Tampereen ammattikorkeakoulu

The Study of Semi-Automated Football Table

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MOHEBI, DANI:
Tutkimus puoliautomaattisen jalkapallopöydän rakentaminen

Opinnäytetyö 72 sivua, joista liitteitä 1 sivua
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Puoliautomaattinen jalkapallopöytä antaa ihmisille mahdollisuuden pelata pöytäjalkapalloa tietokonetta vastaan, joka on yhdistettynä mekaanisiin komponentteihin. Opinnäytetyön tarkoituksena oli tutkia ja suorittaa teknisiä analyyseja erilaisista puoliautomaattisista jalkapallopöydistä, jotta saadaan paras menetelmä järkevän prototyypin kehittämiseksi tästä koneesta. Tämän tavoitteen saavuttamiseksi tutkittiin Internet-verkkoa. Tietoa on poimittu aiheeseen liittyvistä aikaisemmista opinnäytetöistä ja artikkeleista.

Opinnäytetyössä käsiteltiin ensin tavoitteita ja vaatimuksia, jotka on otettava huomioon puoliautomaattisen jalkapallopöydän kehittämisessä, ja sitten niiden perusteella tarkasteltiin mahdollisia ratkaisuja vaatimusten täyttämiseksi. Lopussa suositellaan sopivia menetelmiä puoliautomaattisen jalkapallopöydän rakentamiseksi huokeaan hintaan. Opinnäytetyössä käsitellään myös turvallisuusasioita. Tutkittiin koneen ja pelaajien todennäköisiä vaaroja, esiteltiin keinoja niiden ehkäisemiseksi ja ratkaisuja onnettomuuden sattuessa.

Tutkimus myös osoittaa, että tällaisen automaattisen koneen suunnittelu vaatii erilaisia taitoja, kuten automaatio- ja IT-taitija sekä teollisen suunnittelun ja rakennelaskelminen osaamista. Parhaiden tulosten saavuttamiseksi ja tehokkaan puoliautomaattisen jalkapallopöydän kehittämiseksi suositellaan neljän hengen tiimiä, jolla on mainitut taidot.

Asiasanat: puoliautomaattinen, jalkapallopöytä

ABSTRACT

Tampereen ammattikorkeakoulu
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MOHEBI, DANI:
The Study of Semi-Automated Foosball Table

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The Semi-Automated Foosball Table gives an opportunity for people to play table football against a computer combined with mechanical components. The purpose of this thesis was to study and conduct technical analysis on different Semi-Automated Foosball Tables to derive the best method for developing a reasonable sample of this machine. To reach this goal, the internet network was searched. Data were drawn from previous theses and articles related to the subject.

This study first discussed about objectives and requirements which are necessary to consider them for developing a semi-automated foosball table and then based on the requirements, reviewed possible solutions to fulfill the requests. In the end, suitable methods are recommended to build a semi-automated foosball table at an affordable cost. Safety issues related to the machine and users are also covered in this thesis.

This study also indicates that designing such an automatic machine requires different skills like Automation, IT, industrial design, and structural calculations. To reach the best results and develop an efficient semi-automated foosball table, a four-member team with mentioned skills is suggested.

Keywords: Semi-Automatic Foosball Table

CONTENTS

GLOSSARY

Foosball:	Table football
Foosbot:	Robot which is made to play table football
Puppet:	Foosman, player model in table football
SAFT:	Semi-Automatic Foosball Table
EMI:	Electromagnetic Interference
RFI:	Radio-Frequency Interference

1 INTRODUCTION

Table football or foosball, invented around the 1890s, is based on real football matches. In table football, player-shaped components called puppets or foosmen are placed on spinnable rods which make them able to hit the ball into the opponent's goal or defense against the opponent’s playing attempts. Human players are responsible for rotational and translational motions of rods to hit the ball or prevent the ball from going into the own goal. (Foosball Soccer 2021.)

A quick search on the internet shows that some work regarding semi-automated foosball tables has already been done. Most of these projects followed the same routine. In many of these projects, cameras are responsible for tracking the ball from above or under the table. To move rods in an angular and straight direction, there are two motors for each rod but the construction of the structure and the way motors transfer motion to the rods have differences. For example, in 2009, Eindhoven university developed a semi-automated foosball table with a vision-based ball tracking system. They used camera on top of the table (R.Janssen, J.de Best & R.van de Molengraft 2009). In the other project, in 2010, by J.Lues from Massey University, they used a camera from the bottom of the table and got good results for tracking the ball. At California Polytechnic State University, a group of students used a computer vision camera from the top (J.Gutierrez-Franco, J.Inlow, J.Graham, 2013). Allied Vision Technologies published a video of their developed S.A.F.T which was hard to defeat for human players (Allied Vision Technologies 2007).

There was an objective in Tampere University of Applied Science, TAMK, to develop a Semi-Automated Foosball Table in the future. This thesis was to review the previous works, analyze used technologies and give guidelines to design a proper Semi-Automated Foosball Table based on the possible facilities.

2 DESIGN REQUIREMENTS OF SEMI-AUTOMATED FOOSBALL TABLE

To design a semi-automated foosball table, it is necessary to have a review of geometrical shapes, sizes, and playing rules of standard foosball tables.

2.1 Common standards and rules of foosball game

There are many different types of football tables made for different users from foosball for children and beginners, to skilled and professional players. Figure 1 shows the most common type of foosball table with 4 rods for each opponent.

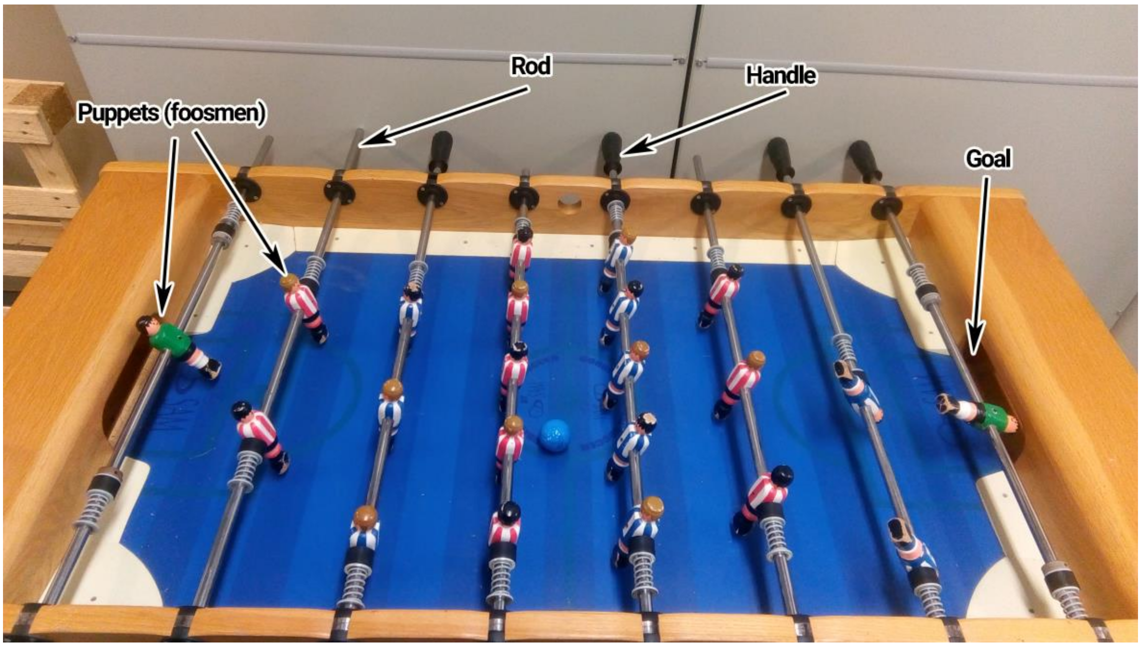


FIGURE 1. 4-rods foosball table

Pitch: All foosball pitches are rectangles and except in front of the goals, they have slop at the sides and corners for the times that the ball is at the sides of the pitch and out of puppets access. (Foosball Australia.)

Ball: based on the net markets and foosball associations web pages, nowadays foosball balls are made from plastic with 33-35 mm diameter and the weight from 13g to 27g. Normally the standard balls for tournaments have 35mm diameter and 18-27g weight. (Foosball Australia.)
Table 1 shows some similarities and differences between different foosball table types.

TABLE 1. Foosball table sizes (Foosball Australia)

STYLE	Make	Playing area(cm)	3-bar spacing(cm)	Goal width (cm)	Ball wgt(g)
Italian	Garlando	114-120x70.5	18,4	19	17,5-18,5
	Roberto Sport(UCD)	111-118x70.5	16,0	19	17,5
	FABI	120x70	16,8	19	17,5
	FAS	117x70	16,4	19,5	17,5
	Longoni	113x70	16,5	21,5	17,5
	Brighouse/FASNA	108x70	16,2	19,8	17,5
	Sardi	120x69	16,5	19,5	17,5
German	Loewen	119x68.5	16,4	17	20,5
	KCE/TS	118.5x68.5	15,9	18	20,5
French	Bonzini	119x69	17,0	19	14
	Rene Pierre	119.5x69	17,8	20	11
Benlux/Gr	Soccer 2000	116.x69	16,0	19	14,5
	Jupiter	117x68	16,0	19	11,2
	Topper 2000	111x65	16,4	18	15,4
Spanish	Biufca	134x75	n/a	25	28
American	Tornado	120x68.5	16,2	20,5	27
	Sivissidis	119x68.5	18,5	20,5	27

To make a robot that plays foosball, first should think about how human players, play this game and what kind of rules are applied. In pro table football tournaments, there are regulations and from one tournament to another, the rules may vary but based on the Foosball Soccer web page (Foosball Soccer 2021) there are some common regulations in most table foosball games that are applicable to the semi-automated foosball tables. Here briefly mentioned 5 basic rules which should consider them in designing a semi-automated foosball table.

1. The team who scored the last goal serves the next ball and for the beginning of the game, flipping a coin determine who put the ball.
2. Spinning rods is illegal. A spin is 360° rotation of a rod.
3. No jarring. It is not allowed to lift the table or slam anything plus rods against foosball table in attempt to distract other player or change the ball position/moving direction. In such conditions, the game should stop.
4. Dead ball rule is when the ball stops in a place where none of the teams can kick it. In a dead ball situation, the ball must be picked up and the team who

served the last ball will serve it again. The same rule is for when the ball goes out of the table area and comes back to it again.
5. Time limits. This rule is to avoid a player holding ball for long time. The time limitations are maximum 15 seconds for Goalkeeper and 3-man rod and 10 seconds for 5-man rod.

It is possible to read more details about foosball rules in the official website. (Foosball Soccer 2021.)

2.2 Users requirements

Foosball robot is not cheap and there are many foosball tables in use and production. Tables have different sizes and numbers of rods per opponent. One of the important points of such systems is the ability to apply them to different tables with the least of changes. This useful point makes its use wider than constantly-attached systems and more on-demand for users.

2.2.1 User’s friendly

Easy to use: Users with different skills may try to use this system. It should be easy for all types of users to use that.

Easily attachable and detachable: There is always this possibility that people want to play against human players. In designing the structures, should consider this ability too.

Financial expenses: It is possible to use very high quality and expensive components in this project to get better results but on the other side, it raises the costs. Using reasonable components and having affordable cost is another thing that should consider in making a user’s friendly system.

Noise: There are many moving mechanical parts in this system. Highly noisy device bothers users thus should consider this factor in planning and doing the project.

Adjustable for different human players: There are many foosball players with different levels of playing skills. In making a foosball player robot, it is important to make the system adjustable for different levels of playing (Hard, medium, and beginners).

Space occupying: Each normal foosball table takes about $1m^3$ space. It is reasonable that the component of the robot part occupies the least possible space or designing the automatic part with folding capability.

Availability of spare parts in markets: As this system has many mechanical and electrical parts, failure or malfunction of components is always possible. It is easier for repairing if spare parts are easily available on markets.

Updating: Ability to update the program and components helps improving the game compatibility with users demand and fixing errors and malfunctions of devices.

User’s safety: Having fast-moving components and electric devices in a system makes it a significant source of danger. This is very important that the system does not hurt or even put any danger for the users or other people and devices around.

2.2.2 Safety

As mentioned before, there are several fast-moving components and electric devices in this project, besides the user’s safety, have to provide safety for the whole system too. There are some main situations that may harm the semi-automatic foosball table:

- Actuators have fast translational and rotational moves. This may vibrate the structure of the table too much and harm it after a short or long time.
- The heat made by friction between mechanical parts or in the electric devices.
- Malfunction of a device might make them out of control. It can even be loosened some screws, programming errors, or a sensor malfunction.

- Opponents' dangerous acts like putting hands in the game area or trying to change the position of the table or devices during the game.

2.3 System and components requirements

Designing a robot to play foosball versus humans requires knowledge about systems engineering, control systems, IT, and real-time processing. Tracking the ball, foosmen, and having suitable reactions needs sensing and intelligence. Another additional requirement would be machine learning to perform a strategic game play in real-time interaction (Figure 2).

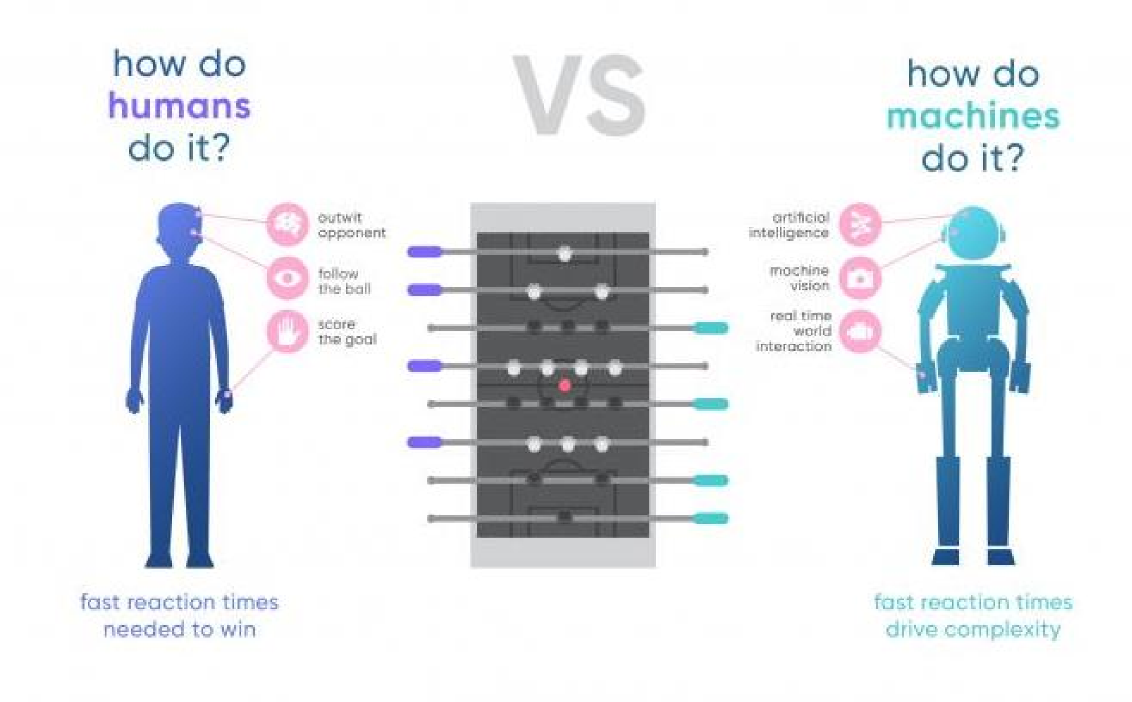


FIGURE 2. Robot vs human in semi-automatic foosball (Cambridge Consultants)

2.3.1 Requirements for motion control

To know what components and devices we need for the project, it is necessary to know the maximum required velocity, torque, and reaction time of moving rods in a normal foosball game. To achieve more standard statistics, a search on the internet and checking foosball tournaments is very useful. Table 2 shows general data about these required statistics. (Stoltenborg 2008, 5-7.)

TABLE 2. Requirements for actuators moving the rods (Stoltenberg 2008, 5-7; Guenat et al. 2012, 3)

the ball velocity(max)	10-12 m/s
rod's angular velocity	314 rad/s
rod's angular acceleration	3140 rad/s2
rod's lateral velocity	4,5 m/s
Lateral accuracy	±3mm
Angular accuracy	8°

The other requirement is the maximum distance each rod can move or in other words, it is necessary to know the maximum lateral motion that actuators should provide for each rod. Figure 3 shows the measured maximum lateral movement for each rod and the distance between foosmen for the table in TAMK.

