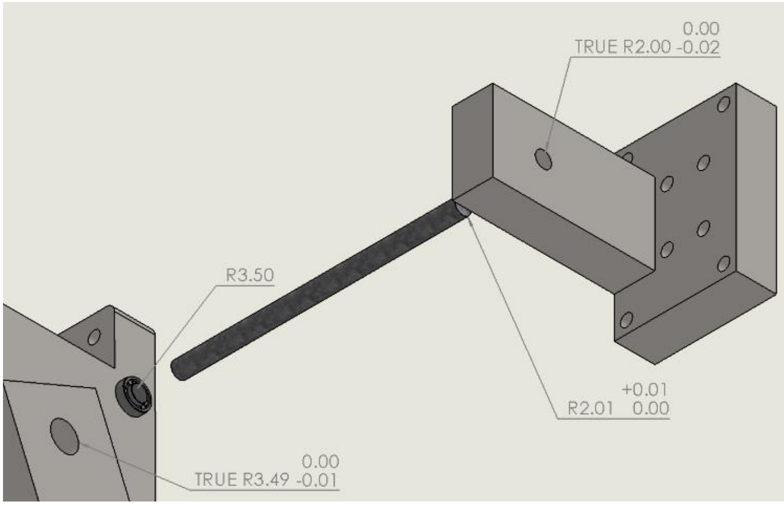
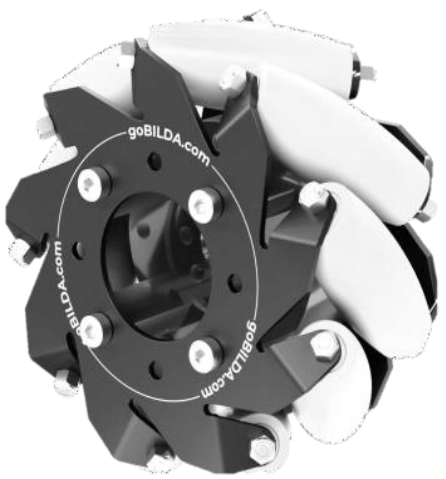


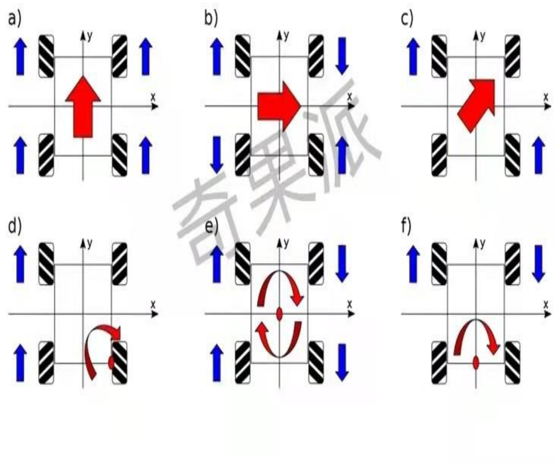
Figure 2.4 Solidworks Engineering Drawings

3 Manufacturing & Methodology

3.1 Moving system

In this project, we used the Mecanum wheel to control prototype movement. Mecanum wheel is a kind of omnidirectional wheel that can move in all directions. The angle between the axis of roller and hub axis is 45°. The roller is a kind of small roller without power. The busbar of the small roller is very special. When the wheel rotates around the fixed spindle of the wheel, the envelope of each small roller is cylindrical, so the wheel can continuously roll forward. The combination of four of these wheels gives prototype omnidirectional mobility. The appearance of Mecanum wheels is shown in below.





(a) Mecanum wheels (b) Principle of Mecanum wheels

Figure 3.1: Appearance and principle of Mecanum wheels

The principle of Mecanum wheels is shown in the above figure. The different combinations of different wheels turning forward or backward can cause prototype to move back and forth or turn back and forth. For example, prototype moves left when the left front wheel and right rear wheel move forward and the right front wheel and left rear wheel move back.

3.2 Control system

To express how the control system works, we should start from the central control module, Arduino single chip, which is an open source electronic prototype platform that is convenient, flexible and easy to use. It is a microcontroller application development board mainly based on AVR microcontroller. The single chip is a kind of integrated circuit chip, is a small and perfect microcomputer system. The Arduino single chip is shown in the next figure.

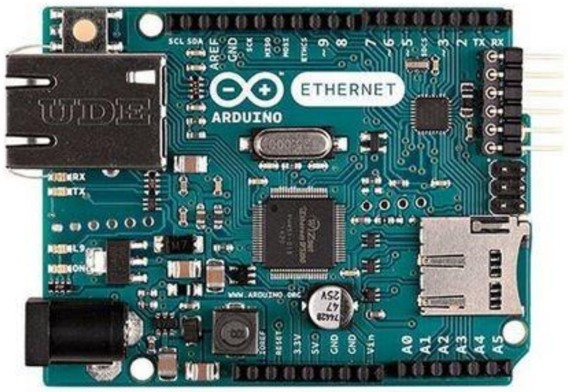


Figure 3.2-1: Arduino single chip

A figure of the working principle of our control system is shown in below, which clearly shows all necessary components and the relation between them. Components are divided into four main categories: control boards & modules, sensors, motors, power supplies.

