# Babyfoot

Automatic Control Laboratory

EPFL Concurrent Engineering Project

Spring 2024

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Supervised by Prof. Salzmann

# Contents

# Preface

I had the opportunity to start working on the foosball project over the summer of 2023 during an internship in the EPFL Automatic Control Laboratory. For my concurrent engineering project, I had the privilege to continue working on the automatic foosball under the supervision of Professor Salzmann. In this report, after briefly presenting the work done before the concurrent engineering project, I will focus on the advancements made in the context of the project (i.e. the last 5 months).

As part of this project, I was able to delve into an exciting world where technology and mechanics converge innovatively. This project, initiated by students before me, revolves around a bold concept: a foosball table where one side is controlled by motors that react in real-time to the ball's movements and the opponents'.

In terms of its use, the automated foosball project maintains interest in foosball within both competitive and recreational contexts. By integrating advanced technologies and innovative strategies, the game remains stimulating and relevant, offering a rewarding experience for passionate players and leisure enthusiasts alike. It also provides the owner with the opportunity to play foosball anytime, without necessarily needing a human opponent to play against.

At the heart of this system is a cleverly positioned camera to track the ball's trajectory, while sensors detect the position and orientation of opposing players. This entire setup is synchronised and controlled via a LabVIEW interface, providing an ideal platform to develop complex gaming strategies.

Working on this project has allowed me to develop a diverse set of skills. On one hand, I have deepened my programming knowledge through LabVIEW, learning to design robust control algorithms to coordinate the players' movements in a more or less dynamic environment. On the other hand, I have gained practical mechanical experience by participating in adjusting the motors and sensors to ensure the system functioned optimally. I have also learned to creatively solve problems and turn ideas into concrete solutions.

Beyond technical skills, this project has also helped me develop essential qualities such as perseverance and the ability to manage complex projects over an extended period. The iterative and continuous improvement process was rewarding, as each challenge overcome brought me closer to a perfectly functional automated foosball table.

# Acknowledgments

I would like to express my sincere appreciation to Prof. Salzmann for his invaluable support and guidance throughout the development of the automatic foosball project. Mr. Salzmann's expertise and encouragement were instrumental in shaping the project's success, and his willingness to provide feedback and assistance significantly enhanced its quality.

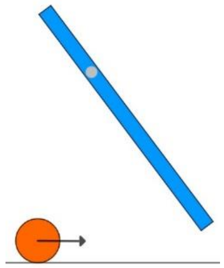
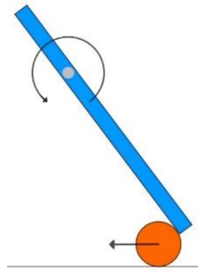
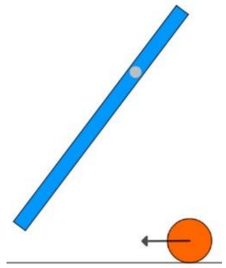
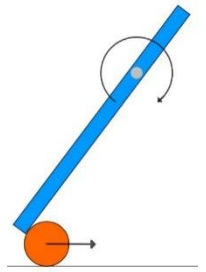
I am truly grateful for Mr. Salzmann's mentorship and patience during this endeavour. His insights and advice have been immensely beneficial to my learning and growth.

Thank you, Mr. Salzmann, for your dedication and support throughout this project. Your contributions have made a lasting impact, and I am privileged to have had the opportunity to work under your guidance.

# Internship: August 2023 – December 2023

From August to December 2023, I had the opportunity to work on strategies related to ball control and spatial awareness related to the position of the opponent's players. These strategies include:

- ***Summer_2023_Horizontal_Juggling*** consists in making two players from the same rod (i.e. two strikers, two midfielders, two defenders) juggle the ball side to side between themselves.
- ***Summer_2023_Horizontal_Juggling_with_Swtich*** is a variant of the previous strategy where the user can choose to change the two players juggling within the same row. For example, suppose the middle and right strikers are juggling. The user can then press on a button on the front panel and transfer the juggling to the other side i.e. make the middle and left strikers juggle together.
- ***Summer_2023_Juggling_Shoot*** is also a variant of the first strategy where, as its name suggests, the user can choose to interrupt the juggling and make the nearest player to the ball take a straight shot.
- ***Summer_2023_Vertical_Juggling*** consists in making the goalkeeper juggle back and forth with the defenders.
- ***Summer_2023_Damper*** consists in controlling the ball using what I've called the "magic angle". When the player is at this angle it is more or less able to control any shots, even high-speed ones.
- ***Summer_2023_Turn_Around*** consists in making a player turn around the ball continuously. This strategy has been built in a way that the player's trajectory around the ball is adjusted if the ball is not exactly underneath him (i.e. slightly in front of him, behind him, on his right or his left), as long as it is within reach.
- ***Summer_2023_Scan_Shoot_Straight*** consists in analysing the position of the opponent's defenders and goalkeeper to determine whether or not it is possible to take a straight shot in the goal for the strikers. If it is the case, the strikers move the ball to the required $y$ position by taping it using the side of their "foot" and taking the shot.
- ***Summer_2023_Super_Stopper*** consists in literally stopping shots by blocking the ball between the players' foot and the foosball ground. It basically pinches the ball, hereby stopping it immediately.
- ***Summer_2023_Damper_with_Capture*** is explained with the following schematic.

| | | | | |
|---|---|---|---|---|
|  |  |  |  | REPEAT:<br>Repeat the 3 last steps until the ball has fully stopped moving. |
| Step 1: As the ball arrives, the player rotates to the "magic angle". | Step 2: As the ball bounces off the player's foot, the player rotates to the negative "magic angle". | Step 3: The player waits for the ball to arrive. | Step 4: The ball then bounces off the player's foot again, and the player rotates back to the "magic angle". | |

Two versions of this strategy have been created:

- ***Summer_2023_Damper_In_Front_with_Caputre*** when the ball arrives towards a player from the front.
- ***Summer_2023_Damper_Behind_with_Caputre*** when the ball arrives towards a player from behind.

- ***Summer_2023_Damper_Smooth*** consists in damping the ball as it comes in range of a player by rotating the rod to progressively reduce its speed to a stop. This strategy reads the ball's speed as it approaches a player to adjust the player's rotation speed accordingly.

# Concurrent engineering project: February 2024 – June 2024

I will now present in detail the work done in the context of the concurrent engineering project.

## I. Extra strategies

### A. Shooting at an angle

The first task we talked about with Mr. Salzmann was to find consistency in the shooting, specifically in directional shooting. The first step was therefore to collect a decent amount of data to be able to find what factors came into play when shooting at an angle and how predominant each of these factors are.