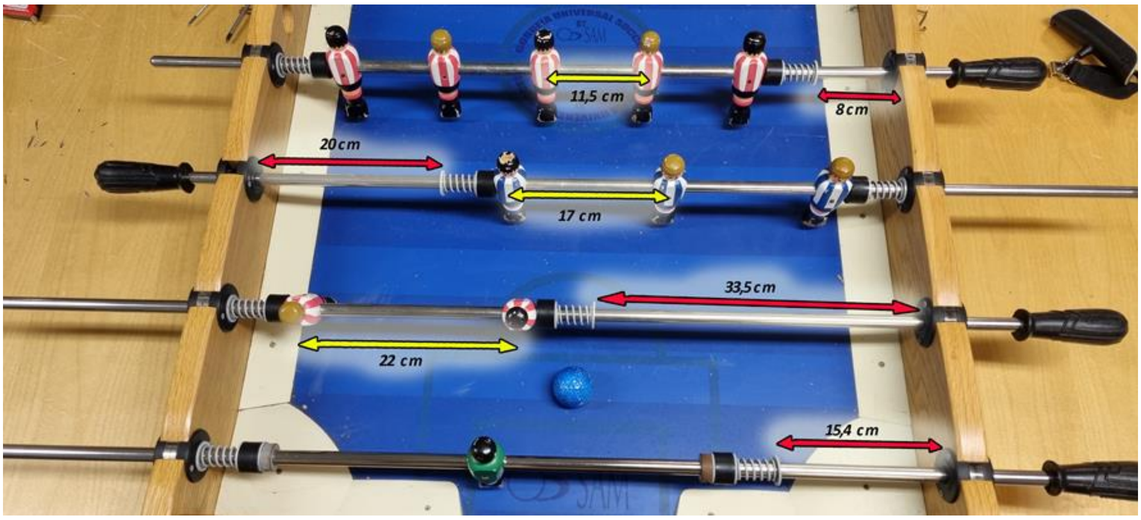


FIGURE 3. Measured the maximum lateral movement of each rod

Linear motion: As the Table 2 shows, the ball's velocity is about $\mathbf{v}$=12m/s (at almost the highest speed). Considering the distances between two adjacent bars is about s=15cm, then by using equation (1), the passing time from a bar to the next one in a straight shoot is about 12ms.

$$t = \frac{v}{s} \tag{1}$$

The reaction time should be about half of this time because the camera should check at least two points of the ball passage to determine the direction.

At the other side, after intercept the ball, the rods should have enough lateral move that the nearest puppet reaches the ball on time. It means the time for reaction is less than 12ms and depends on the processing unit, reaction time of motor and speed of the rod's moves. To have a good estimation, in searches, the time for half of the distance between the two adjacent rods considered for processing time and command to the actuator and the other half for the rod's move to reach the ball. It means 6ms for the processing and command and 6ms left for the rod to catch the ball by the nearest puppet. (Guenat et al. 2012, 11.)

Now we know that the maximum time for the puppet to catch a ball (as a defendant) is 6ms. When a puppet needs to move the maximum distance to reach the ball, then the necessary speed for lateral move will be:

$$v_{rod} = \frac{s_{rod}}{0.5t} = \frac{20\ cm}{6ms} \approx 34m/s$$

Where $\boldsymbol{v_{rod}}$ is the rod's velocity and S_{rod} is the distance.

The foosball robot should be at the level of a good human player. It means the ball speed and puppet's reaction should be close to a skilled player.

In a real game, the lateral movement of rods does not have a constant speed. According to some searches, in a straight movement of the ball, if we suppose that the positive constant acceleration happens in half of this distance, the maximal lateral rod speed should be 3,5 m/s and required acceleration to reach this maximal velocity would be 35 m/s^2. (Guenat et al. 2012, 11.)

Rotational motion: The angular move of rods (and puppets) is the other important part of the measurement. The first thing is that in some tournaments it is illegal to spin the rod more than 360° and as shown in Figure 4, the maximum rotation ranges a foosball robot might need is between -90° - +90°.

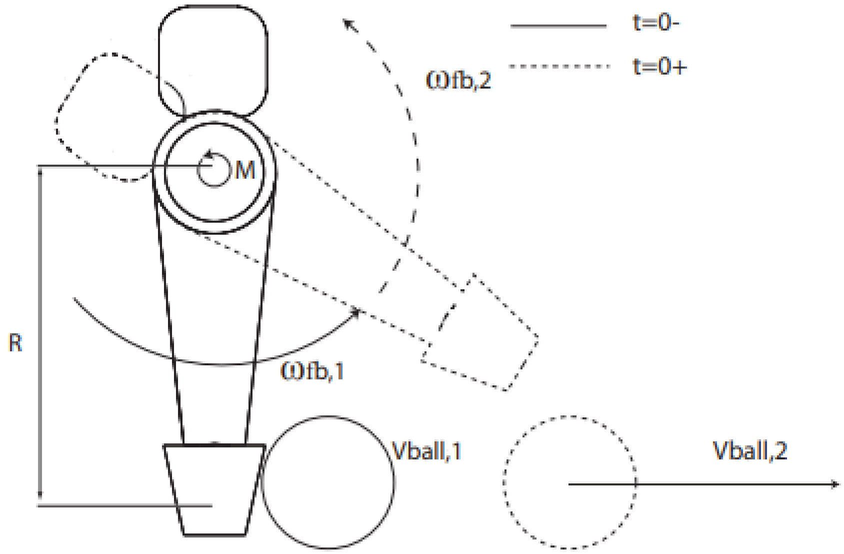


FIGURE 4. Angular motion and velocity of the puppet (Stoltenberg 2008, 9)

In lateral move, as shown in Figure 5, considering the distance between the ball and goal is about 230mm, every 0,5° mistake makes about 2,9mm error.

Error = *S. tan(θ_e)* = 330mm.tan (0,5°) = 2.9mm

Where θ_e is the angular error and *S* is the distance.

With 2,9mm error it is still possible that the ball goes toward the goal. When the maximum error in the destination is 2,9 mm, then the error of the puppet positioning behind the ball should be maximum:

$\text{Error}_{\text{puppet}} = \frac{0.5}{3,5} = \pm 0,14$ mm

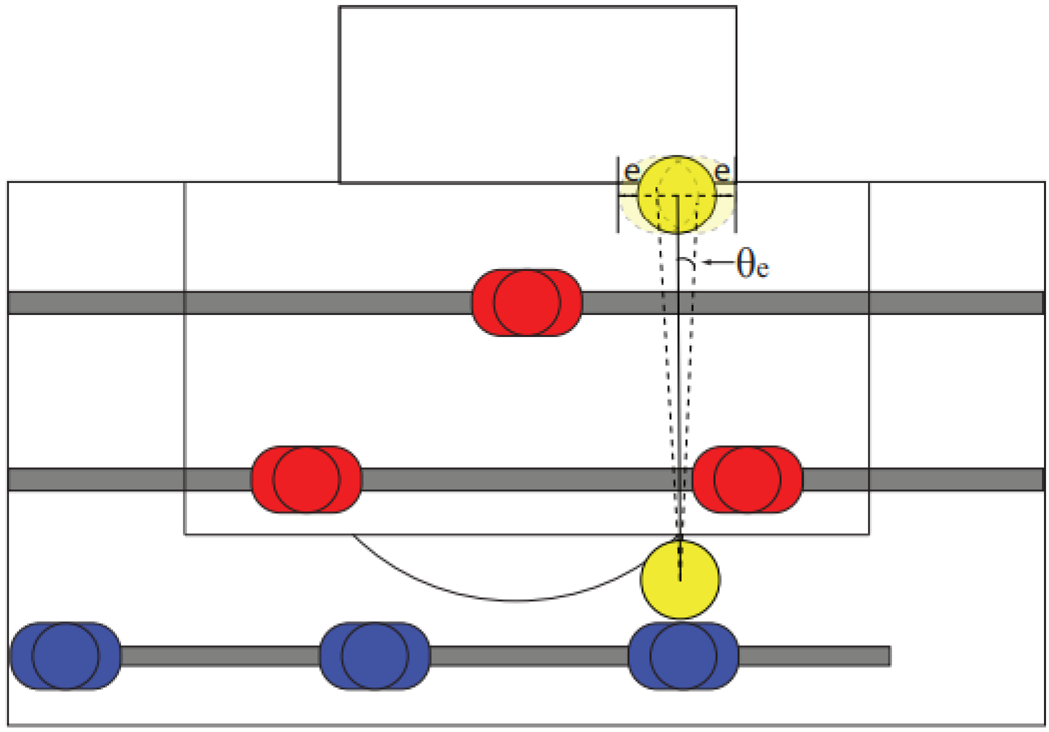


FIGURE 5. Error analyzing (Stoltenborg 2008, 13)

Note! The ±0,14 mm relates to deviation of hitting point from central axis of the ball.

Angular accuracy is less sensitive to the puppet angular position. Figure 6 shows how deviation from 0° affects the shooting condition. Based on some research, if the puppet hits the ball at the θ_e=8°, then the ball gives a loss in forwarding speed of 1 percent. (Stoltenborg 2008, 13)

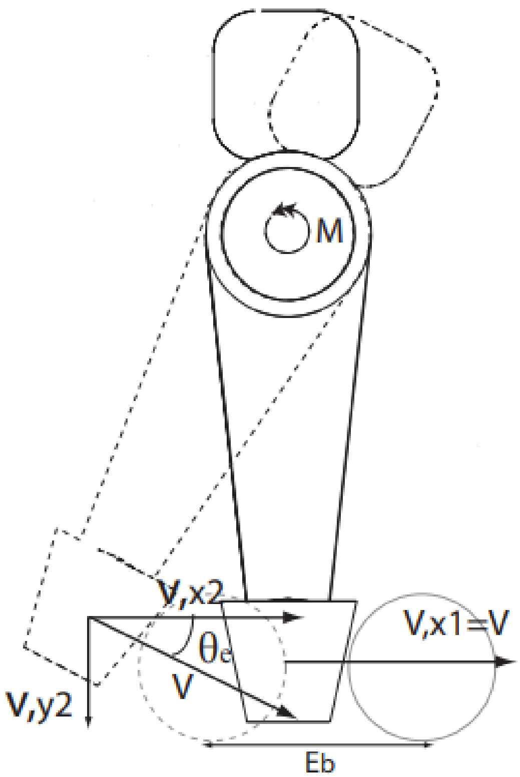


FIGURE 6. Angular velocity of the puppet analyzing (Stoltenborg 2008, 14)

2.3.2 Requirements for tracking

Tracking an object means detecting its position. By tracking the position regularly it is possible to detect the movement direction and also the speed. Tracking is one of the most important part of foosball robot. It consists both tracking the ball and also tracking foosmen.

Requirements for tracking puppet’s position

When the robot wants to play the game, it is important to detect where are its own foosmen and also the opponent’s players. Detecting foosmen position accurately helps the system to choose the best option between own puppets to catch the ball and also accurately kick the ball toward the opponent's goal. In most of the foosball tables, the foosmen feet has normally 16mm in width. In the best situation, foosman catches the ball in the centre of the feet. As shown in Figure 7, the puppet’s legs width is also important in the accuracy of a lateral movement and shoot. From a puppet’s view the range for an accurate shoot is ±8mm (in this case for puppet with 16mm leg's width). In some studies, they consider this error is ±3mm to make more accurate output. (Stoltenborg 2008. 13.)

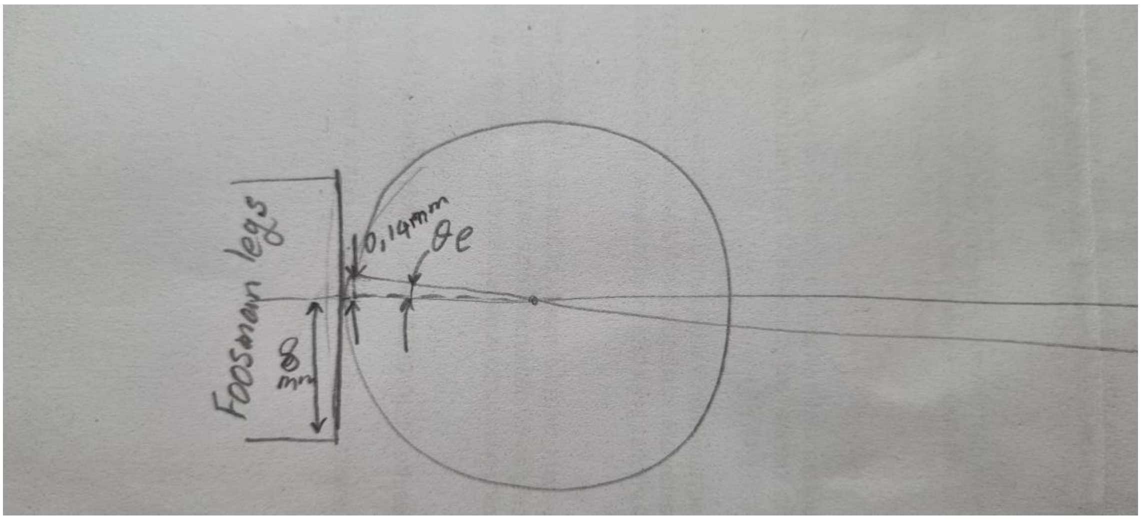


FIGURE 7. Angular error analyzing.

Requirements for tracking the ball position

The ball moves fast. Sometimes it goes under foosmen and rods and almost disappears from sight. The first objective for tracking the ball is that the ball should be under detection of the tracking device or the tracking device should detect it quickly after appearing. The other objective relates to the direction and velocity of the ball. The normal velocity of the ball is about 4,5m/s and sometimes the maximum velocity reaches 10m/s or even 12m/s (Guenat et al. 2012, 3). In most of the studied semi-automated foosball table projects, detection of the position of the ball and the moving direction should happen before the ball reaches half of the distance between the two adjacent rods (Guenat et al. 2012, 11). Considering the distance between adjacent rod's axes is about 15cm, then the ball position should be tracked on the kicking time and before it travels 7,5cm from kicking. By tracking the two positions of the ball in a specified time, it is possible to calculate the direction and speed of the ball and determine which puppet has the best situation to do the suitable reaction.

In the case of 4,5m/s velocity of the ball, the maximum time for tracking the ball after kicking before it reaches half distance to the next rod is:

$$t = \frac{d}{\boldsymbol{v}} = \frac{75mm}{4500mm/s} \approx 16ms$$

t : is the time

d : is half distance between two adjacent rods

$\boldsymbol{v}$ *: normal velocity of the ball*

The tracking system should be able to track the ball every 16ms at the worst situation and if we consider the 12m/s velocity of the ball, the time between two continuous positionings should be a maximum of 6ms.

2.3.3 Requirements for mechanical design

Mechanical design consists of selecting suitable components and designing how to assemble these components together to have the desired result (Figure 8). There are some important factors to consider in mechanical design in this project:

- Should not bother other players
- Fast and accurate enough for playing
- Applicable to different tables is a positive point
- Should be possible to detach from the table in case of human vs human playing
- Safety
- Adjustable playing level for different player’s level
- Long-lasting components
- Not harming the table construction

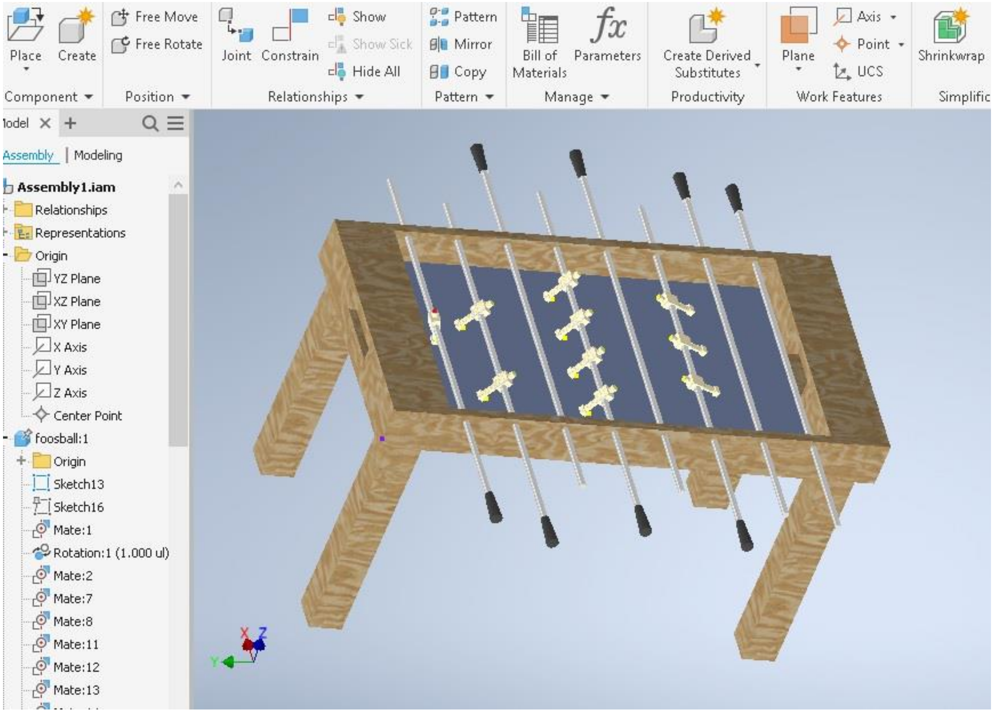


FIGURE 8. Designing the the table by Inventor software.