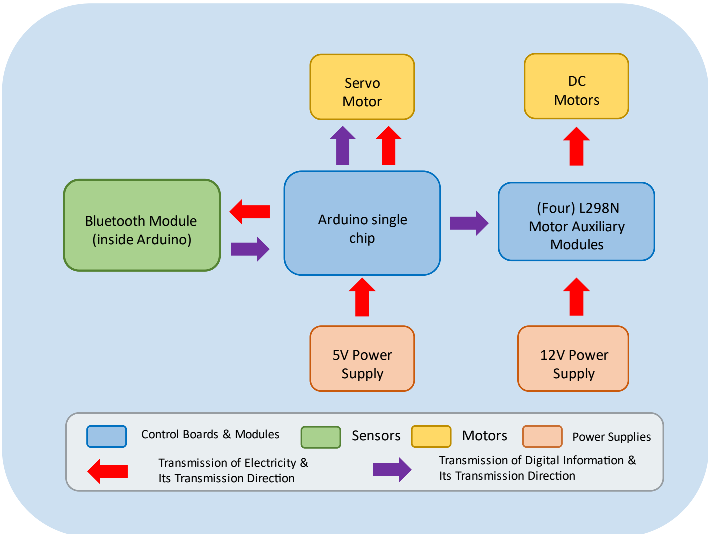


Figure 3.2-2: The working principle of our control system

In the figure above, the red arrow represents the transmission of electricity and its direction, and the purple represents the transmission of digital information and its direction. There are two main power supply systems in our system: 5V power supply for Arduino and 12V power supply for L298N drive board. The drive board supplies power to the DC motor, while the Arduino Micro controller supplies power to the Bluetooth module and steering gear. At the same time, the digital signal of the system is sent to Arduino by Bluetooth module, and then sent to L298N drive board and steering gear by Arduino.

In this project, we use ps2 controller to send messages to blue tooth module. PS2 controller consists of a gamepad and a receiver. The controller is mainly responsible for sending button information. The receiver is connected with the microcontroller to receive the information from the handle and transfer it to the microcontroller. The microcontroller can also send commands to the handle through the receiver and configure the sending mode of the handle.

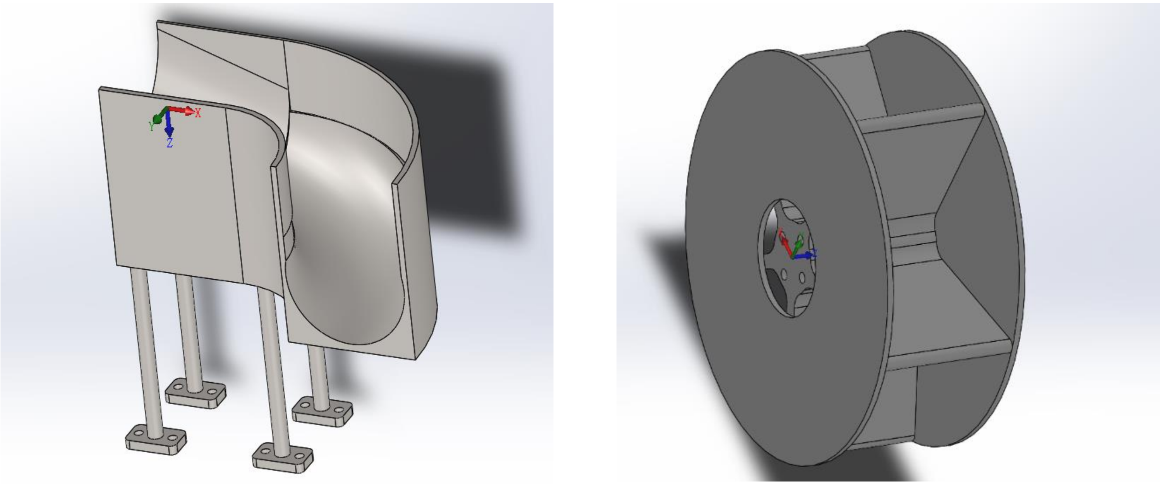
Figure 3.2-3: The PS2 controller

3.3 Shooting System & Reloading system

This article will further explain the emission and reloading manufacture and methodology of Prototype. There are two main launchers in this paper. One is a friction wheel launcher for throwing ping-pong balls and rocket balls, and the other is a Stone Catapult for throwing tennis balls. For the reloading system, the container track is designed for reloading balls, and the ferris wheel controlled by the steering gear is used to make balls enter the friction wheel device one by one. We will first elaborate on the manufacturing and launching methodology of the reloading system.

3.3.1 Manufacture and methodology of reloading system

Considering that the project requires us to design at least one kind of ball for reloading and that tennis balls are too large for reloading, our reloading system is mainly used for loading pin-pong balls and rocket balls. The reloading system is mainly composed of two parts, namely, ball storage container track and ferris wheel.