This was done using in the ***Summer_2023_Angled_shooting_testing*** strategy: the idea behind this VI was first and foremost to position the ball at a recorded horizontal distance (X-offset) from a player's rod and use the ball's position along the Y-axis to position the player's foot at the ball's level. From there, the user then manually applies an offset (using a control on the front panel) between the centre of the player's foot and the ball's centre by adjusting the position of the rod, therefore creating what we will call the Y-offset. For this positioning phase the player shooting is in "ready-to-shoot" position ($rod_{angle} = 134°$). Once the user has taken notes of the X-offset and the imposed Y-offset, he can release the shot. When the shot is taken, the VI records the exact position of the ball at impact and $100\ ms$ afterwards. From there we can calculate the angle at which the ball is shot $\alpha$ and the speed at which it is shot $v_{ball}$ using the following calculations:

$$\alpha = \arctan\left(\frac{y_{100\ ms} - y_{impact}}{x_{100\ ms} - x_{impact}}\right)$$

$$v_{ball} = \sqrt{v_{x,ball}^2 + v_{y,ball}^2} = \sqrt{\left(\frac{x_{100\ ms} - x_{impact}}{100\ ms}\right)^2 + \left(\frac{y_{100\ ms} - y_{impact}}{100\ ms}\right)^2}$$

Let's have a look at the different factors mentioned just now and the extent of the impact they can have on the ball's trajectory:

- Y-offset: When the centre of the shooter's foot is not aligned vertically with the centre of the ball, the ball will move in a straight line but at an angle. The bigger this offset is, the bigger the angle at which the ball is shot is and the slower the ball is.
- X-offset: When the position of the player's rod is not aligned horizontally with the centre of the ball, the effect of the Y-offset on the angle at which the ball is shot will be more a less augmented or diminished. This factor also influences the speed of the ball.
- Speed of the ball: It is worth noting that the speed at which the ball travels also affects the ball's trajectory: the potential irregularities on the surface of the ball affect its trajectory more at low speed where they can cause small random deviations. That being said, considering the randomness and the smallness of the impact of this factor, we will not take this factor into account.

To better visualise and understand these factors, on the next page is a schematic of the foosball pitch (Fig. 1) with the mentioned measurements and factors (we will take the middle striker as shooter). The ball and its trajectory are represented in orange. Please note the different elements have been positioned to maximise clarity and do not represent in any way a certain playing situation.

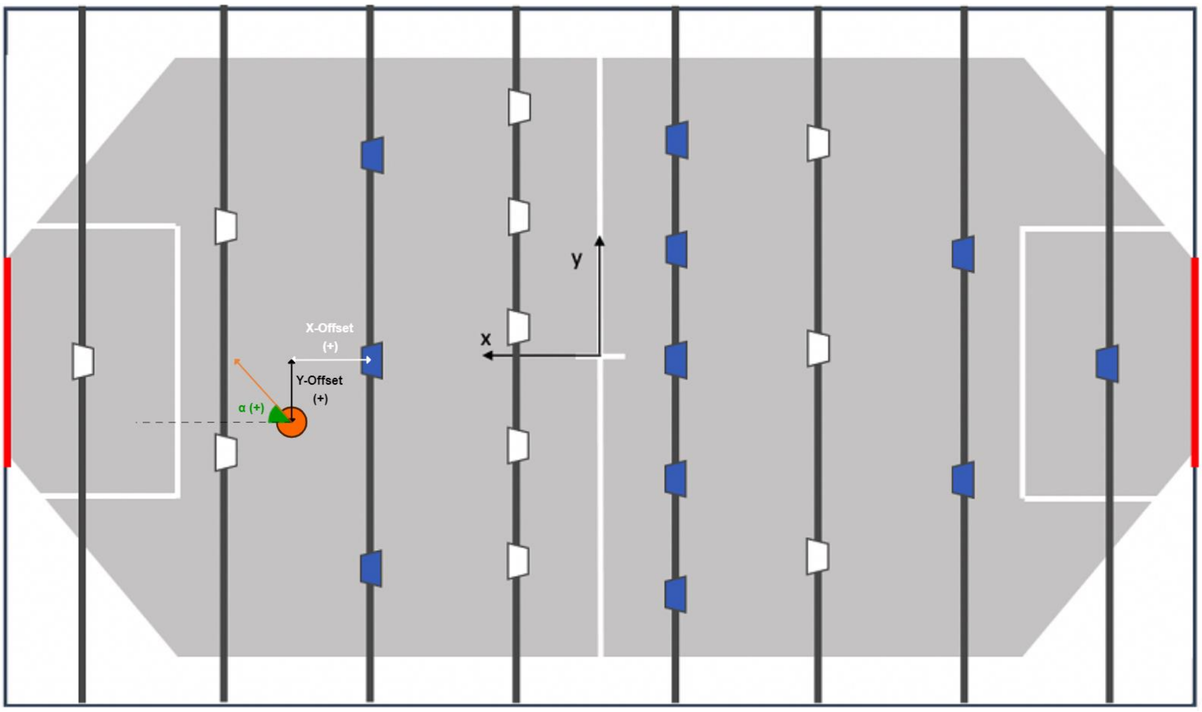



*Figure 1: Schematic of the foosball pitch seen from above showing the different factors and measurements mentioned.*

We will focus on the angle at which the ball is shot for now. After recording several shots, we can generate the graphs below (Fig. 2). The black curve corresponds to the points registered with an X-offset of $0\,mm$, the green curve corresponds to the points registered with an X-offset of $+19\,mm$ and the orange curve corresponds to the points registered with an X-offset of $-19\,mm$.