2.3.4 Requirements for moving rods

To reach the desired mechanical design, first, it is necessary to calculate the required factors that are necessary for selecting suitable actuators and structure components.

In this project, actuators should do rotational moves to kick the ball and lateral moves to follow it in the playfield.

2.3.5 Requirements for control the system

Software and coding work as the brain for the semi-automated foosball table. Sensors and the tracking system are input sources for the software. The algorithm should analyze received data, process them and send the suitable output to the mechanical devices. Besides the accuracy and volume of received data, the appropriate processing and speed of the process are significant factors in the system's functionality. In fact, even with the best design, used components, and tracking system, if the program does not work correctly, the system may face failure or latency. To reach the goal of suitable programming in a semi-automated foosball table there are some common factors that should consider them in coding:

- Determining the current position of the ball and foosmen
- Calculating speed and direction of the ball
- Determining the best foosman to catch the ball
- Safety of the system and users
- Ignoring unnecessary data processing to avoid the system latency
- Removing accumulated unnecessary data from the temporary memory to have free space for new data receiving and analyzing.

3 SOLUTIONS

3.1 Solutions for tracking foosmen

3.1.1 Detecting positions by programming

In this method, an algorithm in the programming should define the robot's own puppet's coordination and angular position after any rod's move. To reach this goal, the programmer has to define each puppet with a name (Figure 9). The point of origin as (x=0, y=0) can be anywhere on the table but selecting it at a corner of the playing surface, makes it easier to determine each puppet's coordination based on the origin point. As the game starts, the algorithm calculates and defines new coordination and angular positions. Considering that puppets on the same rod have constant distance from each other and puppets do not have motion in the Y-direction, the algorithm needs to calculate positions only in the X-direction. Depending on the actuator type, the movements of rods are generally in linear proportion to the actuator's moves.

FIGURE 9. Defining the rods and foosmen by names

In this method, if the computer wants to detect the opponent puppets' position, should attach some sensors to the opponent's rods and it might affect the opponent's playing. The other problem happens if the opponent makes point-less additional rod moves. Tracking these pointless motions increases the processing time for the computer and it may cause latency in the system response.

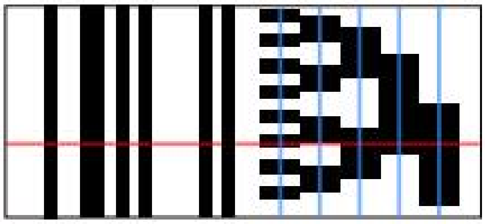
There are some other important disadvantages to this method. Considering the movements often have some small tolerances and probable errors, these errors might accumulate during a game and make positioning detection go wrong. To solve this problem, it is also possible to reset the position of the rods to their initial coordination. Doing reset position returns puppets to the basic positions with origin point and calibrates the position of puppets. But in case, if it is necessary to do one or several reset positions during the game, it might have an unwanted effect on the game result.

3.1.2 Detecting positions by computer vision camera

In the computer vision method, a camera takes digital images or videos from an object and sends them to a computer for analysis. The algorithm in the computer processes the image and derives the information from it based on the program. It is possible to use a computer vision camera to detect each puppet's coordination and angular position.

The advantage of a computer vision camera over blind position detection by programing is that by any image frame from the playing field, the program can analyze and update foosmen positions in real-time. It significantly decreases the positioning mistakes which might happen in other position-defining methods. Later in this report, we will talk more about how to analyze the position of puppets and the ball by computer vision camera system.

In an interesting research at the University of Ljubljana (Bošnak & Klanˇcar, 2020), they used graphic patterns on the rods to track both translational and angular positions of foosmen (Figure 10).



(a) Marker pattern graphics with illustrated L_m line data (red) and bit spaces sampling points (intersection of blue and red lines)

(b) Marker, as installed on the playing rod

FIGURE 10. Using graphic pattern to track pupets (Bošnak & Klanˇcar 2020, 6)

3.1.3 Potentiometers for tracking position of foosmen

The other option to track lateral and angular movements of the rods is using a potentiometer. A potentiometer is a device to divide voltage. It consists of a three-terminal resistor with a sliding or rotating contact that changes and adjusts the output voltage of the resistor (The electricity forum 2021).

By inputing voltage to a potentiometer and attaching its shaft to the actuator (here is a motor), rotation of actuator will rotate the shaft of the potentiometer. Rotating the shaft will change the resistance and it will effect on the output voltage of the potentiometer. As the resistance changes is constantly proportional to the rod's movements (and the motor rotation), it is possible to determine position of foosmen by measuring the output voltage of the potentiometer.

For example, if the potentiometer has a range between 0Ω-1000Ω and the input voltage is 5v, then the output voltage will be between 5mv – 5v. In this case, if the full motion of a rod is 40cm, then every 1mv change in the output voltage indicates 0,08mm movement of the rod.

$$S = \frac{400mm}{5000mv - 5mv} = 0{,}08\ mm/mv$$

S: is the motion of the rod per 1mv changes in output voltage

But in this case, should notice some important points:

- The total motion of the rod should be in the range of the potentiometer's shaft motion. Otherwise, it may destroy the potentiometer or affect the movement of rods.
- It is better to leave some free ranges at the beginning and end of the potentiometer to avoid harming it. For example, if the range of the potentiometer is between 0Ω-1000Ω, and the distance range of the rod is 0mm-400mm, it is better to adjust them the way that for 0mm position of the rod, the potentiometer has 200Ω and for the 400mm, it reaches 800Ω. In this way, if the output voltage shows that the movement of the rod is out of 200Ω-800Ω, then the software realizes there is a problem in the calibration or the mechanical moves and stops the system. In fact, in this way, potentiometers act as both positioning devices and system safety sensors.

Almost the same system can use for the rotational motion of the rods. In this case, the changes in the potentiometer output voltage are constantly proportional to the angular changes of the rods.

3.1.4 Linear positioning sensors

A positioning sensor is a device that can detect the movement of an object and determine the position of the object relative to a reference point. Then the sensor converts these data into signals suitable for processing, transmission, or control (THOMAS A Xometry Co, 2022.). There are several different types of positioning sensors:

Inductive Position Sensors work based on changes in the magnetic field characteristics of the coils which include in the sensor. Figure 11 shows Linear Variable Differential Transformer or LVDT type of inductive position sensor.

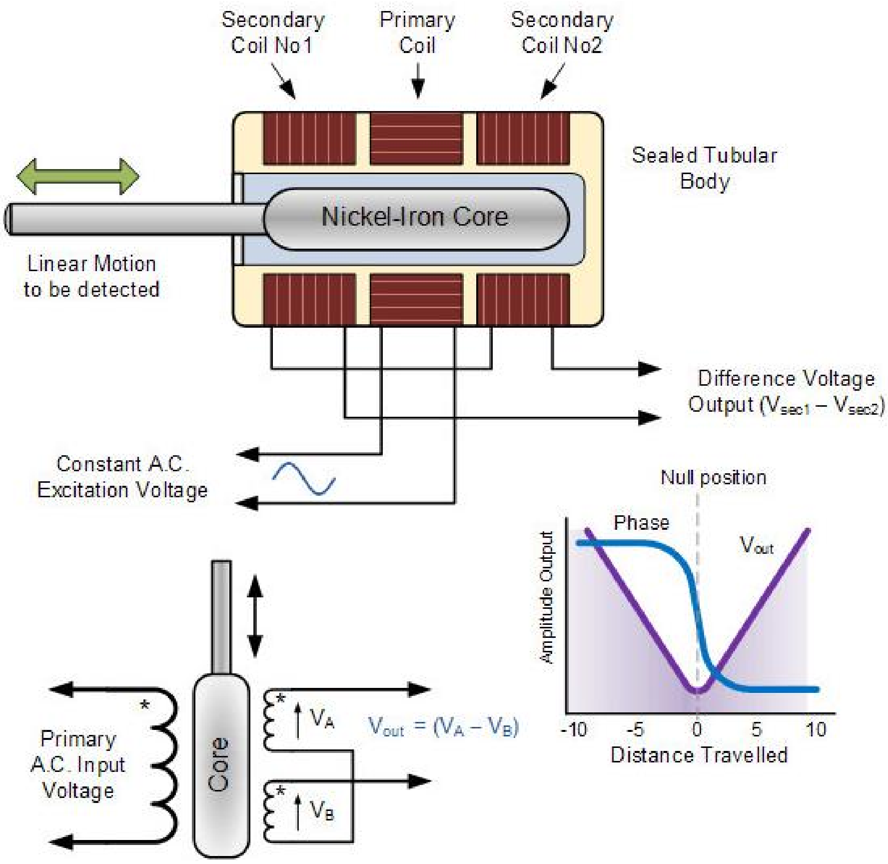


FIGURE 11. LVDT Inductive Positioning Sensor (THOMAS A Xometry Co. 2022)

Hall Effect-Based Magnetic Position Sensors works based on the Hall effect. In this type of sensor, a magnet is placed in the shaft of the sensor. when the object moves, the location of the magnet changes in relation to the Hall element in the positioning sensor. (THOMAS A Xometry Co, 2022.)

According to THOMAS A Xometry Co, (2022), there are some other positioning sensor types beside inductive ones includes:

- Resistance-based Positioning Sensors
- Optical Positioning Sensors
- Eddy Current-Based Positioning Sensors
- Capacitive Positioning Sensors
- Magnetostrictive Positioning Sensors
- Fiber-Optic Positioning Sensors
- Ultrasonic Positioning Sensors

Based on THOMAS A Xometry Company's (2022) guidance on their web page, there are parameters that should consider in selecting the right position sensor for a system. Some main specifications are as follows:

- Measurement range: is the distance range the sensor can measure.
- Resolution: is the value of the smallest position changes that a sensor is able to measure.
- Accuracy: shows how much the measured position is close to the real position of the target object.
- Repeatability: reflects how many times a sensor can measure a position when it repeatedly does measurement over time.
- Linearity: tells how much a sensor has linear behavior

Additional considerations for a linear positioning sensor include:

- The weight and size of the sensor
- Checking if the sensor provides incremental or absolute positioning information
- The operating temperature range of the sensor
- The sensor’s ability to operate correctly in other environmental situations, such as vibration, condensation, contamination, or mechanical shock
- The simplicity of installation and using the sensor
- The cost

Figure 12 is a good example of a linear positioning sensor for use with a pneumatic actuator.

Figure 12. Linear actuator positioning sensor (SMC Corporate 2021)

3.2 Solutions for tracking the ball

Tracking the ball is the other important part of any semi-automatic foosball table. Technology gives us several options to achieve this objective.

- Toch screen
- Bluetooth
- Light sensors
- Computer vision camera

3.2.1 Touch screen

Nowadays, touch screen technology is widely used. A touchscreen technology commonly is a 2-dimensional sensing device. It consista a surface that has the ability to detect touches and by some processing, determine the coordination of touching points (Figure 13). For this simple reason if it is possible to track the ball by touchscreen technology, then it can be an option for this project.

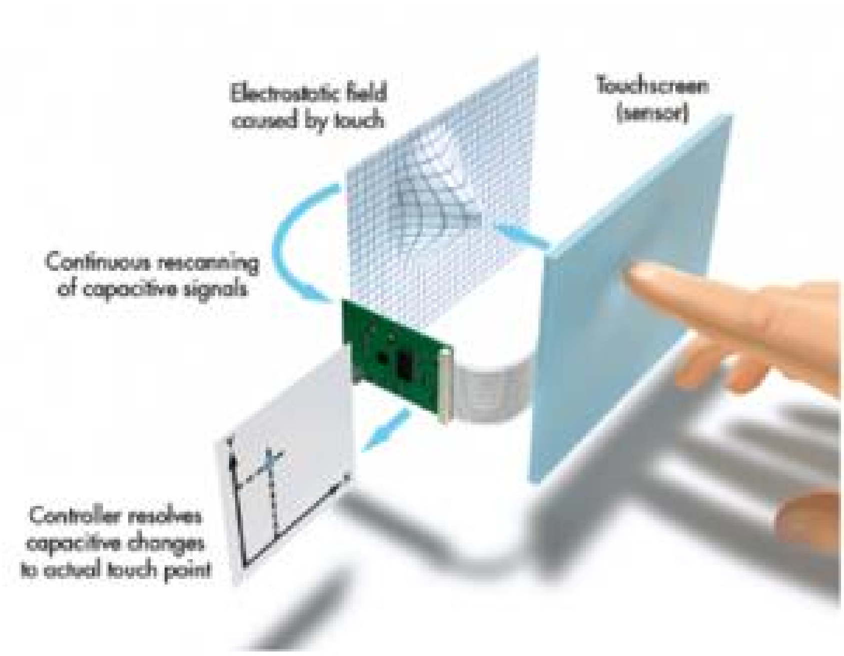


FIGURE 13. How touch screen panel works (Electronics Projects Focus 2021)

There are several touch screen technologies nowadays. Here are four main of them.

- Resistive
- Capacitive
- Surface Acoustical wave (SAW)
- Infrared(IR) touch

Besides these four main touchscreen types, there are also Virtual Touch Screen, Projected capacitive (PCAP), Optical Imaging Touchscreen, Acoustic Pulse Recognition Touchscreen, and Transparent Touch Screen technologies which have their special uses. (Electronics Projects Focus 2021.)

Note! It is not possible to track foosmen position by any touch screen system.

Resistive touchscreen: As the Figure 14 shows, a resistive touchscreen consists a glass panel and a film screen. They covered with a very thin layer of metal. These two layers are separated by a very narrow gap. touching the screen make contact between the two metalic layers and the result is an electric current flow. Changes in the voltage after the touch make it is possible to detect the coordination of the touch point. (Electronics Projects Focus 2021)

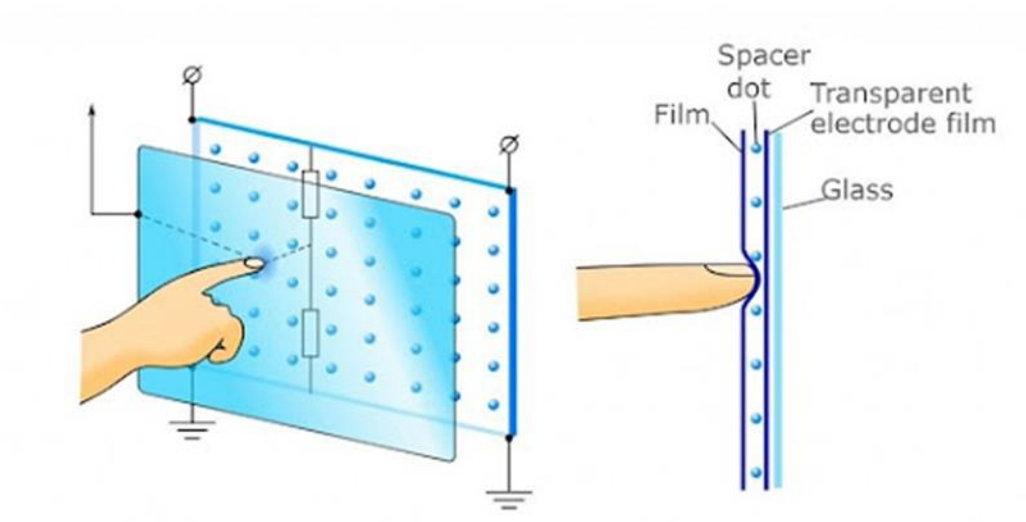


FIGURE 14. Resistive touch screen technology (Electronics Projects Focus 2021)

Resistive touchscreen has several advantages and disadvantages.