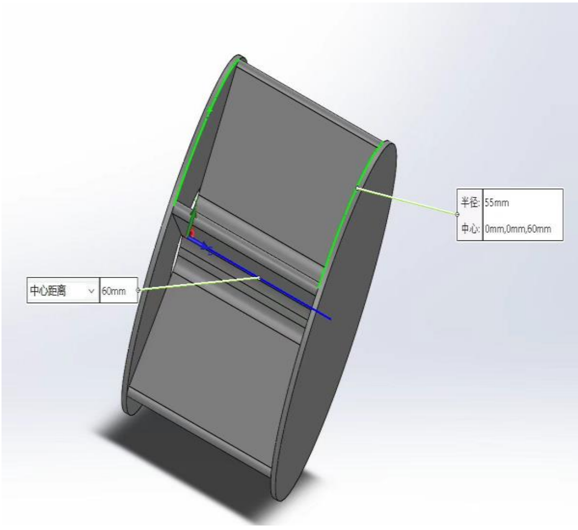


(a) The ball storage container track (b) The ferris wheel

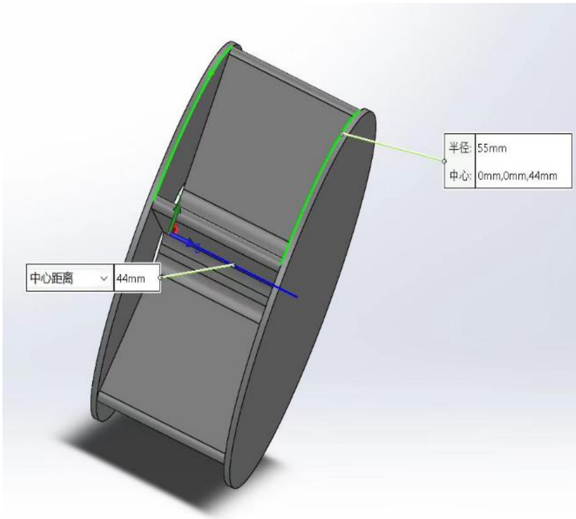
Figure 3.3.1-1: The container track and ferris wheel

Ball storage Container Track is shown in the figure above on the left. The radius of the track we designed is slightly larger than that of table tennis and squash to facilitate the loading of these balls. The track length is moderate and can hold 4-5 ping-pong balls or squash balls at the same time. We can find that the track has a certain downward tilt angle, which can make the ball gently roll down into the ferris wheel, and the speed of the ball rolling is not high, the whole process is relatively stable.

We use 3D printing technology to manufacture the ferris wheel. Several holes are punched on the left side of the ferris wheel to facilitate the connection between the steering gear and the ferris wheel. We use remote bluetooth technology to control the rotation of the steering gear, so that the balls smoothly into the launcher one by one. Meanwhile, due to the large radius of the ferris wheel we designed at the beginning, on the one hand, the alignment of the ferris wheel and the launching device will be affected, increasing the instability of launching. Also, it takes up more space. So, we improved the thickness of the ferris wheel according to the actual size of the ball.



(a) The ferris wheel before improving the thickness



(b) The ferris wheel after improving the thickness

Figure 3.3.1-2: The ferris wheel before and after improving the thickness

The overall design of the reloading device combined with ferris wheel and container track is shown in the figure below：

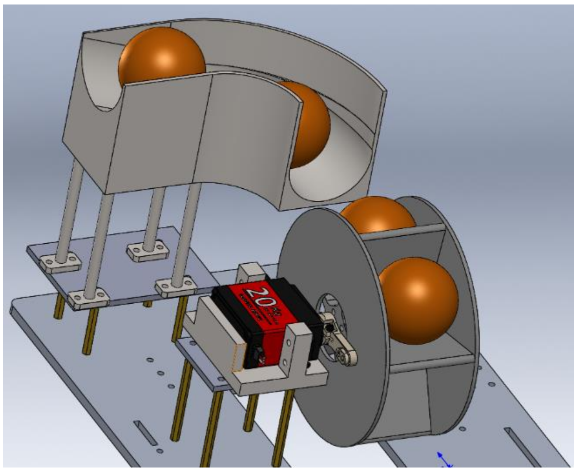
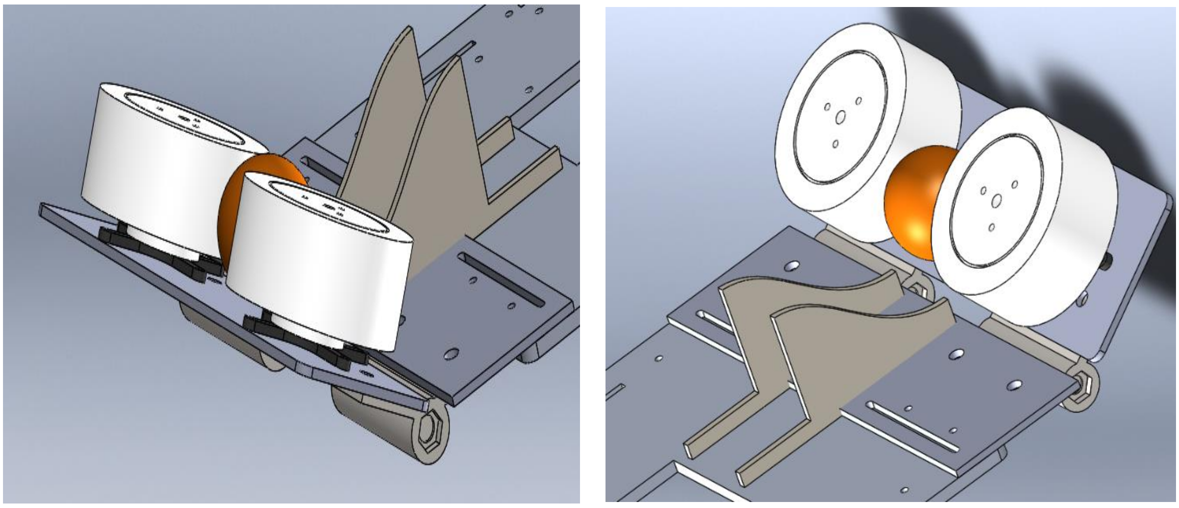