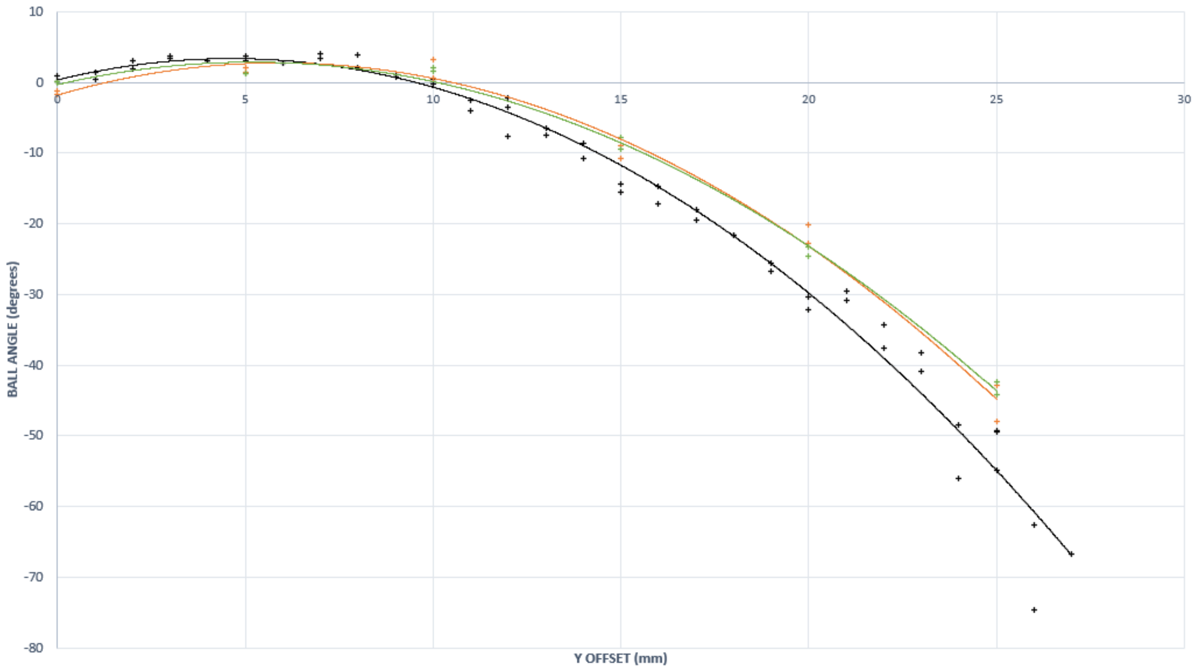



*Figure 2: Angle at which the ball is shot at as a function of the Y-offset.*

It is now time to implement everything we have uncovered in a VI. This has been done in the ***curve_fiiting_2nd_order_with_roots*** VI. This VI takes as input the X-offset as well as the angle we want the player to shoot at. It starts by opening and reading the text files containing the previously recorded shot-related data (i.e. Y-offset and the resulting angle the ball is shot at). The VI then determines a $2^{nd}$ order polynomial that best fits the data. To compensate for any X-offset, I deemed it wiser to adjust the determined polynomial coefficients proportionally using the polynomial coefficients found for the orange curve above to increase or decrease the coefficients accordingly. Finally, the VI returns the optimal Y-offset given the X-offset and the wanted angle.

## B. Passing from midfielders to strikers at an angle

The second task we discussed with Mr Salzmann was to pass the ball from any midfielder to any striker making sure that the strikers are able to control the ball properly.

For this task, to facilitate testing and understand the required player dynamics, I first studied the simple case of the middle midfielder passing the ball individually to each of the strikers without any opponents (i.e. the white midfielders are ignored and therefore their "foot" is rotated in a top position).

### i. Theory

To get a rough idea of the angle at which the ball needs to be shot at from the middle midfielder to each of the strikers, we can start off by doing a little bit of trigonometry.

These are the dimensions of the foosball pitch (Fig. 3).

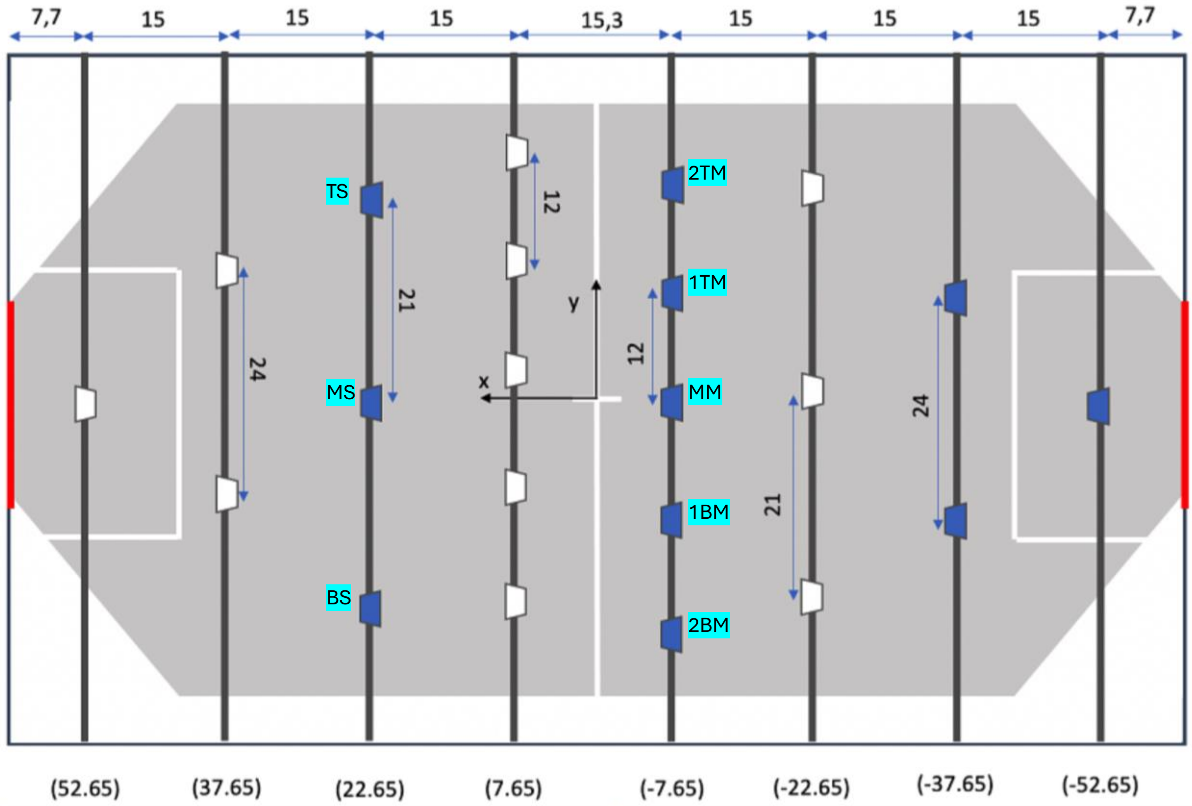



*Figure 3: Schematic of the foosball pitch seen from above with dimensions and player names.*

We can hereby determine the following:

$$\alpha_{MM\to MS} = 0°$$

$$\alpha_{MM\to TS} = \operatorname{atan}\left(\frac{210}{150+153}\right) \approx 34.7°$$

$$\alpha_{MM\to BS} = \operatorname{atan}\left(-\frac{210}{150+153}\right) \approx -34.7°$$

In turn, using the ***curve_fiiting_2nd_order_with_roots*** VI, we can find the required Y-offset for each of these shots (we set X-offset to 0 $mm$):

$$\text{Y-offset}_{MM\to MS} = 0\ mm$$

$$\text{Y-offset}_{MM\rightarrow TS} = -21.1009\ mm$$

$$\text{Y-offset}_{MM\rightarrow BS} = 21.1009\ mm$$

Using the same reasoning we can find the other theoretical angles the ball needs to be shot at by all the midfielders to reach all the strikers. We have recorded these in the following table:

| FROM / TO | 2BM | 1BM | MM | 1TM | 2TM |
|---|---|---|---|---|---|
| BS | $5.7°$ | $-16.5°$ | $-34.7°$ | $-47.4°$ | $-56.0°$ |
| MS | $38.4°$ | $21.6$ | $0°$ | $-21.6$ | $-38.4°$ |
| TS | $56.0°$ | $47.4°$ | $34.7°$ | $16.5°$ | $-5.7°$ |