Advantages:

- The lowest cost between touchscreen types
- Low power consumption
- Any object (conductive and none-conductive) can activate it
- Moisture, liquids, dust etc, does not effect on that

Disadvantages:

- The outer polyester surface easily get damage by sharp objects

Capacitive touch screen: Capacitive touch screen technology consists of Surface Capacitive and Projected Capacitive(PCAP) types. As Figure 15 shows, a surface capacitive touch screen consists of a glass panel coated with a thin layer of transparent electrode film. This layer is also covered by a protective cover on top. Touching the surface by finger causes changes(normally decrease) in electric charges in the area of the touch. By measuring the charges in capacitances at the four corners of the panel, it is possible to detect the coordination of the touch. (Electronics Projects Focus 2021)

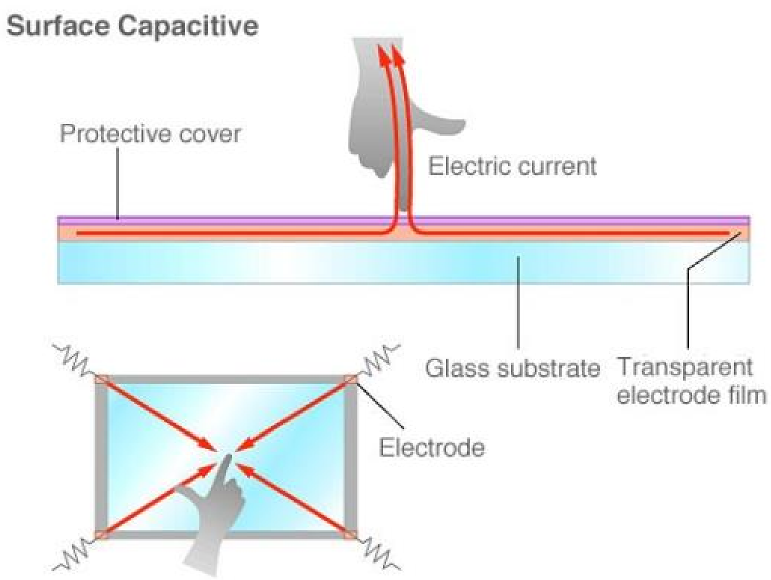


FIGURE 15. Surface Capacitive touch screen technology (Electronics Projects Focus 2021)

In Projected Capacitive touch screen technology or PCAP, the conductive layer is in form of a horizontal and vertical grid (Figure 16). When a human finger is close enough to the surface, it causes a change in an electric field. The controller senses this change and can detect the coordination of that.
Capacitive touchscreen advantages and disadvantages are:

Advantages:

- More resistant to surface scratches than resistive touch screen
- Good image clearity
- Good resistance to moisture, liquids, dust etc,

Disadvantages:

- It requires changes in electric charges to activate. That means it is necessary to use a conductive material attached to different static charge levels (preferably earth) to activate the capacitive touch screen.
- It is sensitive to EMI/RFI (Electromagnetic Interference/Radio-Frequency Interference)

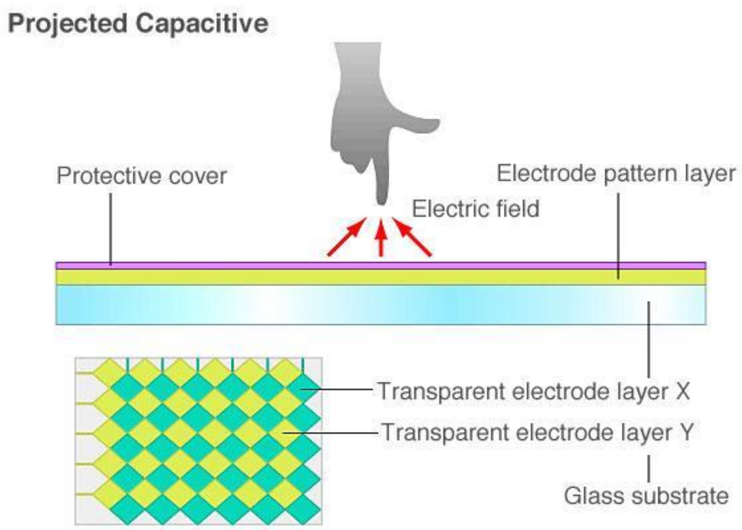


FIGURE 16. Projected Capacitive touch screen technology (Electronics Projects Focus 2021)

Projected Capacitive touch screen advantages and disadvantages are almost the same as surface capacitive ones but there is an extra advantage for the projected ones which enables them to use thin surgical or cotton gloves to activate them.(Electronics Projects Focus 2021)

Surface Acoustical wave (SAW) touchscreen: This touch screen type contains two ultrasonic transducers placed along both the Y-axis and X-axis of the panel along with some reflectors. Transducers create ultrasonic waves on the surface of the panel. Touching the screen absorbs a portion of the amplitude of the waves and receiving units detect the touch as a drop in the ultrasonic wave amplitude occurs (Figure 17).

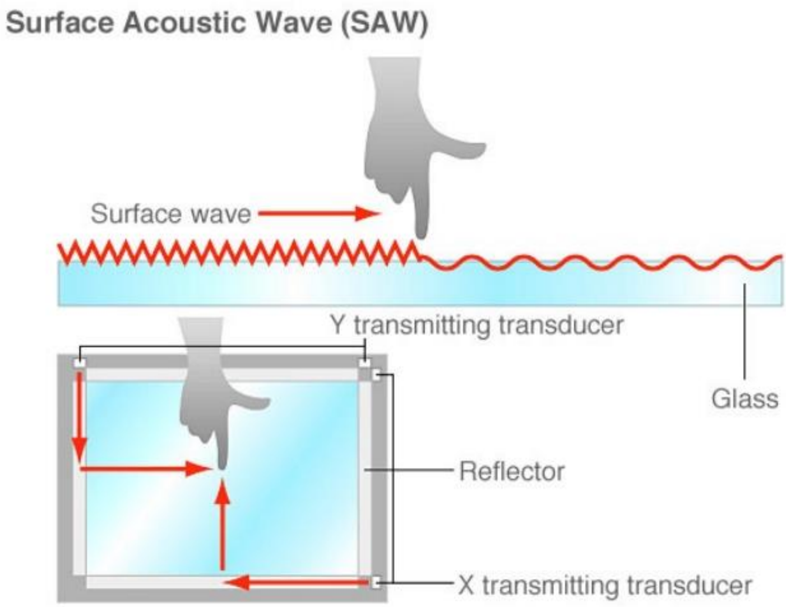


FIGURE 17. Surface Acoustical wave (SAW) touchscreen technology (Electronics Projects Focus 2021)

Like other touch screen technologies, there are some advantages and disadvantages in SAW touchscreen:

Advantages:

- Better scratch resistance than resistive and capacitive touch screens
- Durable construction

Disadvantages:

- Hard items like pen, credit cards etc, does not activate them
- Requires periodic calibration[7]
- Water droplets may cause false signals.

Infrared(IR) touchscreen: In infrared touch screen technology, two arrays of IR emitters in X and Y axises make a plaid grid of infrared beams. In front of any emitters, at the other side of the panel edge, there is a light detector to receive the beam emitted by IR emitter. Any touching the screen makes an interupt in receiving the beam by front light detector and this way it is posible to locate the touch X and Y coordination (Figure 18).

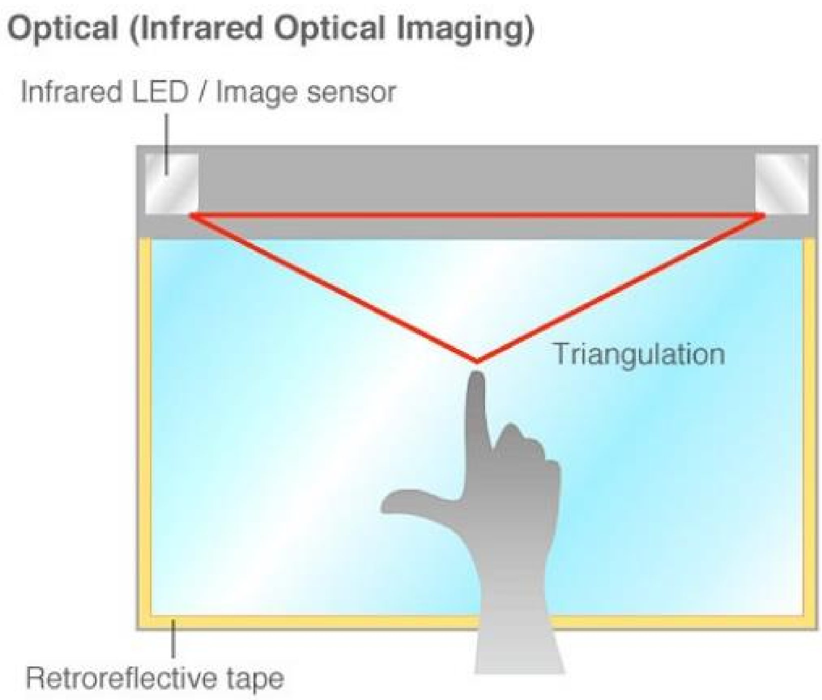


Figure 18. Infrared(IR) touchscreen technology (Electronics Projects Focus 2021)

Infrared touchscreen has some advantages and disadvantages.

Advantages:

- Unlimited touch life
- Sensitive to all objects(except transparent ones)
- Surface scratch does not effect on it function

Disadvantages:

- Ambient light may activate some detectors
- Sensitive to water, snow, rain
- Grease, oil, dust buildup on the panel may block the emitter's light and send wrong signals.
- Higher cost in comparison with other touch screen technologies

Touchscreen comparison

In the case of using a touch screen panel in a semi-automatic foosball table, the touch screen panel will act as the surface of the foosball table. The ball moves along it and the touch screen should track it in real-time during the game. Considering the ball is so light (25-35g), from none-conductive materials and it is not possible to make the earth-connection for that during the game, resistive and capacitive touch screens are not useful here.
The other options are SAW and Infrared touch screens. As mentioned above, some hard materials do not activate the SAW touch screen, and also it requires periodic calibration. Thus in between these touch screen technologies, infrared one seems to be the best option for tracking the ball in Semi-Automatic Foosball Table. Below is the comparison table of different touch screen technologies (Table 3).

TABLE 3. Touch screen technologies comparison (Electronics Projects Focus 2021)

TOUCH SCREEN COMPARISON

	5-Wire Resistive	Capacitive (surface)	Projected Capacitive	SAW	Infrared
Transmissivity/ Clarity	Good 75-85%	Very Good 90-98%	Very Good 90-98%	Very Good 90-98%	Best 95-100%
Sensor Substrate	Polyester top sheet. Glass substrate w/ ITO coating	Glass w/ ITO coating	Glass w/ ITO coating	Glass w/ ITO coating	Any Substrate
Activate With Any Object	Best Any object	Poor Finger or capacitive stylus	Good Finger, capacitive stylus, surgical glove	Good Finger, gloved hand, soft/ pliable stylus	Very Good Most objects
High Sensitivity (Light Touch)	Good	Very Good	Very Good	Very Good	Best
Stable Calibration	Very Good	Good	Very Good	Very Good	Best
High Accuracy & Repeatability	Very Good	Good	Best	Very Good	Very Good
Scratch Resistance	Poor	Very Good	Best	Best	Best
Not Sensitive to Humidity	Best	Best	Best	Very Good	Very Good
Not Sensitive to Rain/Snow	Best	Average	Very Good	Average	Best
Not Sensitive to Cleaning Chemicals	Very Good	Very Good	Best	Very Good	Best
Not Sensitive to Surface Contaminants	Best	Good	Very Good	Average	Good
Not Sensitive to EMI/RFI	Best	Average	Average	Very Good	Best
Not Sensitive to Vibration	Best	Very Good	Very Good	Very Good	Best
Not Sensitive to Ambient Light	Best	Best	Best	Best	Very Good

3.2.2 Bluetooth ball

Bluetooth uses 2,4GHz band to provide a wireless connection. It is a low-cost and low-energy device for short distances (0-10m) safe and secure connection.

The idea of using Bluetooth technology to track the ball sounds good. In theory, we can imagine using a Bluetooth device in the ball and three antennas to receive the signals from the ball. A computer can process the time differences between arrived signals and calculate the position of the ball at that moment. But in real-

world and real-time tracking we have several difficulties which make this idea almost impossible. (Scientific American 2021.)
The accuracy of the ball positioning should have a maximum of 3mm error. by considering the wave speed ($3x10^{12}$ mm/s), and the area of playing which is about 120cmx70cm, the time differences between the signals each antenna receive are too small.

For example, if the distance between antenna 1 and the ball is 9000mm and from the second antenna (antenna 2) is 300mm then

$$t_1 = \frac{9000mm}{3*10^{12}mm/s} = 3 * 10^{-9}\text{s}$$

$$t_2 = \frac{300mm}{3*10^{12}mm/s} = 0.1 * 10^{-9}\text{s}$$

In one of the best situations, the time difference between the received signal by antenna1 and antenna2 is very short.

$$\Delta t = t_1 - t_2 = 2{,}9 * 10^{-9}s$$

Besides the necessity of very fast data processing, there are several other disadvantages in using Bluetooth technology for tracking the ball which make us ignore it for this project.

First, to define the accurate position of the ball, the source of the Bluetooth wave should place in the center of the ball. Considering the required real-time positioning accuracy tolerance in this project is about 3mm, then if the source of the wave is a bit at the side of the ball, by rotation at the same coordination, it might give ±17,5mm error in X or Y directions which increases the total error of the system (Figure 19).

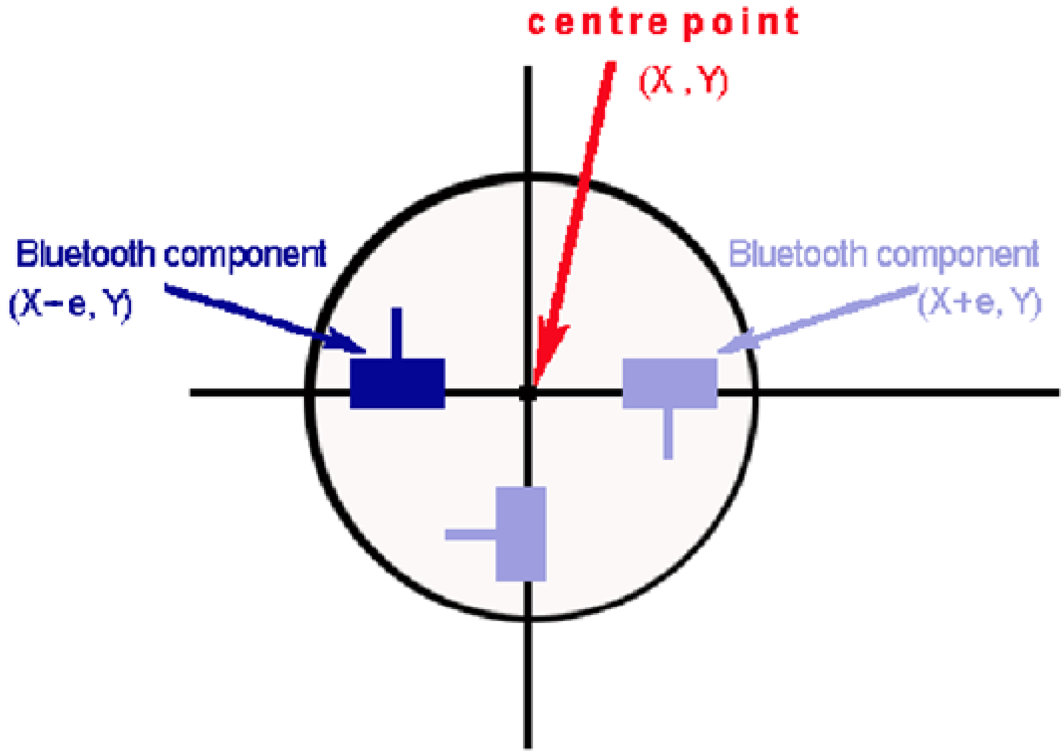


FIGURE 19. Bluetooth ball and diffeerent positions of the bluetooth device

The second case which should consider in bluetooth ball is uniform scattering of its mass. If one part of the ball is heavier or lighter than other parts, it will effect on its movement direction significantly and it might move in curves even after a straight shoot.

The third disadvantage of the Bluetooth ball relates to necessity of using and changing the energy source (here is the battery).

The fourth disadvantage is malfunction of the Bluetooth device because of kicking and hitting during the game. In case of interfering with other Bluetooth devices might make errors in detecting the right coordination.