Figure 3.3.1-3: The overall design of reloading system

3.3.2 Manufacture and methodology of friction wheel shooting device

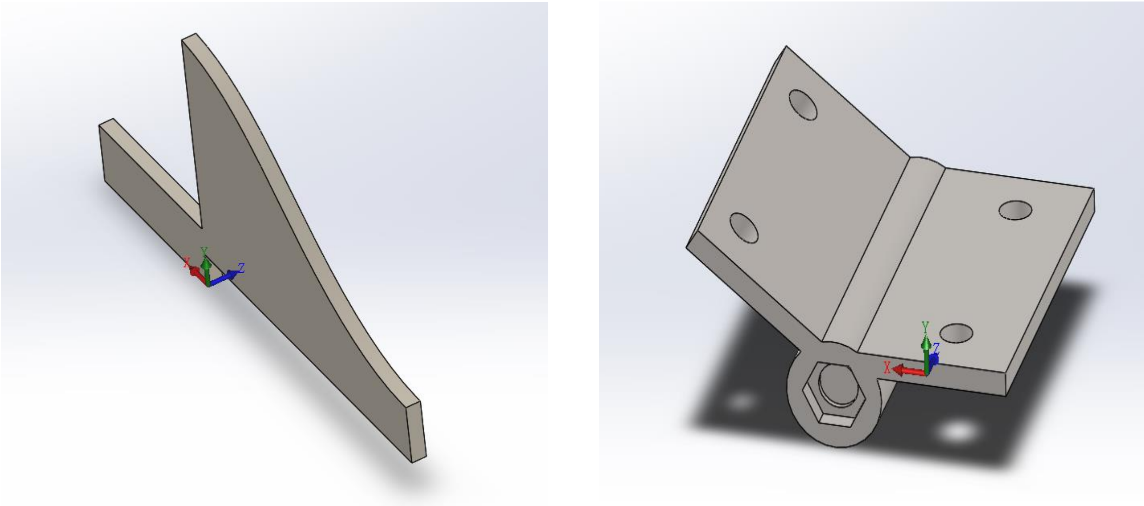
Previously, we introduced the reloading device of rocket balls and pin-pong balls, and now we introduce their launching device. We mainly use friction wheel launchers to launch ping-pong balls and rockets. The overall design of friction wheel shooting device is shown as below.



(a) (b)

Figure 3.3.2-1: The overall design of friction wheel

We will focus on two important components of the friction wheel launcher: the launch track and the adjustable angle fixed friction wheel bracket, which are shown in below.



(a) The launch track (b) The adjustable angle fixed friction wheel bracket

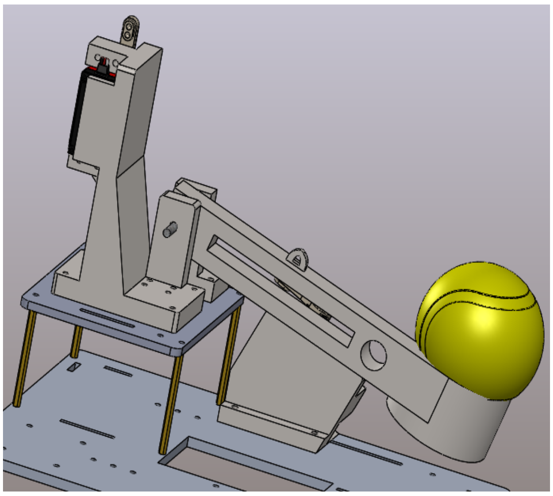
Figure 3.3.2-2: The overall design of friction wheel

Although the design of the launch orbit is very simple, it also contains some subtlety. Our track is not ordinary inclined straight orbit, but designed a certain curve arc, so that the ball can not only smoothly fall into the friction wheel, but also slow down the falling speed of the friction wheel, increasing the stability of the launch. Our track also has a rectangular bar extending forward, its role is to help the ball and the friction wheel uniform contact, to avoid the uneven force on the ball on both sides of the friction wheel.