And we can now construct the table that regroups all the required Y-offsets:

| FROM / TO | 2BM | 1BM | MM | 1TM | 2TM |
|---|---|---|---|---|---|
| BS | $-12.6702\ mm$ | $16.531\ mm$ | $21.1009\ mm$ | $23.6495\ mm$ | $25.1966\ mm$ |
| MS | $-21.8824\ mm$ | $-17.9706\ mm$ | $0\ mm$ | $17.9706\ mm$ | $21.8824\ mm$ |
| TS | $-25.1966\ mm$ | $-23.6495\ mm$ | $-21.1009\ mm$ | $-16.531\ mm$ | $12.6702\ mm$ |

### ii. Practice

Testing out these values of Y-offset on the foosball pitch more or less validates our model for angled shots presented previously (section I. A.) and at the core of the ***curve_fiiting_2nd_order_with_roots*** VI: there are of course some minor angle offsets when jumping from one shooter to the other (rod and player) – this is due to the fact that all measurements to construct the model were taken with the middle striker as shooter –.

## C. Midfielder/striker passing and controlling

Now that we have determined the angles the ball needs to be shot at from all the midfielders to reach all the strikers, we can now build the ultimate passing VI that enables the user to pass the ball from any midfielders to any striker and vice-versa.

### i. Idea

To do so, I have created the ***Spring_2024_Passing_Madness*** strategy. This strategy follows the following steps:

- Identifying which rod is in possession of the ball (midfielders or strikers). We will call this the "Passing Rod". With that information, we can also deduce which rod is going to control the ball i.e. the "Controlling Rod".
- Acknowledging the user's choice of player, from the "Controlling Rod", we want to pass the ball to i.e. the "Controlling Player".
- Identifying the required angle (and in turn, the required Y-offset) for such a pass using the following formula:

$$\alpha = \text{atan}\left(\frac{y_{Controlling\ Player} - y_{Ball}}{150 + 153 + 25}\right)$$

  To determine the required Y-offset, the VI also identifies the X-offset. Note that we have added $+25\ mm$ to the distance between the midfielder rod and the striker rod. This is to account for the "rotation" at which the players will be at to control the ball i.e. the magic angle.
- Considering the ball's position as well as the required Y-offset, identifying which player from the "Passing Rod" is best suited to make the pass.
- Adjusting the Y-offset if needed, depending on who the "Controlling Player" and "Passing Player" are.
- Passing the ball when the user presses the "PASS" button.
- To avoid any erratic translational movement from the "Controlling Rod", the ball is followed along the Y axis only when it comes in Y range of the "Controlling Player". After the first touch, this is disabled, and the "Controlling Rod" follows the ball using the best suited player.
  Note that this has only been implemented when the strikers must control the ball because they have a bigger translational movement range (from $-90\ mm$ to $+90\ mm$) than the midfielders (from $-60\ mm$ to $+65\ mm$) which increases the risk of erratic movements. Therefore, the midfielders always follow the ball along the Y-axis.
- Making sure the "Controlling Player" controls the ball using the ***Damper_with_Capture*** VIs.
- Once the ball is controlled, repeat!
  Note that if the strikers are controlling the ball, a reset is required due to motor setup limitations. See below for the explanation regarding the motors' setup limitations and the induced steps for the reset.

### ii. Limitations

#### 1. Angle

As of the end of February 2024, the rotative motors' setup limitations are as follows (Fig.4):

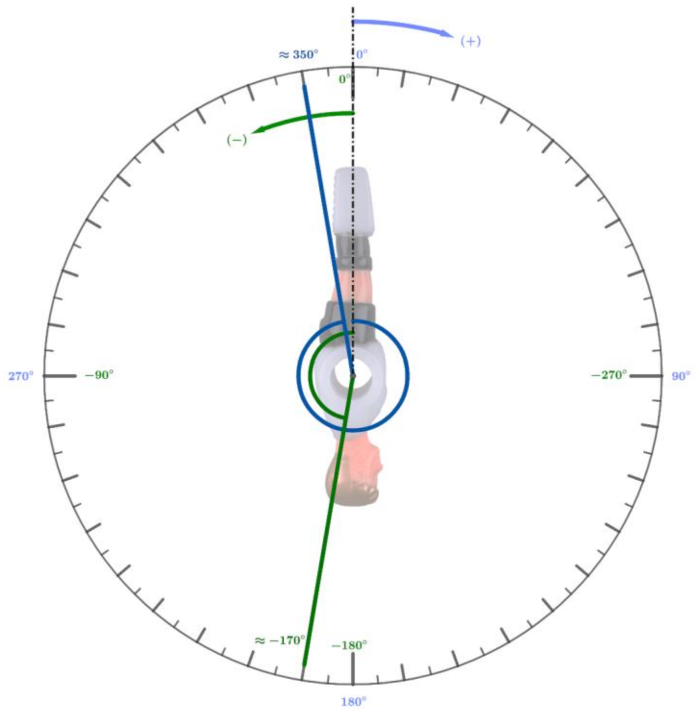



*Figure 4: Schematic showing the limits of the players' rotation in the positive and negative direction (Feb 2024). The dark blue line refers to the positive limit and the dark green line refers to the negative limit.*

Due the limitation on the negative rotation, the angle we need to be at to shoot backwards is $226°$ (as opposed to $-134°$). Indeed, suppose we are in the following situation: the ball has been controlled by one of the strikers and we now want to shoot it backwards, in the direction of the dark blue dotted arrow (Fig. 5). The red arrow shows the simplest solution but sadly it's infeasible: we are here trying to go from $-134°$ to at least $-185°$ to shoot the ball and being that we cannot go below $-170°$, this is impossible. We have therefore determined that the starting angle to shoot backwards is $226°$.

One could then argue that we can directly position the player at $226°$ to control the ball. However here, the $350°$ angle limitation comes into play: when controlling the ball using the ***Damper_Behind_with_Capture*** VI, this situation would imply having to alternate between $226°$ and $506°$ $(= 146° + 360°)$ to control the ball. This is to ensure that the player doesn't shoot the ball as it rotates i.e. that his foot goes over his head as he rotates.