3.2.3 Light sensors

In similar to infrared touch screen technology, it is possible to use rows of light emitters and reflectors(or light detectors) in the X and Y grid to detect the ball position on the surface of the foosball table. Installing light emitters and sensors manually has some advantages and disadvantages in comparison with infrared touch screen one:

Advantages:

- Considering the ball has over 30mm diameter, it is possible to install the light emitters and detectors about 15mm above the surface and avoid disturbance of the dirt on the surface.
- The distance between the two adjacent emitters can be flexible between 5-30mm.
- Just by adding or decreasing the emitters and detectors it easily fits with any table size.
- Cheaper in comparison with the whole touch screen panel in markets.
- In case of malfunction of one or some parts, no need to change the whole tracking system.

Disadvantages:

- Requires programming to track the ball.
- There will be limitations in how close the two adjacent emitters can be. It affects the accuracy of tracking.

3.2.4 Computer vision camera

Likewise using a computer vision camera to track the foosmen, it is possible to use it for tracking the ball also.

Using a camera for tracking the ball is a little bit more challenging than tracking the puppets. That's because if the camera takes images from above the table, at some points, the ball hides under the foosmen and makes it hard for the camera to detect the position of the ball. To solve this problem it is possible to use the camera from the bottom of the table. Based on some researches we analyze these two options for the camera positions.

Camera from above

This is a very common way to track objects by machine vision from above. In this method, the camera mimics a human eye, detecting the ball and following it till it is visible. In this process, the ball defines by its shape, color or size, or all of them. There are several important considerations in using a computer vision camera from above the table:

- In the case of using color recognition for the ball, it is important that the ball had different colors than other parts of the table. For the same reason, it is better to use simply one-color ball.
- Using a monochrome camera helps to do faster processing of an image but is not recommended if the camera should detect components by color differences. For example, maybe the ball is red, and the surface is blue but in the monochrome image, they have the same darkness/brightness for the camera. The other difficult situation might be Shining surfaces that a monochrome camera cannot help to detect a curved shining object correctly (Figure 20).

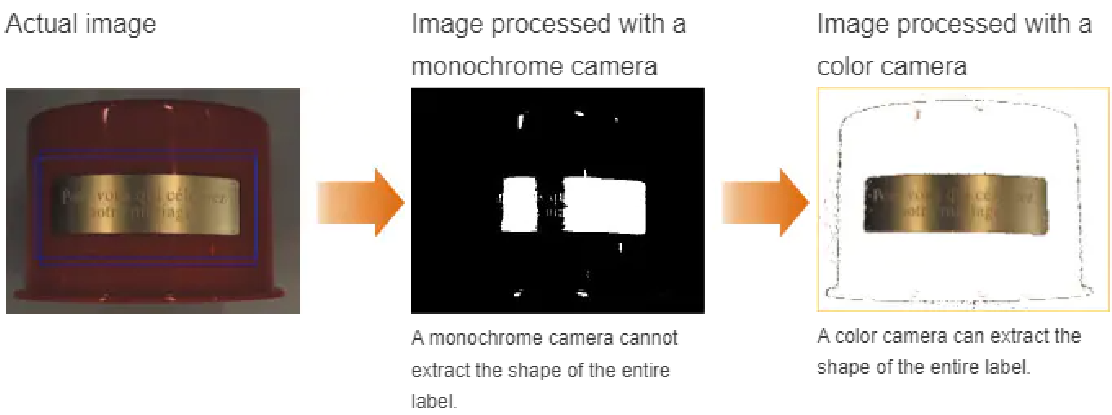


FIGURE 20. Problem with using monochrome camera (Machine Vision Basics 2021)

- Glossy curved surfaces reflect the lights. These reflections may affect on recognition of the color, size, or shape by the camera. Thus, it is better to use opaque balls to avoid this problem in intensity.
- It is possible that some other parts of the foosball table have the same shape as the ball (like head of puppets from top), that's why defining the diameter of the ball is important for tracking.
- Calibration of the camera vision is the other important case. The Figure 21 and 22 show how none-calibrated camera can affect on the tracking the objects. The calibration also consists of contrast, brightness, gain, resolution etc.

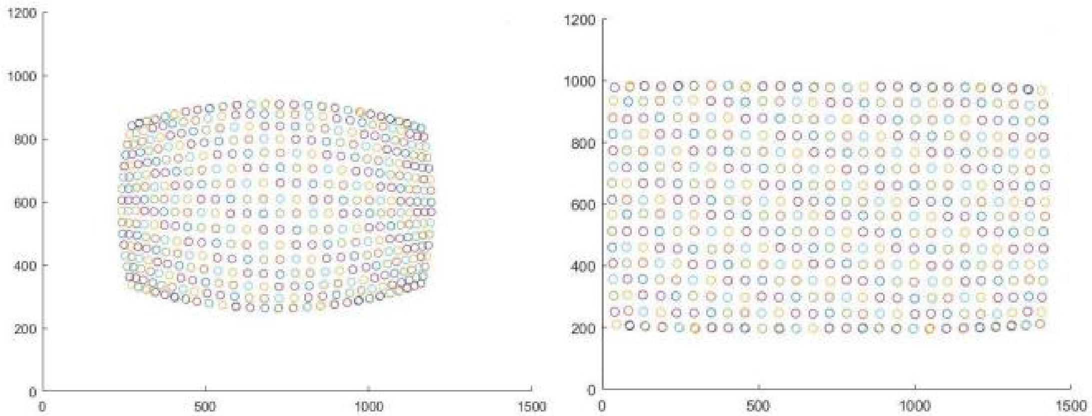


FIGURE 21. Uncalibrated (left) and calibrated (right) distortion point map (Lues 2018, 61)

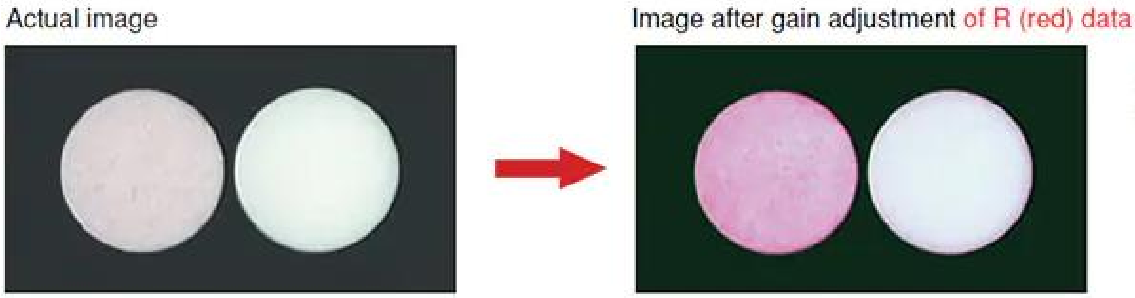


FIGURE 22. Example of gain djustment. The red color shon more vividy and different after adjustment (Machine Vision Basics 2021)

- Reflection of light sources makes blind spots for the camera vision

Camera from bottom

Using vision camera from the bottom of the table requires a transparent table surface. Simply because the camera should be able to detect the ball from behind the surface.

In a thesis at Massey University, they used a camera from the bottom of the table (Lues 2018, 39). As Figure 23 shows, the ball is easily detectable even by the monochromic camera.

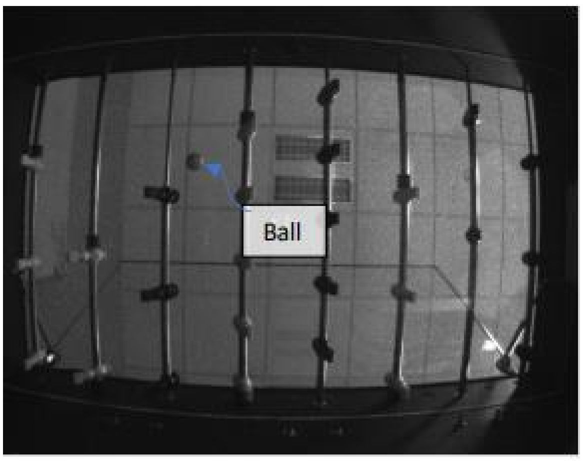


FIGURE 23. Camera view from bottom of the table (Lues 2018, 39)

Advantages of this method are:

- The ball is visible to the camera at every point of the surface
- Tracking by monochrome camera is also possible
- Less disturbances by environmental light reflections

Disadvantages:

- It is not possible foosmen positions in this method
- Any source of light from direct above the table may disturbs the tracking

Requirements of camera

Resolution and frame rate of the camera determines how much data is sent for processing each second during the game.
Resolution is the total amount of pixels captured by a camera in an image. For example, a photo that has 1200 pixels by 1920 pixels, means the resolution is:

(1200 pixels) x (1920 pixels)= 2,3 Megapixels

The camera should cover the whole playing area which is 117cm x 74cm. Using the right resolution and frame rate decreases the data flow to the processors and helps to have more fast processing and reactions.

Ball segmentation: To track the ball, first should separate it from the environment. The circle shape and diameter are good characteristics to use for this goal. But in some coordinations, the ball is under other foosball table parts, and not easy for the camera to define the ball. The worst situation is when it is under the puppet's body. Figure 24 shows this situation. In this condition cropping the image to Region Of Interest or ROI, helps to remove the excessive image data.(E. Stoltenborg 2008, 4.)

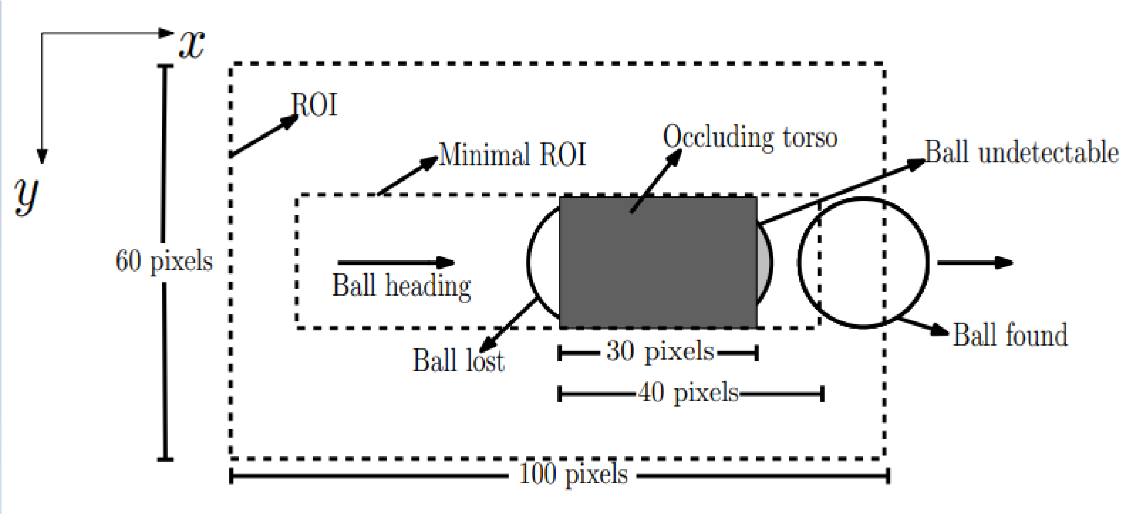


FIGURE 24. Region of interest or ROI (Janssen, De Best & Van de Molengraft 2009, 5)

We can define this occluding torso by a 30x20 rectangle of pixels (Figure 24). The ball of 20 pixels can become completely occluded underthe torso. When the ball is lost, the position of the ROI remains static. Most of the times, the camera needs approximately 1/4th of the diameter of the ball to detect it. Figure 24 shows the worst case, where the ball disappears under a puppet while the ROI stays at the position where the ball is lost. (Janssen, De Best & Van de Molengraft 2009, 5.)

The 40 pixels length allows the ROI to detect the ball as it appears again. The direction of movement might be in the negative X or positive X, then the minimum size for the ROI to detect moves in both directions should be 80 pixels. With the same logic, the minimum ROI size for ROI in the Y direction should be 20 pixels but in have to consider the rod influence in occluding the ball. Thus a good estimate for the ROI in the Y direction should be 60 pixels and 100 pixels in the X direction. Figure 25 shows the ball position and estimate for ROI size. (Janssen, De Best & Van de Molengraft 2009, 5.)

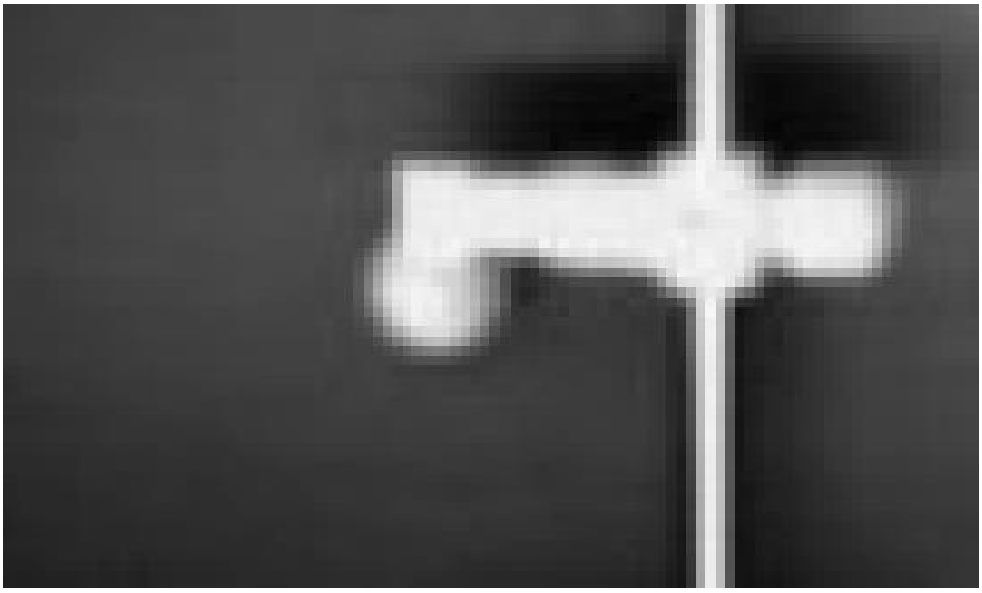


FIGURE 25. Example of 100x60 pixel image quality (Janssen, De Best & Van de Molengraft 2009)

- Minimum required frame rate: After determining the minimum size for ROI, it is possible to calculate the minimum frame rate. Frame rate is the number of images a camera takes in one second in a video. Below is the equation to calculate the frame size. (Janssen, De Best & Van de Molengraft 2009, 6.)

$$FPS_{min} = \frac{V_{max} \cdot P_{res}}{r_{ball} \cdot \frac{1}{2} ROI_x}$$

In this equation:

FPS_{min} : The minimum frame per second

V_{max}: The maximum ball velosity (here is 10m/s)

P_{res}: pixel resolution(here is 584 pixel/m)

r_{ball}: radious of the ball (in pixels)

ROI_x: Length of the ROI in X direction

$$FPS_{min} = \frac{10\frac{m}{s}.584\frac{pixel}{m}}{10pixel.\frac{1}{2}.100pixel} = 97{,}3\ Hz \approx 100Hz$$

The minimum required frame rate is *97,3 Hz* which can be assumed as *100Hz.*

3.3 Solutions for moving the rods

Rotation of the rods calculations

To calculate the required torque for angular rotation, it is necessary to calculate the puppets' velocity, acceleration, and moment of inertia. In foosball, the puppets should have balance in every angular position. It means if a player turns the front rods 60° backward to remove puppets from the ball's route, they should keep this angular position(Picture 1). It simply means the gravity point of the rod-puppets is so close to the center point of the rod. Therefore it is easier to consider them together as a solid cylindrical shape with the highest mass density close to the center axis. The radius of this cylinder can be approximately half of the distance between the rod's center and the puppet's feet.