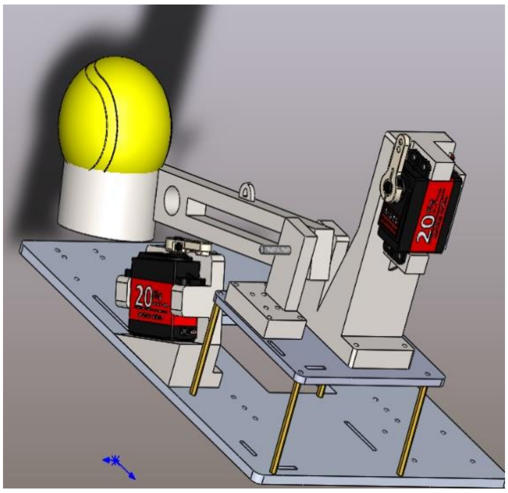
The initial launch angle of the launcher will have an important impact on the launch effect of the ball, and we want to test the perfect angle so that the ball makes a perfect projectile motion, and hits the center of the basket. Therefore, we design a fixed friction wheel bracket that is convenient to adjust the angle, so that we can adjust the angle of the friction wheel during debugging. The adjustable angle fixed friction wheel bracket we designed is shown in the diagram on the right. The designed rotation place has a bolt, which is convenient for angle adjustment.

3.3.3 Manufacture and methodology of stone catapult

Next, we introduce stone catapult's manufacture and methodology. We first designed a catapult arm for throwing tennis balls, and connected the springs to the catapult arm. We use one steering engine to control the elongation of the spring, and the second steering engine to control the timing of the launch of the catapult arm. The overall design drawing is shown in the figure below.



(a)



(b)

Figure 3.3.3-1: The overall design of stone catapult

The stone catapult arm is shown in the figure below. We use a spring to drive the rotation of the sling arm. We restore it to its original position and hold it in place with steering gear 2. We stretch the spring attached to the trebuchet arm with steering gear 1, and then we release steering gear 2. As the spring needs to regain its original length, the catapult arm moves up to project the tennis ball.

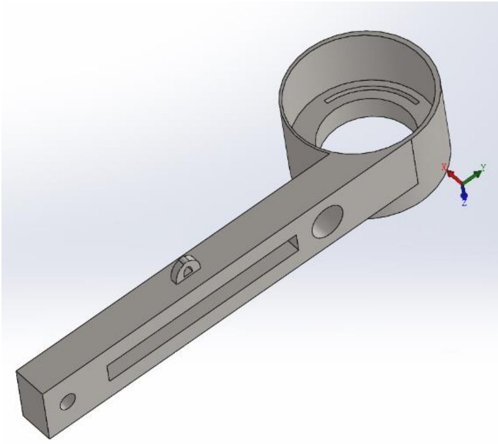
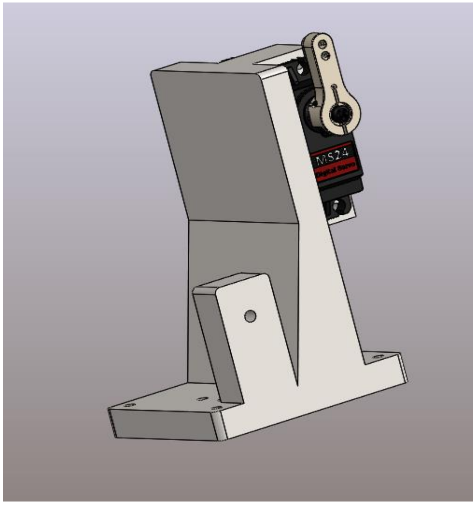
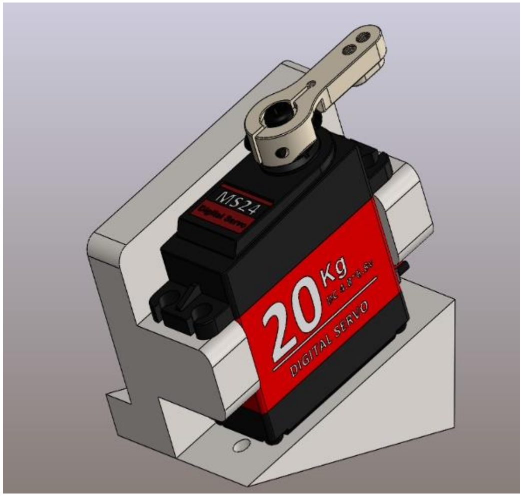


Figure 3.3.3-2: The arm of stone catapult

We designed two brackets for fixing the steering gear, as shown in the figure below.