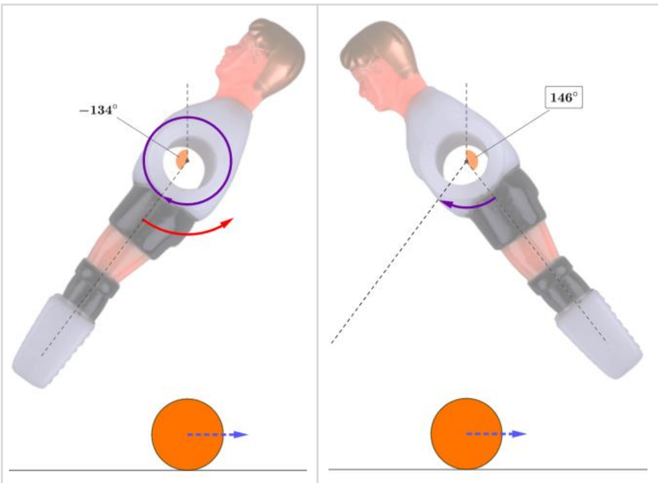



*Figure 5: Explanatory schematics.*

This implies doing the following rotation to shoot: $226° \rightarrow 170°$. The question is how do we get to the starting angle of $226°$ without shooting the ball involuntarily as we rotate? As shown in the schematics above (Fig. 5), as long as the ball is underneath the player, this is impossible, whatever the player's angle is when he has finished controlling the ball i.e. $-134°$ or $146°$. This infeasibility is shown by the purple arrows.

This is why we need to follow these steps after the strikers have controlled the ball to then be able to pass the ball back to the midfielders:

1. Move to the ball's right- or left-hand side, depending on how much more translational distance can be covered by the rod in either direction, until the ball is no longer underneath the player.
2. Rotate to $226°$.
3. Go back to the ball's level.

It is important to note that a minimum amount of time must be left between each of these steps to make sure the ball is no longer in range when rotating (step 1 to 2) and that the player is not moving back to the ball's level before the rotation is finished (step 2 to 3).

### 2. Update: no more angle limitations

After discussing this issue with Mr Salzmann, we were able to troubleshoot where this limitation was coming from and remove it. Therefore, we are now able to rotate from $0°$ to $350°$ (as before) but also from $0°$ to $-350°$! This means that the reset steps are no longer needed.

This limitation is adjustable using the "Global Angle Offset" control on the ***=Spring_2024=tf*** VI's front panel.

### 3. Camera limitations

To be able to control the ball accurately it is essential for the camera to track the ball with precision at all times. It is for this reason that the speed of the passing was rather slow to permit for accurate ball position readings and maximise controllability.

Additionally, when the ball is near the pitch's borders, the camera has a hard time finding the ball due to changes in the lighting: the LEDs that light up the foosball pitch disrupt the ball-position readings when it is close to the edges. This leads to a decrease in the VI's performance when passing or controlling the ball with the players on the extremities of the rods.

### 4. Striker rod dead spots

Unlike the midfielders, the strikers do not offer full lateral pitch coverage. Indeed, the striker's rod maximum displacement along the Y-axis is $91\ mm$ in the positive direction and $94\ mm$ in the negative direction. The table below shows that there are dead spots:

| POSITION \ PLAYER | BS | MS | TS |
|---|---|---|---|
| $Y_{max}$ | $-119\ mm$ | $91\ mm$ | $116\ mm$ |
| $Y_{min}$ | $-304\ mm$ | $-94\ mm$ | $301\ mm$ |

As we can see there are two blind spots of $25\ mm$ centred at $-106.5\ mm$ and $103.5\ mm$. In the context of the ***Spring_2024_Passing_Madness*** strategy, the presence of these dead spots induces a need for a very localised control of the ball and high precision of the passes.

### iii. Speeding things up

In the spirit of the ***Summer_2023_Vertical_Juggling*** strategy, the goal is now to pass the ball "tiki-taka" style: using what we have learned previously regarding the required Y-offset to shoot the ball at a certain angle, we now want to be able to pass the ball quicker between the midfielder rod and the striker rod. This means skipping the controlling phase and playing one touch between the players. This has been done in the ***Spring_2024_Crown_1*** strategy.

#### 1. Passing pattern: the crown

The first pattern we will look at is the following (Fig. 6):

$$1BM \rightarrow MS \rightarrow 1TM \rightarrow 1TS \rightarrow MM \rightarrow BS \rightarrow 1BM$$

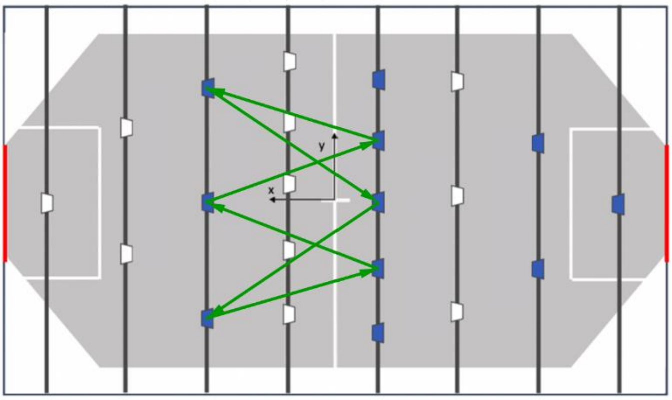


*Figure 6: Crown 1 Passing Pattern.*

Whilst this passing pattern is interesting, it is not applicable during a match. As shown in Fig. 6, whatever the white midfielders' positions, at multiple instances, the ball would be naturally intercepted i.e. the passing pattern is strictly impossible as long as the white midfielders do not have their foot in the air.

Let's have a look at another pattern (Fig. 7):

$$2BM \rightarrow MS \rightarrow 2TM \rightarrow 1TS \rightarrow MM \rightarrow BS \rightarrow 2BM$$

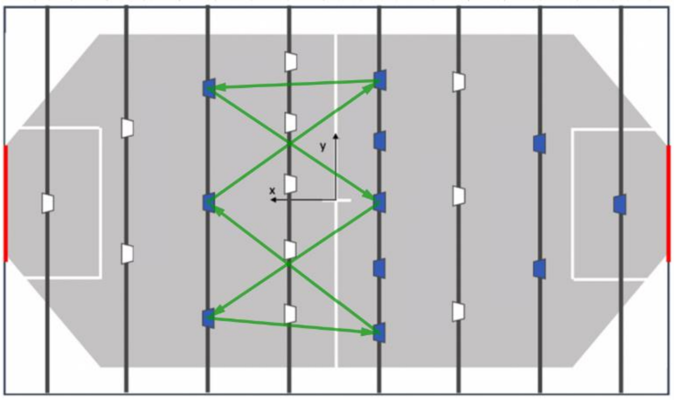


*Figure 7: Crown 2 Passing Pattern.*

Unlike the Crown 1 passing pattern, this one seems feasible: when the white midfielders are at a certain position, we can start the passing pattern without it being intercepted "naturally"! However, this passing pattern also has its drawbacks: it requires passing the ball at high angles. One could argue that this isn't a problem because if the ball arrives at an angle, then the ball will bounce off the players' foot with the opposite angle by symmetry. However, this symmetry rule doesn't apply here because the players' foot structure is built in a way that it straightens the ball's trajectory (Fig. 8) whether it is shooting backwards or forwards.