PICTURE 1. Puppets keep angular positions

By using the moment of inertia equation for solid cylinder (2), It is possible to calculate the approximate moment of inertia for the rod and puppets system.

$$I = \frac{1}{2} M . R^2 \qquad (2)$$

Where:

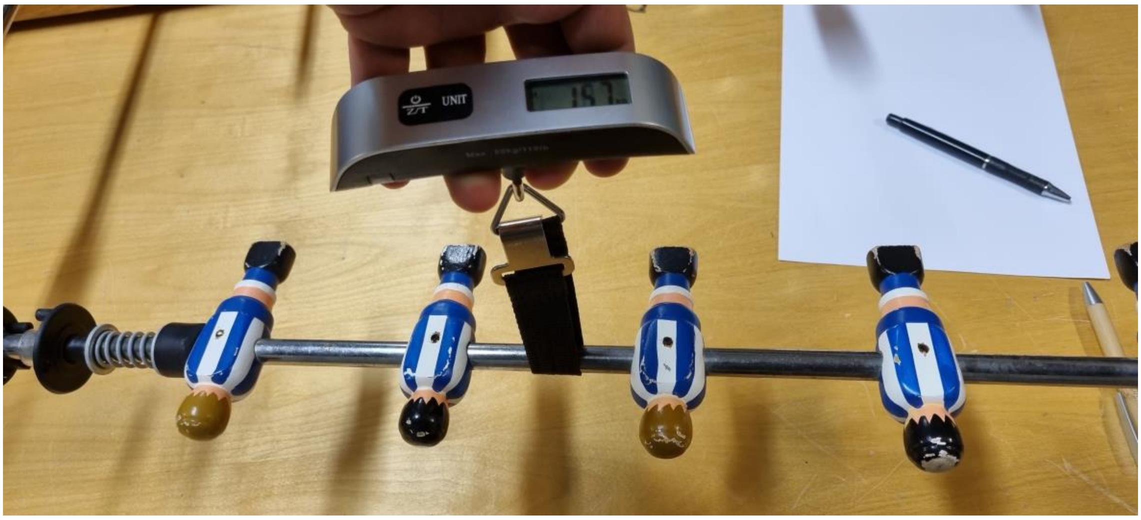
I_r: Inertia of the rod with puppets

M: Total mass of the rod and puppets (Picture 2)

R: Radius of the cylinder (here is about 3cm)

$$I_r = \frac{1}{2}.(1{,}57kg).(0{,}03m)^2 = 7{,}07.10^{-4}kg.m^2$$

Note! Considering each rod has a different number of puppets, the mass of the system is different from one rod to another one and also for different tables. Here the mass of the heaviest rod is measured to have the maximum required inertia value.



PICTURE 2. Measuring the mass of the rod with five puppets.

To reach the desired velocity of the ball, the foosman should kick it with the same velocity at the contact point. We know the puppet starts from the rest (ω_0=0), then it is necessary to calculate acceleration time to reach the desired angular velocity at the contact point. At the other side, most of the actuators use gears or pulleys and have to consider gear ratio, efficiency, and inertia in this equations too.

r: puppet's contact radius (7,5cm measured)
V_{ball}: velocity of the foosball (10m/s)
V_P: velocity of the puppet's feet at the contact point
ω: Angular velocity of the puppet
α: Angular acceleration of puppet
θ: angular displacement (Here from -60° to +60° or totally 120°)
m_{ball}: mass of foosball (here 20,5 g)
I_r: Rod and foosmen inertia (7,07.10^{-4} kg.m^2 calculated)

F: Force on the ball during impact

$I_{tot} = I_r = 7{,}07.10^{-4} kg.m^2$

$V_{ball}=V_p= 10\ m/s$

$$\omega = \frac{V_p}{r} = \frac{10m/s}{.075m} = 133{,}4\,rad/s$$

$\omega^2 = \omega_0^2 + 2\alpha\theta \quad , \quad \omega_0=0$

$$\alpha = \frac{\omega^2}{2\theta}$$

$t = \frac{\omega}{\alpha} = \frac{\omega}{\omega^2} 2\theta = 0{,}07839\ s \approx 78ms$ (spining time)

$F = m\frac{V_{ball}}{t} = 0{,}020\ kg.\frac{10\ m/s}{0{,}078s} = 2{,}6\ N$ (force on the ball)

$T_{rod} = F.r = 2{,}6N\ .\ 0{,}075\ m = 0{,}195\ N.m \approx 0{,}20\ N.m$

Where:

I_{tot}: The total inertia of the gear and rod together.

T_{rod}: Required torque to shoot the ball referred to the rod.

T_{ball}: Required torque to shoot ball referred to the actuator

Note!

In calculating the required torque for rotational motion, we used the maximum velocity that the ball has in a game($V_{f\text{-}max}$=*10m/s).* The average velocity of the ball is about 4,5 m/s.

Lateral moves of the rods calculations

Since the avarage velocity of the ball is about 4,5 m/s, here we use also the same velocity in the calculations.

V_b: Velocity of the moving ball (here 4,5 m/s)

d: The distance between shooting point from the goal (here is 370mm)

d_{goal}: Width of the goal (here is 200mm)

d_p: Width of the puppet’s feet (here is 20mm)

d_{ball}: Diameter of the ball (here is 34mm)

To calculate the velocity and acceleration of the translation motion, it is necessary to consider some important conditions and factors:
First, the lateral velocity is not constant. We can suppose that the acceleration is done on half of the distance and then the velocity slows down to reach zero velocity at the target point. It means the maximum velocity happens in half of the moving distance. (Guenat et al. 2012, 11.)
Second, As Figure 26 shows, if the robot keeps the goalkeeper in the middle of the own goal, then the worst situation will be the time that the ball goes toward the right (or left) corner of the goal. In this situation, the required distance to prevent the ball from entering the goal is:

$$d_r = \frac{d_{goal}}{2} - \left(\frac{d_p}{2} + \frac{d_{ball}}{2}\right) = 100mm - 10mm - 17mm = 72mm$$

d_r: Is the total distance goalkeeper puppet required to move to prevent the ball (in the worst case).

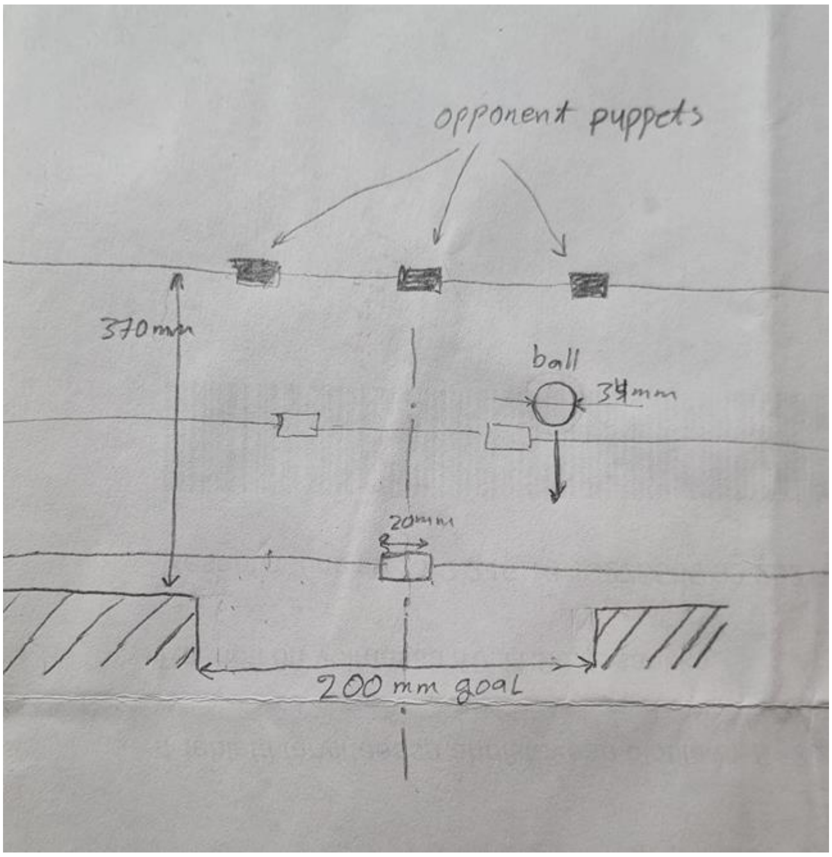


FIGURE 26. One of the worst situations for defending.

$$t = \frac{d}{V_b} = \frac{0{,}370\ m}{4{,}5\ m/s} = 0{,}082s \approx 0{,}08s$$

t: Is the time that the ball reaches the goal from the shooting point

Since the maximum velocity happens in half of d_r, then:

$$t_{half} = \frac{t}{2} = 0{,}04\ s$$

$$\frac{d_r}{2} = d_0 + V_0 t + \frac{1}{2} a t_{half}{}^2$$

$d_r/2$: Is the distance which velocity has the maximum

d_0: Is the beginning point distance from the center. (here is 0 m)

V_0: Is the starting speed at the center. (here is 0 m/s)

$$a = \frac{0{,}072\ m}{(0{,}04\ s)^2} = 45\ m/s^2$$

$$V_{max} = a.t = 45\frac{m}{s^2}\ .0{,}04s = 1{,}8\ m/s$$

a: Required constant velocity from *t=0s* to *t=0,04s*

V_{max}: Maximum velocity (at the half distance)

To calculate the required force, we need to estimate the mass of the lateral moving system which consists of the rod, puppet(s), rotational motion actuator, gears etc. There is also friction which is ignorable.
In research by Gutierrez-Franco et al. (2013), the mass is 3,2 kg and in other one by Guenat et al. (2013), it is 1,5 kg. considering our measurements and calculation results are closer to the project developed by Guenat et al. (2013), here also we use 1,5kg as the total mass of the lateral motion system.

$$F_{rod} = m.a = 1{,}5\ kg\ .45\frac{m}{s^2} = 67{,}5\ N$$

m: The mass of load

a: Acceleration of the rod

Now we have the required force to move the rod with a total of 1,5kg mass with 45m/s^2 acceleration. Some actuators present lateral moves but some others produce rotational motion which is necessary to change their rotational motions into translational to be able to use them for the lateral rod's moves.

3.3.1 Hydraulic system

When high density of power required, hydraulic systems are good options. In this project hydraulic system has several disadvantages which make it ignorable as an option:

- Slow
- Leakage of liquid in some components
- Space limitations
- Components are often heavy

3.3.2 Pneumatic system

Pneumatic systems are faster than hydraulic systems and often more complicated. Pneumatic systems have also some disadvantages which make in unsuitable for an accurate semi-automatic foosball.

- Because of the design of such systems, the acceleration of pistons depends on the shaft position.
- difficulties in controlling the pressure in the pistons make problem in precisely controlling the rod movement.
- lack of air rigidity is an other disadvatage for the required accuracy of the system

On another side, the pneumatic system is cheaper than other systems and quite fast. In a case that accuracy does not matter so much, electro-pneumatic positioning is an alternative to electro-mechanical positioning.

According to Vincent & Bridges (2015), Typical components of an electro-pneumatic positioning system consist of a pneumatic cylinder, electro-pneumatic pressure regulators(ED02), a position controller(EPPC), and a SM6-AL sensor

(Figure 27). This component utilizes direct-acting proportional pressure control to increase the system's accuracy and efficiency.

FIGURE 27.Typical components of an electro-pneumatic positioning system (Vincent & Bridges 2015)

Figure 28 shows the two suitable solutions for the rod's lateral motion. The most common solution for pneumatic projects is a single double effect piston with a spring to help the piston move backward as fast as forward. These systems are designed the way that the acceleration and strength of the piston depend on the position of the stroke and the spring would be used to compensate for this effect.

To solve this problem it is possible to use two single effect pistons. This way, the acceleration would be the same in both forward and backward directions. (Guenat et al. 2012, 3.)

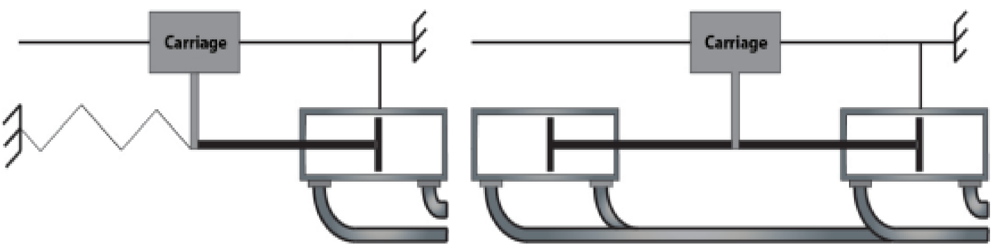


FIGURE 28. One piston and two pistons solutions(Guenat et al. 2012)

Rodless cylinders are the other options (Figure 29). A rodless pneumatic cylinder is a pneumatic actuator that is able to move a load in a linear path using compressed air. A traditional pneumatic cylinder uses a rod to push or pull the piston or the load, but in a rodless one, the load is attached to the side or top of the piston and moving alongside with it. This type of cylinder takes less space than normal ones because it can have the same stroke length but takes smaller space. (Vincent & Bridges 2015.)

FIGURE 29. Rodless pneumatic cylinder (Vincent & Bridges 2015)

For selecting a suitable size of pneumatics cylinder we already have some required parameter:

F: Required force (here is 67,5 N)

V: Required velocity (here is 1,8 m/s)

d: The distance cylinder's strock should move in 0,04s (here is 210mm)

t: The time for 210mm move of the cylinder (here is 0,04s)

$$P_{power} = \frac{F.\ d}{t} = \frac{67{,}5N\ .\ 0{,}210m}{0{,}04\ s} = 354{,}4\ w$$

if we choose a cylinder with a 2cm piston diameter, then:

$$P_{pressure} = \frac{\pi . r^2 .\ P_{power}\ .\ d}{t} = 214875\,\frac{N}{m^2} \approx 2{,}15\ bar$$

$P_{pressure}$: Is the required air pressure from the compressor (here is the minimum)

P_{power}: Is the required power for the lateral motion of the foosball rod.

r: The radius of the piston (here 1cm selected)

Note!

- In a pneumatic system, it is also important to check if the valves and pipes are able to pass enough volume of the air in the limited time range.
- For different rods, the required moving distance can be different. As an example, For the goalkeeper rod, the required distance can be up to d=500mm.
- Friction has a very small effect on the system.

Proportional and servo pneumatic valves

Proportional and servo pneumatic valves are the other options in the case of using pneumatic actuators.

Proportional pneumatic valves changes output flows in proportion to the input value and maintain dependable, reasonable, compact solutions for fast response and consistent control at relatively low flow rates. (NUMATICS 2014.)

Servo pneumatic valves commonly is a combination of a proportional valve with a feedback device and a control system to monitor and correct the system's probable errors in speed, position, or torque-force (Figure 30). Using a servo pneumatic valve for positioning the actuator has two main disadvantages. First, it requires higher quality air than standard pneumatics. Typically, a 5-micron filter is recommended for servo pneumatic systems. The other disadvantage of the servo pneumatic system is its price in comparison with other solutions. (Servo pneumatics 2018.)

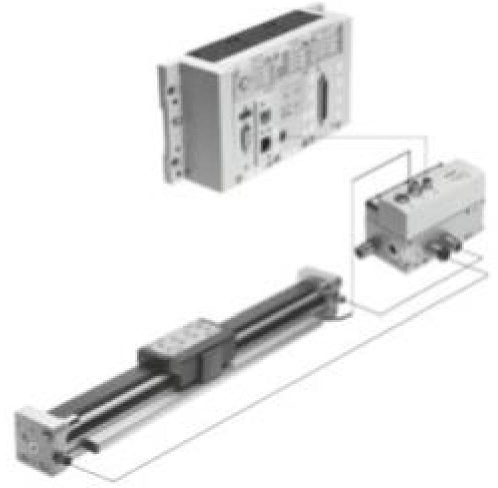


FIGURE 30. Servo pneumatic sysem (Servo pneumatics 2018)

3.3.3 Electric Motors

Electric motors are the other option for rotational and translation moves of foosball rods. Here is comparison between several different types of electric motors.

Note!

In a real condition, the speed of a motor starts from 0rad/s, and with acceleration, it takes a time to reach the maximum speed. On the other side, 34m/s is too high and for an undefeatable ideal system. Besides the difficulties in finding the actuator (motor combined with gears etc.,) to provide 34m/s speed and the budget limitations, such a fast movement is too high and dangerous for the constructions.

Linear motors

There are many different linear motors in size, power, moving velocity and accuracy (Figure 31).

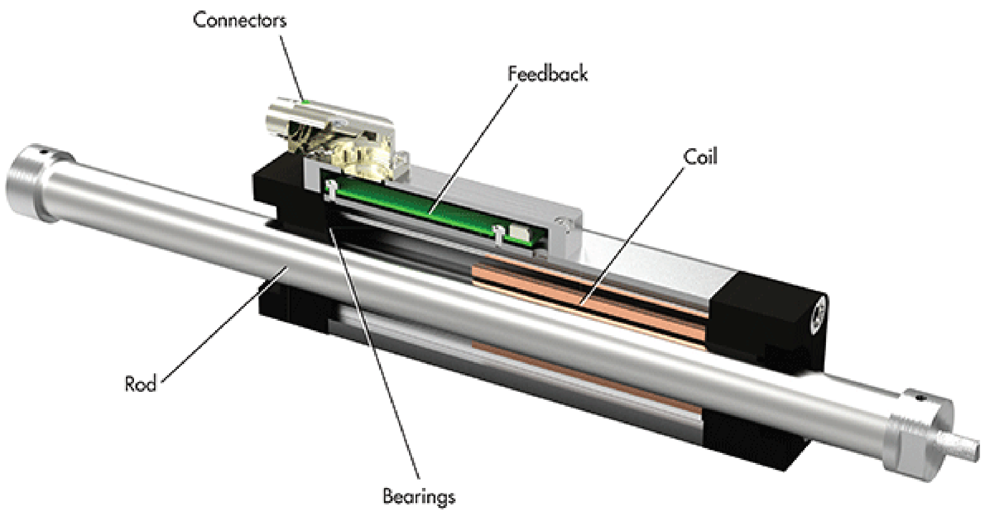


FIGURE 31. ETT050 direct-thrust linear-motor actuator components (Innovative Motors 2020)

It seems a perfect option for translation move of foosball rods but there are two disadvantages which makes them inappropriate for the project.