(a) The bracket to fix the steering gear 1



(b) The bracket to fix the steering gear 2

Figure 3.3.3-3: The brackets to fix the two steering gears

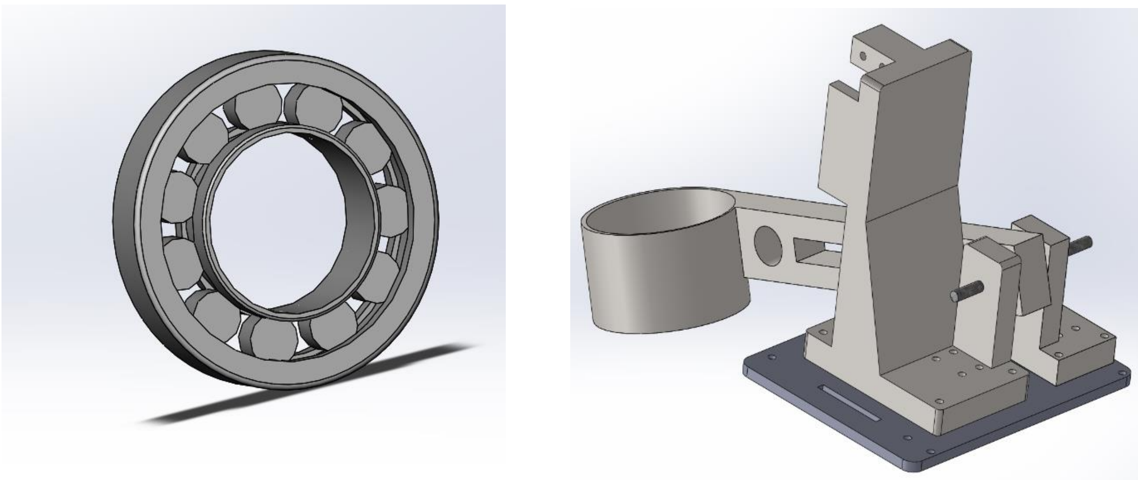
In order to make the structure stable, we added the plate ribs to the first steering gear fixing bracket. In order to match the initial angle of the arm of stone catapult, we made a tilted fixed bracket, as shown in the upper right.

3.4 Details of design and manufacture

In our design and model assembly process, there are some important details which is worth paying attention to. Only when the designs are reasonable, can the functions of the prototype be implemented successfully. Here, we will focus on three details.

- **The bearing of our arm of stone catapult**

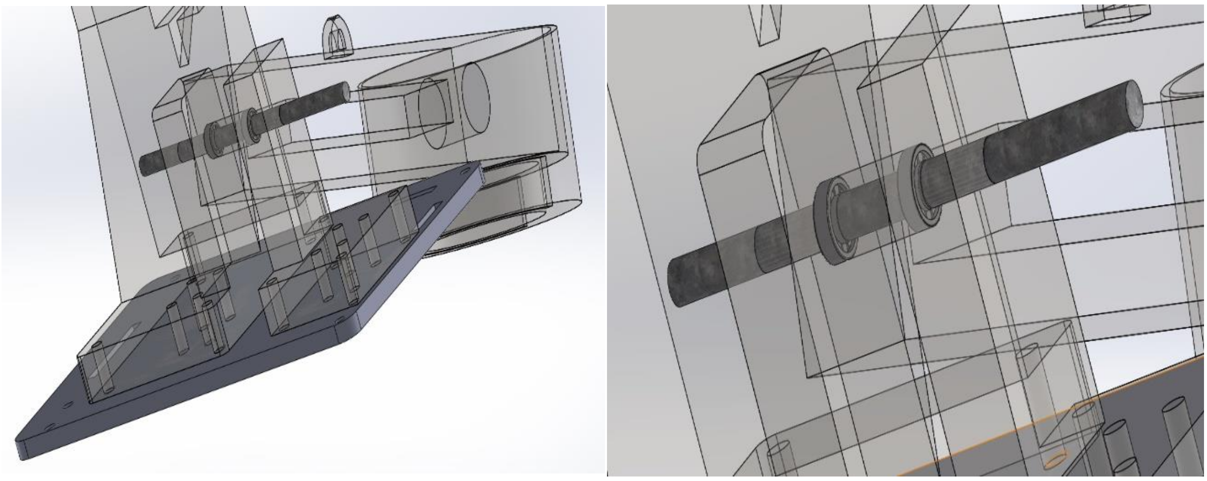
The first detail is the bearing in our arm of stone catapult, which is shown in the figure below. Our design is cylindrical bearing, its role is to support the mechanical rotating body, reduce its friction coefficient in the process of motion, and ensure its rotation accuracy. Bearing is also fixed in the process of mechanical transmission and reduce the load friction coefficient of the components. We adopt a double bearing structure, which greatly avoids the rocking of the rotating rod. The local diagrams of stone catapult is shown below, in order to help readers understand the role of bearings.



(a) The cylindrical bearing (b) The local diagrams

Figure 3.4-1: Cylindrical bearing and local diagrams

We will further show the bearing interior diagram of the stone Catapult with bearing, as shown below.