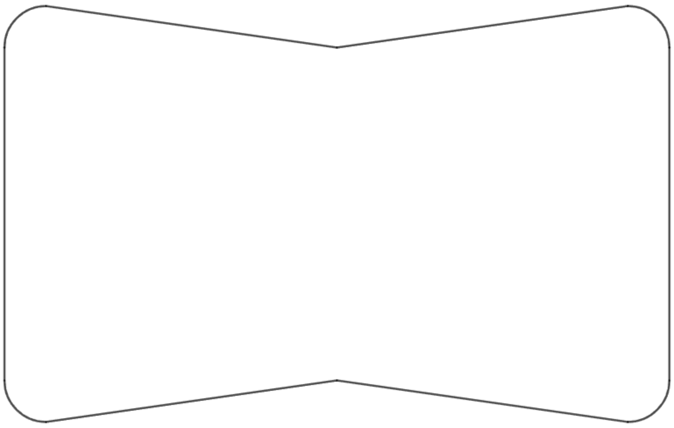


*Figure 8: Players' foot shape.*

After discussing the pros and cons of each pattern with Mr Salzmann, we decided that it would be more interesting to start off with the Crown 1 pattern to better understand the dynamics of passing the ball at angle without controlling it, as it comes towards the shooting player at an angle.

Please note that for experimental purposes this strategy utilises several manually tested constants. This is because for each pass, we must change the lateral position of the midfielder's or the striker's rod to make sure it first touches the ball but also passes it to the next player. In other words, between each pass we must adjust the players' Y-offset to the ball. Being that each passing player receives the ball at an angle, we can't simply use the ***curve_fiiting_2nd_order_with_roots*** VI…

2. Dynamic conditional step by step player movement

Other than learning more about the ball's dynamics, this strategy also explores dynamic conditional step by step player movement. In previous strategies we have explored step by step motion of a player when the ball is static (e.g. reset steps in section C. ii. 1.). However, in this strategy, the ball is always moving, yet we must find a way to adjust the rods' position between every pass (or as we will see later between every two passes).

To do so, we must first understand and identify when we must change the players' Y-offset from the ball. Suppose we start the pattern at 1BM. The individual passes to complete are:

$$PAIR\ 1: \begin{cases} \text{1BM} \rightarrow \text{MS} \\ \text{MS} \rightarrow \text{1TM} \end{cases}$$

$$PAIR\ 2: \begin{cases} \text{1TM} \rightarrow \text{1TS} \\ \text{1TS} \rightarrow \text{MM} \end{cases}$$

$$PAIR\ 3: \begin{cases} \text{MM} \rightarrow \text{1BS} \\ \text{1BS} \rightarrow \text{1BM} \end{cases}$$

First, note that each pair of passes contains one pass from the midfielder rod to the striker rod and one pass from the striker rod to the midfielder. Intuitively, we understand that we have to change the players' positions between each pair, i.e. every two passes. Furthermore, we can go as far to say that we must make the position change during the second pass of each pair (i.e. from striker rod to midfielder rod) because we have started the pattern on the midfielder rod.

To illustrate this, let us follow the ball's movement starting from 1BM. The ball is shot by 1BM to reach MS. To do so 1BM is positioned at a Y-offset from the ball of $Y_{1,M\to S}$. Similarly, MS is positioned at a Y-offset from the ball of $Y_{1,S\to M}$ to not only be able to touch the ball but pass it to 1TM. 1BM shoots the ball to MS who then passes the ball in the direction of 1TM. At this point, the midfielder rod is still positioned such that the players have a Y-offset from the ball of $Y_{1,M\to S}$. However, this offset will not enable 1TM to pass the ball to 1TS. Therefore, after the pass from 1TM to 1TS is initiated, we have to change $Y_{1,M\to S}$ to a new offset $Y_{2,M\to S}$ and whilst we are at it, $Y_{1,S\to M}$ to $Y_{2,S\to M}$ to prepare for the next pass, from 1TS to MM. This means that we must have a total of 3 pairs of offsets that we navigate through one after another. The question now becomes how, where and when do we change offset pairs?

Using a case structure, we can set one case for each pair of offset. To move from one case to the next, the goal is to impose a condition that will be triggered as the ball follows the path described by the second pass of each pair. We know that the second pass of each pair is in the negative X direction which means that for all the second passes of each pair the ball travels with a speed $V_x < 0$. We have our first condition. However, this condition is necessary but not sufficient because the ball has to navigate through all three cases one after the other. Yet if the condition to pass from one case to the next is only based on $V_x$ being $< 0$, then as the ball goes from the striker rod to the midfielder rod i.e. $V_x < 0$, we will loop through all the cases (probably more than once!) and end up on a random offset case as the ball is shot in the other direction (that is if the ball can even be shot)... The second condition therefore has to satisfy the following:

1. It has to initiate the offset change relatively early to let the players stabilise at this new offset before the ball arrives.
2. It has to be punctual to prevent an "over-cycling" of the case structure, as mentioned previously. In other words it has to happen only once when the ball goes from the striker rod to the midfielder rod.

To satisfy 1., we must make sure that the offset change occurs as soon as the pass is initiated. Therefore, we can set a position condition on the ball such as

When $X_{ball} = X_{striker,rod} - MARGIN$, condition 2 is true.

This condition would also satisfy 2. because it happens only once as the ball travels from the striker rod to the midfielder rod. However, it should be noted that it happens at most once. Indeed "$X_{ball} =$"-type conditions are very hard to satisfy due to the fact that the ball's position is registered periodically by a vision loop every $T = 2\ ms$. This means that the ball can travel, for example, from $X_1 = 200\ mm$ to $X_2 = 50\ mm$ without necessarily being recorded at every single point in that interval. If we wanted every single point in that interval to be recorded, we would need $T \to 0$ which is impossible... To solve this issue, we can set a range condition:

When

$$X_{striker,rod} - MARGIN - MARGIN_{left} > X_{ball} > X_{striker,rod} - MARGIN - MARGIN_{right},$$

condition 2 is true.

Nevertheless, with a range-type condition, 2. is not satisfied: if the ball is recorded more than once within the interval $[X_{striker,rod} - MARGIN - MARGIN_{right}\ , X_{striker,rod} - MARGIN - MARGIN_{left}]$, then we will over-cycle through the cases. To solve this problem, we can set a short timer when entering a new case that prevents over-cycling. Let us illustrate this.

The ball still starts at 1BM. It successfully reaches MS, who shoots the ball towards 1TM. As soon as the ball is shot, condition 1 ($V_x < 0$) is satisfied. When the ball passes through $[X_{striker,rod} - MARGIN - MARGIN_{right}, X_{striker,rod} - MARGIN - MARGIN_{left}]$ condition 2 is satisfied. We switch cases. Without a timer, if condition 2 is satisfied more than once i.e. if the ball is registered a second time within the interval, we switch cases again and instead of having the second pair of offsets, the third pair of offsets is applied. Setting a timer when condition 2 is first satisfied, we can prevent any over-cycling: we impose that, to be able to move on from the case corresponding to the second pair of offsets to the third, this timer must run out. The timer has to be set within the following interval (setting $t$(condition 2 is first satisfied) $= 0$):

[Max time taken to go from $X_{striker,rod} - MARGIN - MARGIN_{left}$ to $X_{striker,rod} - MARGIN - MARGIN_{right}$ ,
Minimum time before next pass from the striker rod to the midfielder rod]

This makes sure that any over-cycling is prevented and that the timer runs out before we need to switch cases again.