- Price: In compare with radial motors, the price of high-quality radial motor of the same scale is much lower than linear ones.
- Regularly lubricating: Considering there are very quick movements along the rod, it needs rod lubrication to decrease the friction and heat.

Rotary motors

Rotary motors are the most common type of electric motor. Rotary motors convert electrical energy into rotational motion. It is easy to use this rotational motion for the angular rod’s moves but for the translational motion, it is necessary to convert it to linear movement. Here are three common methods to convert a rotational motion of a motor shaft into a lateral motion:

- Ball-screw system
- Rack and pinion system
- Timing belt

Ball-screw system

A Ball-screw motor is a mechanical system that converts the rotational motion of a motor into linear motion (Figure 32). These types of systems are normally used when both precision and power transmission is required. The axial motion velocity depends on the steps of the screw shaft and the rotational speed of the motors. The price of screw-ball motors is lower than linear motors with the same scales, but still, it is high. On the other side, the required speed for the translational motion of the rods is much higher than what a normal ball-screw system can provide. (Guenat 2012, 4.)

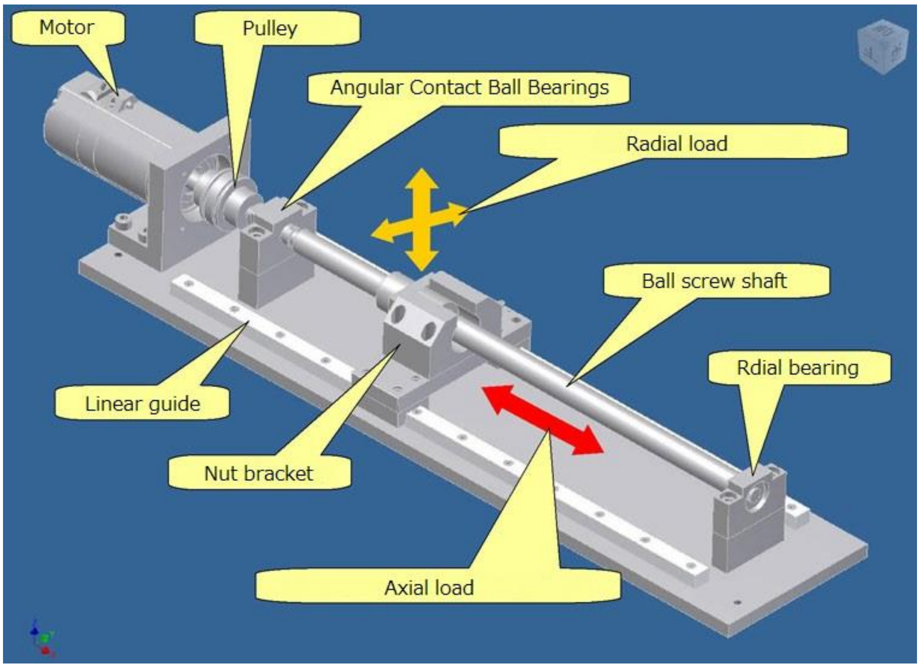


FIGURE 32. Ball screw motor and parts (Kuroda)

Rack and pinion system

Rack and pinion is a system to convert rotational motion into lateral move, using combination of a rack and pinion (Figure 33). In this system the diameter of the pinion has significant affect on the choice of the motor because the required torque to apply is inversly proportional to the diameter of pinion. (Guenat 2012, 4.)

FIGURE 33. Rack and pinion system (Engineering360, 2021)

Using rack and pinion is the most common way to convert the rotational motion of electric motors to translational. As Figure 34 shows, in these types of structures, actuators and their related parts are placed and fastened on a flat surface.

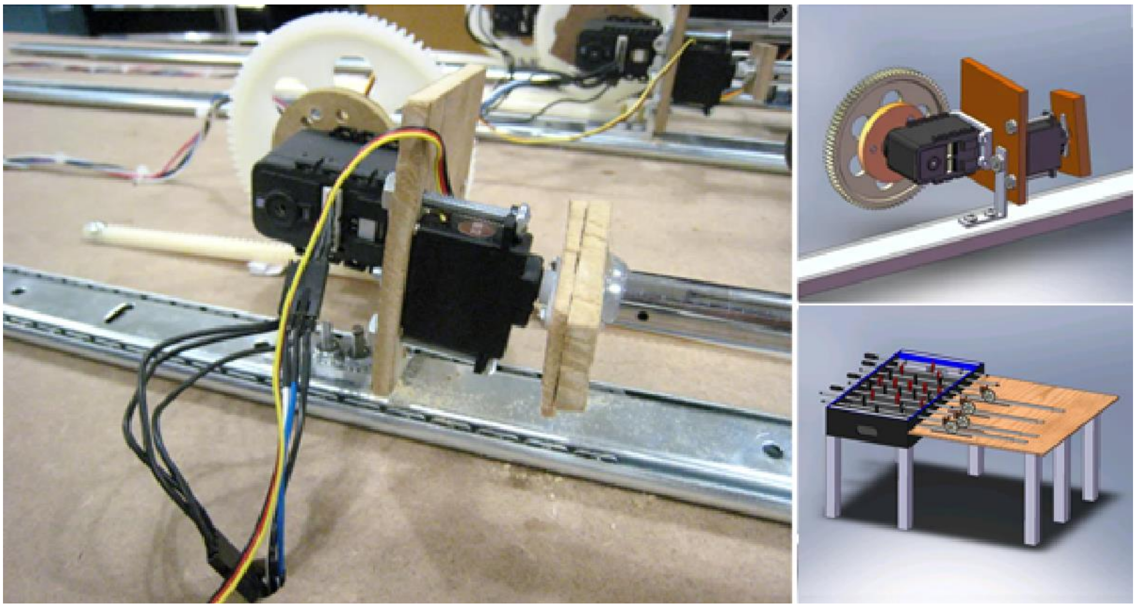


FIGURE 34. Actuator with rack and pinion construction (Autonomous Foosball Table 2009)

Timing belt

Using iming belt between two pulleys and putting the carriage in on that is one of the other common ways to convert the rotational motion of radial motors into translational. In Massey University, 2018 and, Lausanne Polytechnique, 2012 they used this method. Figure 35 shows Massey University’s time belting assembly for the semi-Automated foosball table project. (Guenat et al. 2012, 4-5.)

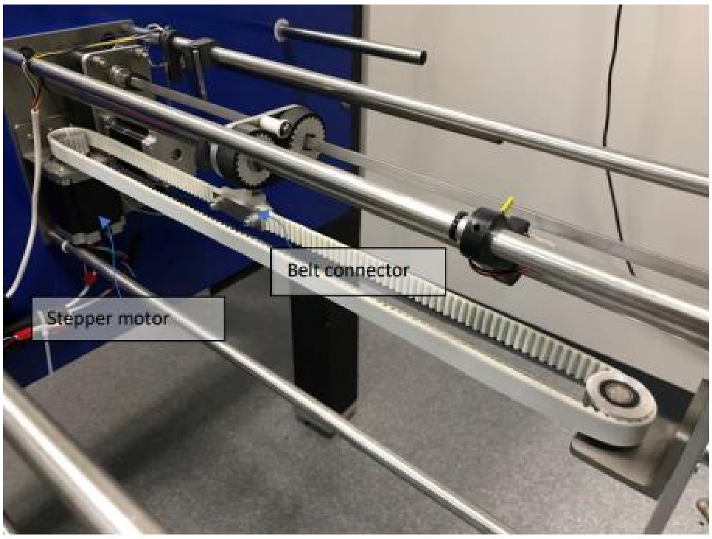


FIGURE 35. Using timing belt to convert rotational motion into translational (Lues 2018, 37)

In a project from Massey University (2018) they used timing belts and made holding construction for each rod separately (Figure 36). In their project, the holding structures are fastened to the table and made it difficult to detach the automated system in case of human vs human playing.

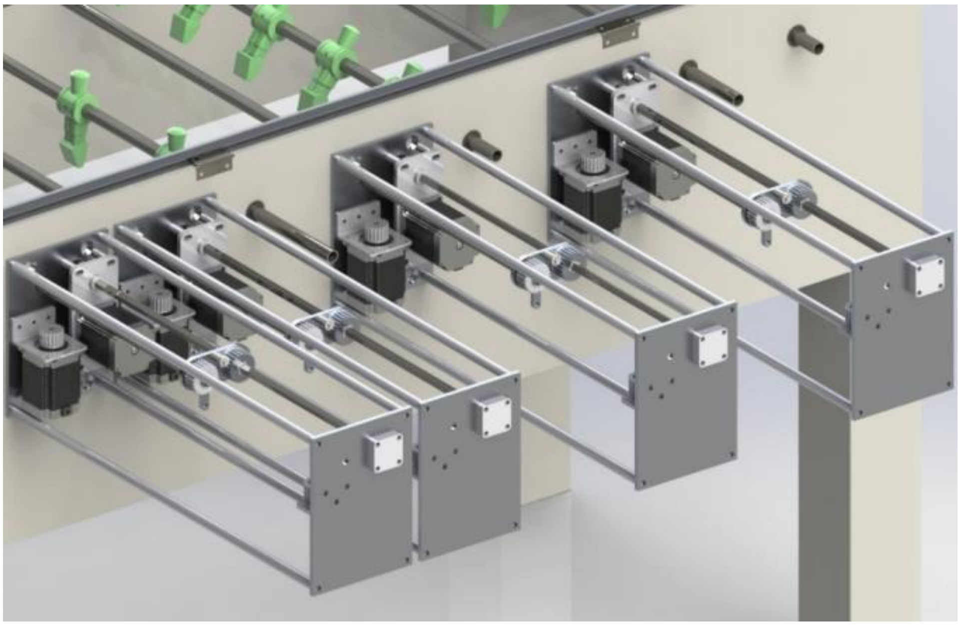


FIGURE 36. Using metal bars to hold actuating systems (Lues 2018. 34)

Servo motor or stepper motor

Stepper and servo motors are the two common options for Automation and robotic projects. Here is a brief introduction to these motors.

Stepper motors

Stepper motors are brushless direct current(DC) electric motors. The 360° rotation of a stepper motor is divided into equal steps. When the motor receives a command to hold at a position, a controlling component sends electric signals to a driver component, which translates these electric signals and responds a proportional voltage signal to the motor. Then in case of an error in the position of the motor, it moves and fixes the error in angle.(EMERGING IOT, 2019.)

Advantages:

- It is easy to control by microcontrollers
- It has very good control over the speed of the motor which makes stepper motor a good option for automation systems and robotics.
- Stepper motors have normally from 50 to 100 pole counts, and it is able to accurately rotate between these poles without the help of a positioning encoder system.
- While normal DC motors or servo motors do not maintain much torque at low speeds(less than 2000 rpm), a stepper motor can provide maximum torque at low speeds.
- High holding torque.

Disadvantages:

- Generally, at high speeds, stepper motors provide low torque.
- Low efficiency is an other disadvantage of stepper motors. Stepper motors current consumption is independent of their load. They constantly take maximum current and for this reason, they tend to become hot.
- Stepper motors might skip steps at high loads.
- They make some noises during operation. (EMERGING IOT, 2019.)

Servomotor

A servo motor is a combination of a suitable motor with gears and a sensor to send position feedback. Arrangement of gears takes the high speed of the internal DC motor and slows the motion down, and they increase the torque at the same time. Positioning sensor, or an encoder, placed on the last gear. Using closed-loop control, helps the microcontroller compare the rotor to the desired position with the actual position. In case of an occuring error, the controlling system sends an error pulse. This pulse creates the right control signal to move and fix the rotor's position. (EMERGING IOT, 2019.)

Advantages:

- High torque at high speed(over 2000rpm)
- Small sized servo motors are not expensive and they use plastic gears, thus they are not heavy either.

Disadvantages:

- Positional rotation is limited to 180 degree.
- The closed feedback loop in servo constantly tries to correct any movement from the desired position. This constant adjustment disturbs holding steady at a position.

3.4 Solutions for safety

Safety is one of the most important factors in using any device. Device safety can be devided in to three main parts:

- User's safety
- System safety
- Environment safety

User’s safety Consists of preventing any risk which the device may make to the user's health. In semi-automated foosball table it might be:
Using the devices in wrong way happens If the users do not understand how to use the device and following the user’s instructions. The user’s instruction should be simply understandable for normal users and in case of requirement of skilled person, have to clearly mention it to the users.
Jumping ball from the playing area out toward users or viewers. In some projects(Gutierrez-Franco et al, 2013), solution is using a transparent cover for the playfield (Picture 3).

PICTURE 3. Using transparent cover for the playfield (Gutierrez-Franco et al, 2013)

The user may be hit by fast-moving rods which are controlled by the machine.
Noises over 70 dB for a long time may cause to damage human hearing.(CDC 2019).

If the device's malfunction goes out of control, it may harm the users. In this case, using sensors and an emergency stop button is recommended. Machine working area should be undercover and use warning signs where it is required to prevent accidents.

System safety Consists of situations that may put machines at risk of breaking down parts or structures. To avoid these situations, first should define edges of damages and make suitable control over machine functions around those edges. Some of these situations are:

- Mistakes in programming may cause the machine to work out of control. For example, if the translational moves are not limited between the right coordination points, it may harm the structure or actuators.
- In case of safety sensors malfunction or any disturbance in devices function, the system should stop and possibly notify the users about the problem.
- Vibration, heat and unbalance table are considerable risks for the system.

Environment safety: Considering some parts may require lubrication, it is good to keep the environment clean from these materials. Also, annoying noises are the other part of the unsafe situation mentioned above.

3.5 Structure

After deciding about the types of devices to use for the project it is necessary to assemble them in the right way to derive the best performance and avoid damage them. In between all devices, actuators and camera (in case of using that) are more important in how and where to assemble in the project. Because the camera should have the best view of the whole playing area and actuators give motion to the robot’s puppets. A search through the semi-automated foosball table projects shows that the Figure 37, (Gutierrez-Franco et al. 2013), is almost the most common type of structure they use.

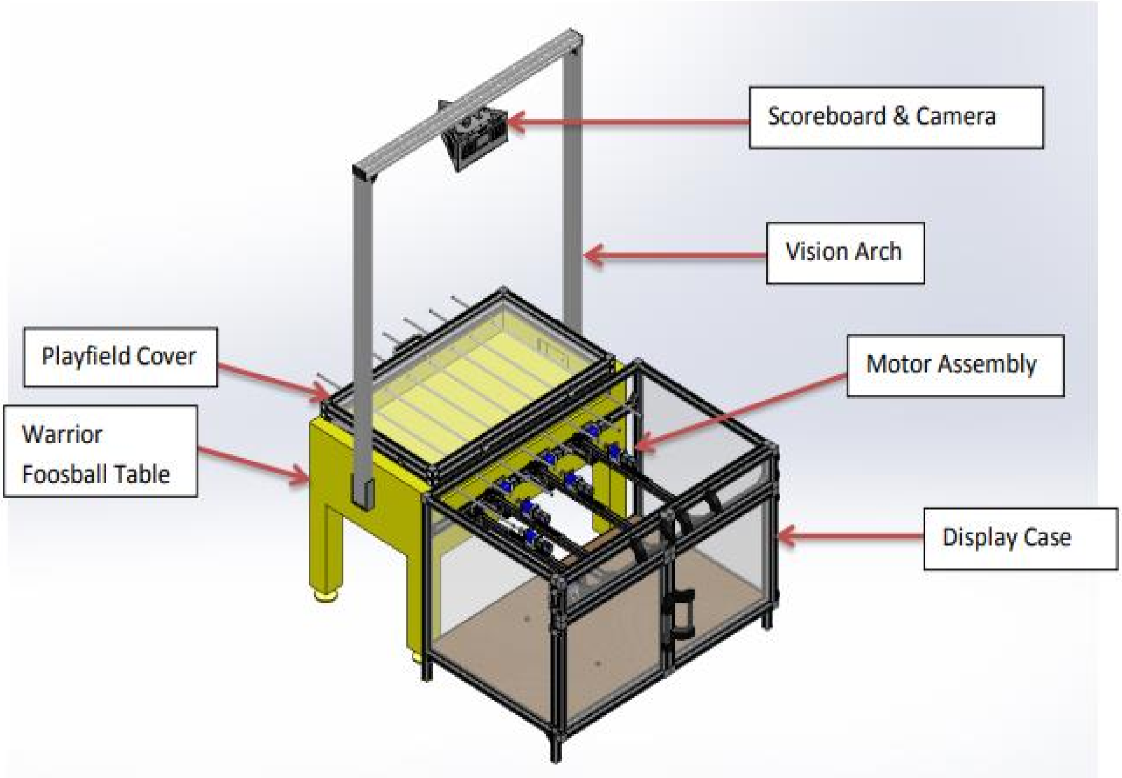


FIGURE 37. A common example of semi-automated foosball table (Gutierrez-Franco et al. 2013, 37).