(a) (b)

Figure 3.4-2: Interior bearing diagram of the stone catapult

- **The spacing adjustment of friction wheel**

At the beginning of the testing period, the success rate of squash goals was not high. We noticed that the distance between the friction wheels was too narrow, which might cause a large deviation in the force exerted by the friction wheels on the ball every time at the moment of launch, resulting in unstable squash projection. Therefore, we increased the spacing of friction wheels, as shown in the figure below.

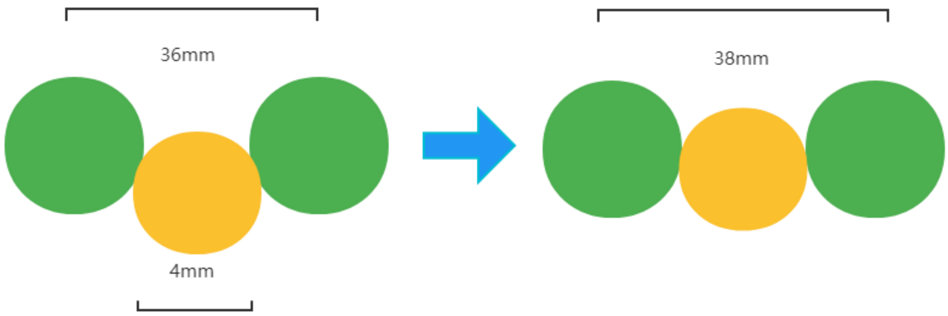


Figure 3.4-3: The schematic diagram of spacing adjustment

We used the friction wheel projection device to launch 5, 10, 15 and 20 squash balls consecutively before and after the spacing adjustment. The number and hit ratio are shown in the table below.

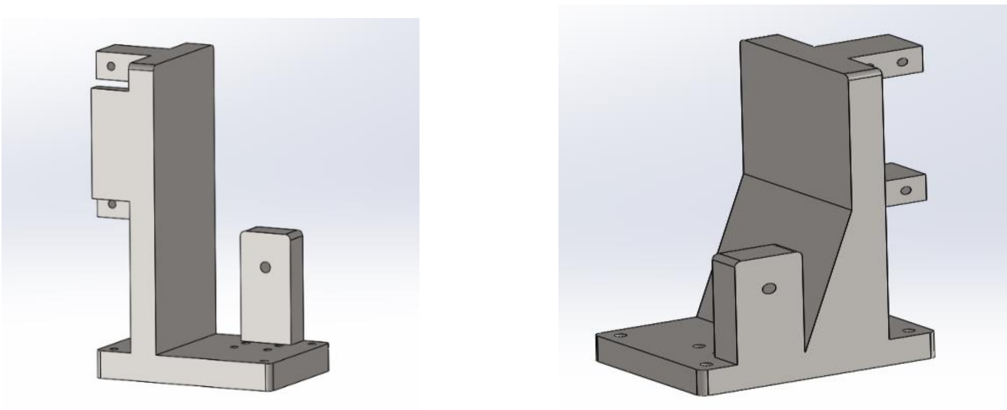
Table 3.4: The projection results of rocket before and after spacing adjustment

Total number of Rockets	5	10	15	20	Average
Successful rate (before adjustment)	40%	50%	46.67%	55%	47.92%
Successful rate (after adjustment)	100%	100%	93.33%	95%	97.08%

As can be seen from the above table, after the spacing adjustment, the success rate of squash projection is greatly improved, from 47.92% to 97.08, so it can be seen that the spacing adjustment is a key step.

- **The Plate steel reinforcement of the bracket in the stone catapult**

In the preliminary test of throwing stone, we found that the structure of throwing arm is not stable enough, it will shake phenomenon, which directly leads to the poor tennis ball shooting effect. Therefore, we improved the structural details of the fixed parts of steering gear 1 and reinforced them with plates and ribs. The specific process is shown in the figure below.



(a) Bracket before reinforcement (b) Bracket after reinforcement

Figure 3.4-4: Bracket before and after reinforcement

After the plate reinforcement of the fastener, the body of the tennis ball will no longer shake in the process of throwing, and the projection stability will be greatly improved.

3.5 Finite Element Method

The finite element method (FEM) is a general numerical method for solving partial differential equations in two or three space variables (i.e., some boundary value problems). To solve a problem, the FEM subdivides a large system into smaller, simpler parts that are called finite elements. This is achieved by a particular space discretization in the space dimensions, which is implemented by the construction of a mesh of the object.

By generating mesh and analyzing the stress condition of each component element, we could determine the deformation of launching structures and ameliorate the concept design. We simulate the force reaction of each component of the catapulting arm in the launching device during the process by using the finite element analysis method.(e.g. the stress at the contact point with the baffle). By establishing the mesh analysis model and solving the integral equations numerically, we plot the following finite element analysis diagram.