Hence, we have the following 3 conditions for case switching:

- Condition 1: $V_x < 0$
- Condition2 : $X_{striker,rod} - MARGIN - MARGIN_{left} > X_{ball} > X_{striker,rod} - MARGIN - MARGIN_{right}$
- Condition 3: Timer started at previous case switch has run out. For the initial shot, there are no “previous case switch", therefore this condition is not needed, and the timer can be set to $0$.

Implementing this in the ***Spring_2024_Crown_1*** strategy allows for smooth and efficient offset transition between each pair of passes.

## D. Controlling the ball at an angle

Being that we are able to follow the ball's movement at every moment in time, this task may not seem necessary. However, as our opponent starts to shoot the ball harder and therefore as the ball starts to move faster, we are limited by the vision loops' sampling period ($\Delta T = 2\ ms$) i.e. for a given distance travelled, less points will be recorded as the ball moves faster. Furthermore, when the ball arrives towards a blue player at high angle, the position of the controlling player needs to be adjusted to maximise our chances of controlling the ball (Fig. 9). The goal is therefore to anticipate the ball's trajectory by using different ball properties such as its speed for example.

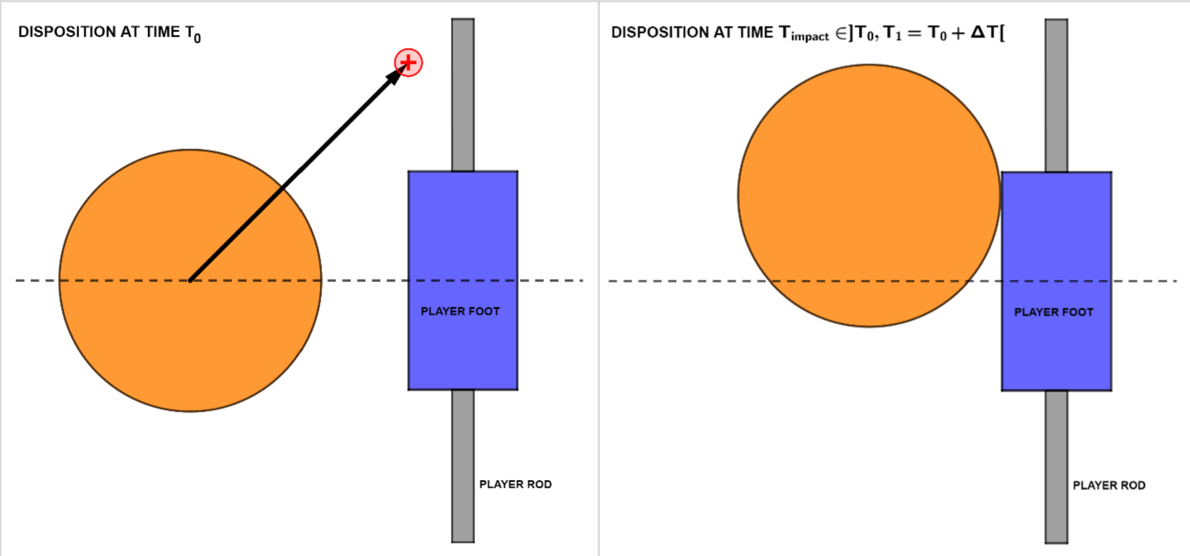



*Figure 9: Explanatory schematics. The black arrow shows the ball's speed vector, the red cross shows the position of the centre of the ball at time $T_1 = T_0 + \Delta T$ if it doesn't deviate from the trajectory defined by the black arrow i.e. if we neglect all obstacles.*

*Explanation: The ball's position is recorded every $\Delta T$. In the scenario depicted on the left in the schematics above, using simple ball tracking to position the player we want to control the ball with, will not work. This is because the ball will touch the player's foot in the short interval of time between $T_0$ and $T_1$. During this interval of time, the controlling player's foot is positioned to control a ball positioned at $\left(X_{ball}(t = T_0), Y_{ball}(t = T_0)\right)$. Therefore, when the ball hits the player's foot at a time $T_{impact} \in ]T_0, T_1[$, odds are that the ball will not be properly controlled (situation depicted on the right).*

One may say that the being that we have such a high sampling frequency for the position of the ball – $f_e = 1/\Delta T = 500\ Hz$ – we do not need to predict the ball's position. However, suppose the ball is travelling at top competitive foosball shot speeds ($13\ m \cdot s^{-1}$) at an angle of $ANGLE_{ball} = 45°$: in this situation the error in the controlling position along the Y axis would be of $V_{ball} \cdot \sin(ANGLE_{ball}) \cdot \Delta T \approx 0.018\ m = 18\ mm$ which is in no way negligible. Even in the context of recreational foosball where the ball is said to reach speeds of about $5\ m \cdot s^{-1}$, with the same shooting angle of $45°$, the error in the controlling position along the Y axis could reach $7\ mm$.

The idea to complete this task is rather straightforward. For visualisation purposes, suppose the following situation: the ball is moving towards a blue players' rod in the negative X direction. Our strategy to attempt to control the ball is the following:

There are two situations:

- EASY: the ball is not travelling too fast and in a more or less straight line. Here we can simply follow the ball along the Y axis with the blue players.

- HARD: the ball is travelling fast and at an angle (Fig. 9). Here to position the blue players along the Y axis we will have to anticipate the ball's position when it arrives at the blue players' rod's level. By predicting the ball's trajectory, we can determine the point at which it will intersect the blue players' rod and hereby position the players accordingly.

The question now becomes: how can we predict the ball's trajectory accurately when it is moving?

### i. Predict the ball's trajectory when it is in motion

Suppose our goal is to control the ball with the blue defenders as it travels fast and at an angle. We can make the accurate hypothesis that the ball is travelling in a straight line.

First and foremost, it is important to note that in the context of this task, when we are estimating the ball's trajectory, we need to make sure that its trajectory is stable. This is to say that before reaching the blue defenders' rod, the ball will not bump into any obstacles such as a player's foot or a wall which would change its travelling direction. To make sure of this stability, we have carefully chosen the area where we will be estimating the ball's trajectory as the area between the limit of the area of control of the white strikers (shown in red on Fig. 11) and the blue defenders' rod. Taking into account that the ball's trajectory has to be determined relatively early to leave time for the adjustment of the defenders' rod translational position, we have reduced this area to the area between the limit of the area of control of the white strikers and the midpoint between the white strikers' rod and the blue defenders' rod. We will call this area the "estimation area" (shown in green on Fig. 11).