In this structure, the camera takes the vision from above while the playing area is protected by transparent glass. The transparent glass may reflect environment lights and make a dead zone for the camera (Figure 38). Increasing the distance between the camera and foosball table helps to decrease this unwanted reflection effect.

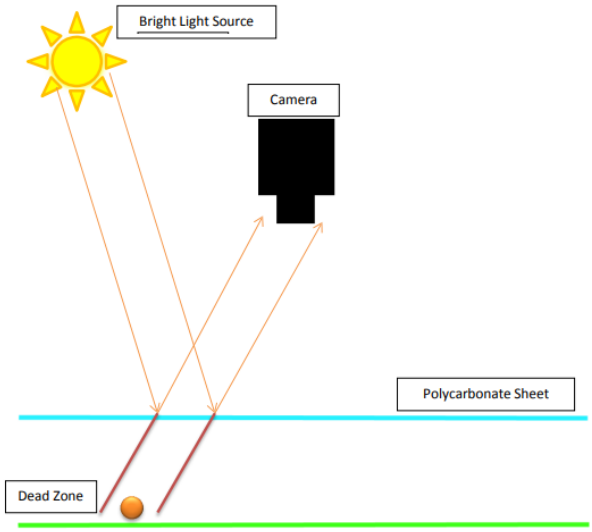


FIGURE 38. Dead zone for camera (Gutierrez-Franco et al. 2013, 97).

In the project sponsored by Soar Tech, 2012, they put the camera at 150cm above the table and decreased the view angle to about 44° (Figure 39).

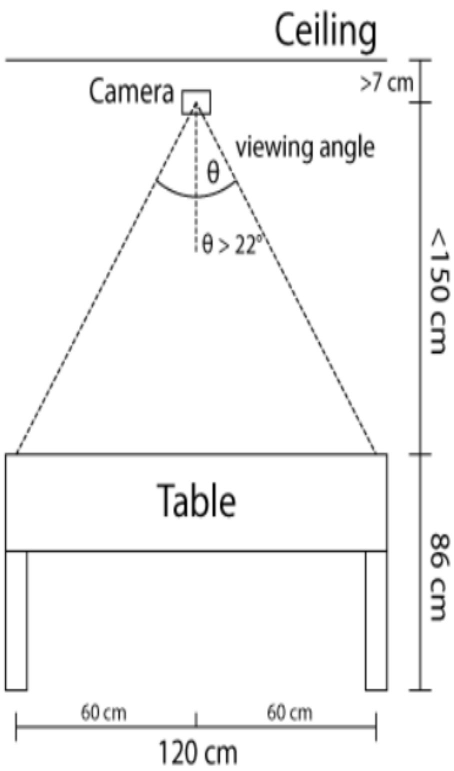


FIGURE 39. Viewing angle for the camera (Enos, Fenelon, Goodell & Phillips 2012, 7)

Using the camera at the bottom of the table has limitations for the distance. Table 4 shows the chart for the camera distance from the table and the minimum of the required view angle.

TABLE 4. Relation between the camera distance and required view angle.

distance(cm)	view angle(°)	table length(cm)
30	127	110-125
40	113	110-125
50	100	110-125
60	90	110-125
70	82	110-125
90	68	110-125
100	62	110-125
120	54	110-125
140	46	110-125
150	44	110-125
180	36	110-125

3.6 Control and programming

Control systems are designed to receive limited inputs and maintain limited outputs. This receiving inputs and providing outputs have to be in a specified range. In this project, inputs are from the camera and safety sensors. Dynamic control systems normally run in closed-loop system. It means that the output component sends feedback into the controlling part of the system by a sensor and then the system adjusts its control input by using that output feedback. In this project, the camera captures an image, and image processing maintains the position of the object (here is the ball or puppets).(Lues 2018.)

In a semi-automatic foosball table, the position of the ball is measured, and then the control algorithms compare it with the positions of the foosmen and decide which foosman intercepts the ball. This feedback is based on positional control. But in practice, controlling process is more difficult than such positional control. The ball moves and direction of that is also important. Therefore the current and past positions of the ball are used to predict the motion and probable destination of the ball. Then the control algorithm should determine which rods and puppets and at what coordination are able to catch the ball. In this situation, the reference signal is predicted ball intercept position and the controlled variable is the foosmen's position. (Lues 2018.)

Programming a foosball robot requires high IT skills, here we just mention some important point to consider them during programming:

- Zero (home) point and reset to home position helps to see if the system needs callibration or not.
- In the attacking mode, own front foosmen positions should not make barrier for the ball movements. In the attack mode it is better to give a -60° (backward) angle to front puppets.
- In kicking the ball, it is better if the foosman start kicking from about -30° angle

- In case of receiving any unsafe situation signal from sensors, the program should stop playing.

Coordination and origin point: To determine the ball and foosmen position should determine coordination's origin point. Since table football is a game on a 2D surface, then only X and Y coordinations are necessary. Origin point can be anywhere in or out of the surface but to simplify the calculation, one corner of the playing ground is a good option.

Moving direction and velocity: To deteermine which puppet ia able to hit the ball first and estimate the time of hiting, have to calculate the velocity and direction of the ball accurately. Of course because of existance of friction and air resistance, the ball face with acceleration whole the moving time but the moving distance is too short and there are interuption of the wall and puppets. Therefore ignoring the acceleration of the ball does not affect on the accuracy of the calculations. (Enos et al, 2012, 56.)

To determine velocity of the ball, simple physic equation for velocity is useful:

$$\nu_x = \frac{X_2 - X_1}{t_2 - t_1} \quad \text{and} \quad \nu_y = \frac{Y_2 - Y_1}{t_2 - t_1}$$

$\mathbf{\nu}_x$: Is the ball velocity in x direction
$\mathbf{\nu}_y$: Is the ball velocity in y direction
t_2 and t_1 : Positioning times
X_2 and X_1: The X coordinations of the ball at t_2 and t_1
Y_2 and Y_1: The Y coordination of the ball at t_2 and t_1

Depending on where the origin point is, the sign of the velocity (negative or positive) can define the direction of the ball.
To determine which puppet is able to catch the ball it is necessary to define the area each puppet can cover (Figure 40).

Note!

Should also consider the possibilities that the ball may hit the wall or other puppets in the way and changes the direction and speed of the moving ball.

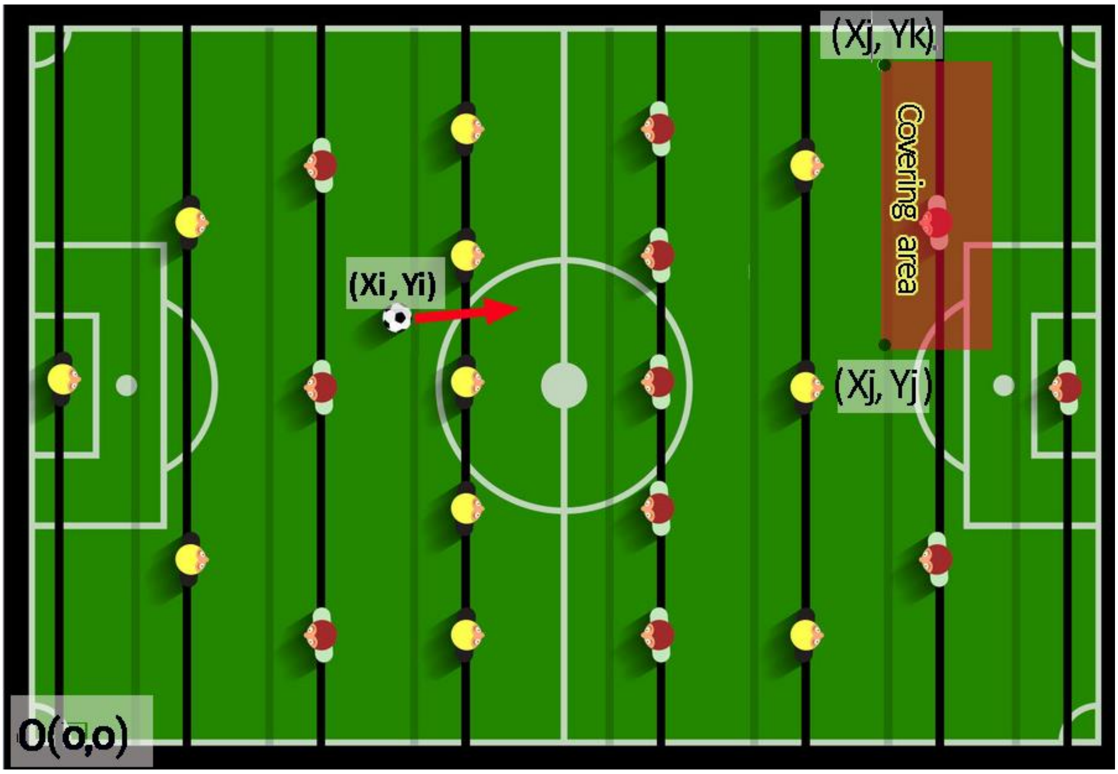


FIGURE 40, Cordinations and covering area (Lues 2018. edited)

Maybe the ball direction passes more than one puppet's coverage area. In such a situation should determine which puppet has enough time to reach the ball and have a suitable reaction. One of the solutions is to calculate the distance between the ball and covering area and then estimate the time that the ball travels to reach the area. If the reaction time of the puppet is equal to or smaller than the ball traveling time, then that puppet is the suitable one. In the case that two or more puppets have possibilities to catch the ball, the one with the smallest time is the best option.

Processing these data and responding to the suitable output in a fraction of the time is a necessity for the system. Thus recommendation is to use a computer for the data processing and PLC for controlling actuators.

4 CONCLUSION

Developing a S.A.F.T requires skills in mechanical engineering, industrial design, and IT but to have the optimal results, it is necessary to consider the budget, select the suitable methods and equipments to reach the intended purpose.
The other important factor is programming. It has a considerable effect on the accuracy and speed of the system because unnecessary data processing may cause latency in responding to the system.

Tracking the ball is the biggest objective in such projects. Depending on the budget, available space, and the possibility to make changes to the table, there are options to track the ball during the game. Using new technologies like touch screens does not mean getting the best results. Sometimes a simple and cheap traditional component can have more satisfying results than using a complicated expensive system.

The other problem would be failures in testing the system, especially in programming. The system may look simple but it is a combination of several devices and software. It is normal to face tens of errors and failures. Patient in fixing problems or trying to find new and better solutions is part of such projects.
Technology is growing fast. Components will be faster and more accurate. Surely in the near future, AI and machine learning will have more roles in such projects.
For the semi-automated foosball table project in TAMK, there are already some useful facilities like pneumatic devices, computers, PLC and vision cameras, etc.
Thus it is more reasonable to use TAMK facilities first and test the results. Then in case of necessity for using different components or updating the system to a higher level, maintaining from other sources.

This thesis studied different semi-automated foosball tables thesis and the technologies used in them to give a better view of such projects. In addition, made some research in advanced related technologies to find suitable options. This study tried to ease the development of a semi-automated foosball table in TAMK in the future.

LIST OF REFERENCES

1. Bachelor's report guide, 2020. Tampere University of Applied Sciences
https://content-webapi.tuni.fi/proxy/public/2020-02/intra_thesis_report_guide_2020_0.pdf

2- E. Stoltenborg, 2008. Technische Universiteit Eindhoven, Design of an autonomous football table, pdf
http://www.mate.tue.nl/mate/pdfs/9139.pdf

3- E.Guenat, C.Picard, R.Serigado & B.Ulrich, 2012. Automatic Foosball Concurrent engineering project
https://www.epfl.ch/labs/la/wp-content/uploads/2018/08/FoosballReport2012.pdf

4. N.Enos, P.Fenelon, S.Goodell, N.Phillips, 2012. Football Operator and Optical Soccer Engine
https://www.ece.ucf.edu/seniordesign/fa2012sp2013/g30/docs/Final%20Paper-%20G30.pdf

5. Electronics Projects Focus, What is a Touch Screen Technology & Its Working, 2021. web page,

https://www.elprocus.com/touch-screen-technology-working/

6. Touch Screen Basics Comparisons, pdf
https://www.controldesign.com/

7.Touch Systems, 2017. web page,
https://www.touchsystems.com/resources/surface-acoustic-wave-technology/

8. Matevž Bošnak, Gregor Klanˇcar, University of Ljubljana 2020. Transformable Objects Using a Network of Image Sensors with Application to Table Football, ,pdf
https://www.researchgate.net/

9. Joshua Lues, Massey University, New Zealand, 2018. Low latency vision-based control for robotics, pdf
https://mro.massey.ac.nz/bitstream/handle/10179/15187/02_whole.pdf?sequence=2&isAllowed=y

10.Machine Vision Basics 2021. web page,
https://www.keyence.com/ss/products/vision/visionbasics/basic/middle/

11. CDC 2019. Center For Desease Control And Preventation. Web page,
https://www.cdc.gov/nceh/hearing_loss/

12. J.Gutierrez-Franco, J.Inlow, J.Graham, 2013. California Polytechnic State University, Automated Foosball Table, pdf
https://core.ac.uk/download/pdf/19161196.pdf

13. Steve Vincent and John Bridges, 2015. web page,
https://www.hydraulicspneumatics.com/

14. Engineering360, 2021. web page,
https://www.globalspec.com/learnmore/motion_controls/linear_rotary_motion_components/rack_pinion_drives

15. EMERGING IOT, 2019. web page,
https://www.seeedstudio.com/

16. Autonomous Foosball Table, 2009. web page,
https://www.instructables.com/Autonomous-Foosball-Table/

17. Rob Janssen, Jeroen de Best, 2009. Eindhoven University of Technology, pdf
https://www.researchgate.net/publication/220797505_Real-Time_Ball_Tracking_in_a_Semi-automated_Foosball_Table

18. Foosball Soccer, 2021. web page,
https://www.foosballsoccer.com/official-foosball-rules.html

19. Foosball Australia, Foosball Association of Australia, Web page,
https://foosballaustralia.com.au/whatis/table-dimensions.html

20. Cambridge Consultants, web page,
https://www.cambridgeconsultants.com/insights/opinion/diary-developer-part-3-foosbot-strategy

21. R.Janssen, J.de Best & R.van de Molengraft 2009. Eindhoven University of Technology, Real-Time Ball Tracking In A Semi-Automated Foosball Table, pdf
https://link.springer.com/content/pdf/10.1007%2F978-3-642-11876-0_12.pdf

22.Bostonglobe 2021. newsletter, web page
https://www.bostonglobe.com

23.Innovative Motors 2020. web page
https://www.innovativeidm.com/rotary-motors-vs-linear-motors/

24.Kuroda, web page,
https://www.kuroda-precision.com/technical-information/bs/bs008.html

25. The electricity forum 2021, web page,
https://www.electricityforum.com/what-is-a-potentiometer

26. Allied Vision Technologies 2007, youtube video
https://www.youtube.com/watch?v=DVM0utYKUOY

27. SMC Corporate 2021, SMC Actuator Position Sensor catalogue, pdf
https://static.smc.eu/binaries/content/assets/smc_global/products/featured-products/d-mp_a_cat_en.pdf
28. THOMAS A Xometry Co, February 4, 2022, Web page,

https://www.thomasnet.com/articles/instruments-controls/all-about-position-sensors/

29. Scientific American 2021, web page, https://www.scientificamerican.com/article/experts-how-does-bluetooth-work/

30. Servo pneumatics 2018, Linear motion tips, web page, https://www.linearmotiontips.com/servo-pneumatics-not-an-oxymoron/

31. NUMATICS 2014, Pneumatic Proportional Valve , pdf, https://www.emerson.com/documents/automation/white-paper-numatics-proportional-valve-asco-en-us-134706.pdf

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