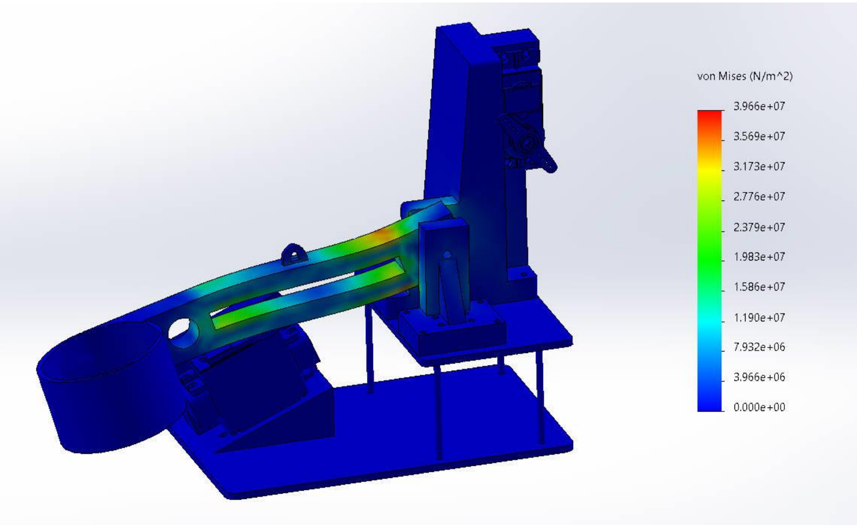


Figure 3.5: FEM of Catapult Arm

As shown in the figure, in the hypothetical simulation, the force on the middle part of the catapult arm could cause great deformation. The catapult arm part holds for the tennis balls and is critical to ensure the stability of launch. Therefore, from the analysis results, we made this part bold to improve the load capacity and launch stability.

4 Project Evaluation and further discussion

4.1 Strengths

1. **Shooting accurately.** We use silica gel friction wheel to launch ping-pong balls and squash balls with high accuracy. We also use the laser lamp auxiliary vehicle projection alignment, improve the success rate of the ball.

2. **Easy to control.** We used a Bluetooth module and a PS2 controller to control Trebuchet remotely. We design the function of each button according to our own preferences and habits, so it's very easy to control.

3. High structure stability. We use two steering gears, springs, and catapults to throw tennis balls. We comprehensively consider the material and specifically consider the design of each part, so that the structure of catapult is stable and the effect of throwing tennis balls is good. We also implement the finite element analysis to prove the stability of our structure of shooting tennis balls.

4. High flexibility. We designed two schemes for throwing a ball, one is the friction wheels for shooting the ping-pong balls and rocket balls. The other is the stone catapult for shooting tennis balls. If we use friction wheels to shoot tennis balls, because of the need to adjust the friction wheel spacing, resulting in structural instability and inflexibility. If we were to shoot ping-pong balls and rocket balls with a stone catapult, it would take more time. Therefore, our design takes stability, time constraints and other factors into consideration. It is very flexible.

4.2 Weaknesses

1.**High maintenance cost.** We have some of the more expensive parts in Trebuchet, for example, the Mega board, silicone friction wheels, brushless motors, etc. In the debugging process, the stability of some parts is not high, which requires us to replace parts. However, our project funds are limited, so the maintenance cost is more troublesome for us.

2. **Moderate stability of shooting rockets.** Since we are firing squash balls at a higher speed, this can create a different impact on each squash ball, making the delivery unstable.

4.3 Further Discussion

1. **Multiple balls catapult.** Catapults on the market are mainly used for launching a single type of ball, such as a tennis catapult or a badminton catapult. We've designed catapults to shoot rocket balls, tennis balls, ping-pong balls all. Perhaps, we can improve our design to launch more kinds of balls at the same time.

2. **Intelligent shooting technology.** In our project, we have implemented automatic projection technology. We can combine machine learning technology with intelligent algorithms to improve the smoothness of motion and accuracy of shooting, and use intelligent engineering methods to innovate shooting technology.

5 Conclusion

In this project, we designed an automatic controlled metal trebuchet, which can be used to shoot pin-pong balls, rocket balls, tennis balls in a remote control.

We used Arduino as the central controller and ps2 controller combined with Bluetooth technology to achieve remote control of trebuchet. We design a container track to store balls and implement a ferris wheel controlled by the steering engine to reload the balls. As for shooting, we employ the friction wheels to shoot pin-pong balls and rocket balls. Inspired by the ancient stone catapult, we design a catapult arm with a spring to control it. We also employ two steering engines, one steering engine is used to control the elongation of the spring, and the other is used to control the timing of the launch of the catapult arm.

Our Trebuchet has a success rate of 96%, 91% and 98% on shooting ping-pong, rocket balls and tennis, respectively. The biggest highlights of our trebuchet are the precision of the shooting and ease to control.

6 Nomenclature

CRs: Customer requirements

ECs: Engineering Characteristics

PDS: Product Design Specifications

HOQ: House of Quality

Stone Catapult: The device used to project the tennis

Prototype: The design of our whole trebuchet

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