From there, the idea is to determine the angle the ball is travelling at, at every position recorded within this area, using the following formula (justification in Fig. 10):

$$\alpha_i = \arctan\left(\frac{y_{i+1} - y_i}{|x_{i+1} - x_i|}\right)$$

And average out all these angles as follows to estimate the balls trajectory:

$$\alpha_{AVG} = \frac{\sum_{i=0}^{N-2} \alpha_{-i}}{N}$$

Where $N$ is the number of times the ball's position is recorded within the "estimation area".

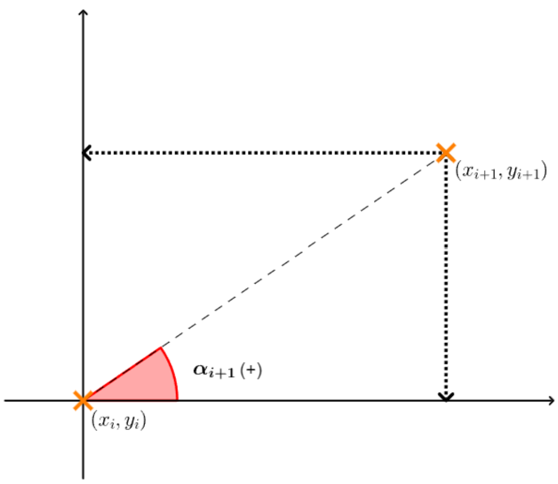



*Figure 10: Explanatory schematic.*

When implementing this prediction method in a VI we need to make sure of a few things:

- Consider the fact that the defender's will be rotated to the "magic angle" when determining the point at which we aim to control the ball at, and in turn the required positioning of the blue defenders' rod to control the ball.
- Check that the ball's trajectory remains stable before reaching the blue defenders i.e. that the ball isn't going to bounce off the wall in the area bordered on one side by the midpoint between the white striker rod and the blue defender rod, and on the other by the blue defenders' foot. We will call this area the "prediction area" (shown in yellow on Fig. 11).

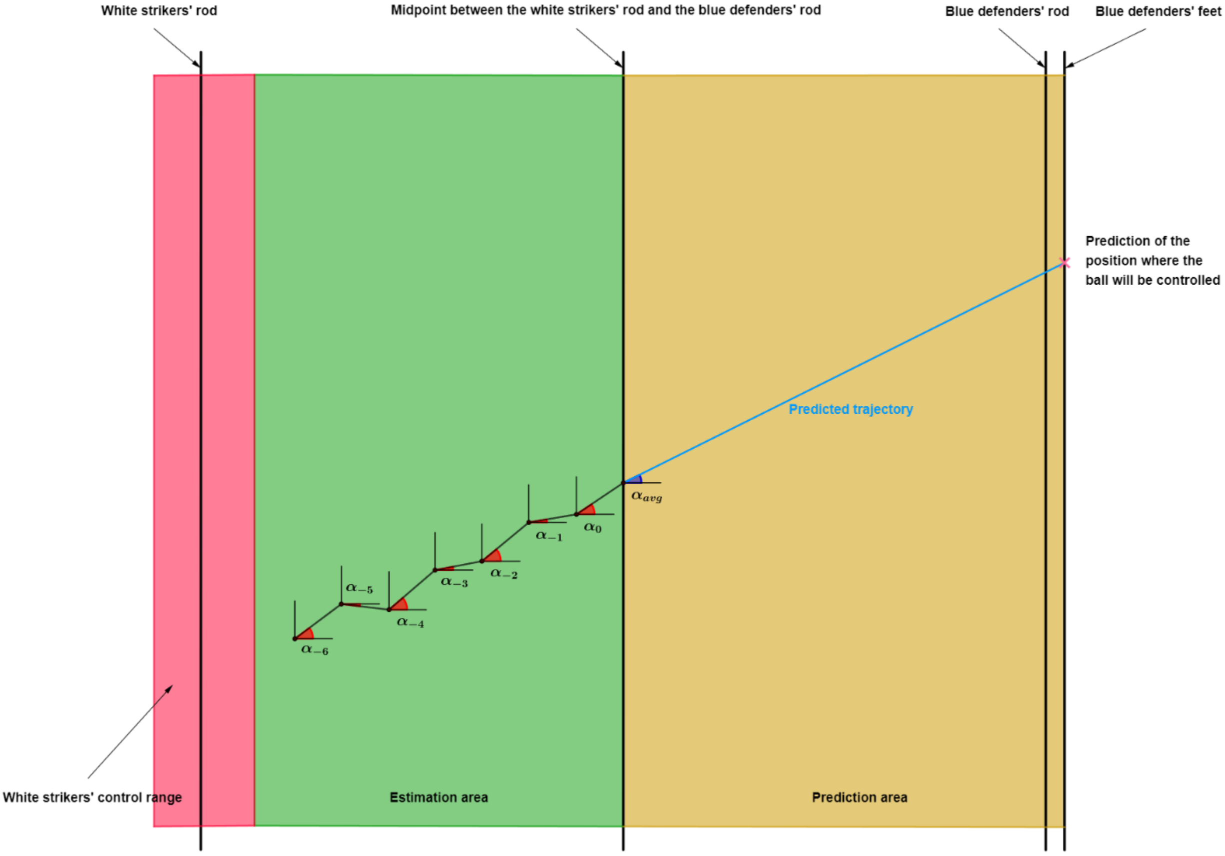



*Figure 11: Explanatory schematic.*

*Please note that a reduced number of registered positions have been represented ($N = 8$) to facilitate the method's comprehension.*

The distance along the X axis between the blue defenders' rod and the blue defenders' feet when they are rotated to the magic angle is 30 $mm$. From this we can now predict the optimal position where the ball needs to be controlled by the defenders as follows:

$$\begin{pmatrix} x_{optimal\ control} \\ y_{optimal\ control} \end{pmatrix} = \begin{pmatrix} x_{blue\ defenders'rod} - 30 \\ \tan(\alpha_{avg}) \cdot \left|(x_{blue\ defenders'rod} - 30) - x_0\right| + y_0 \end{pmatrix}$$

Where $(x_0, y_0)$ is the last recorded ball position within the estimation area.

This strategy has been implemented in the automatic foosball in the ***Spring_2024_Angled_control*** strategy.

## II. Readings and estimations

Ensuring the efficiency and robustness of the automatic foosball relies heavily on the accuracy of camera readings and the subsequent processing of these readings to analyse various characteristics of the ball's dynamics, particularly its speed.

### A. Speed

Considering the critical importance of precise speed estimation in certain strategies, it seemed worthwhile to assess the accuracy of the existing calculations for the ball's speed along both the X and Y axes.

#### i. Testing speed estimation accuracy

As of the 29th of April 2024, the VI used to determine the average speed of the ball is one developed by Yann Morize, ***SpeedEulerYann***. You can read more about this VI and Yann's reasoning in the following report "Vision and strategy: Ball capture, by Yann Morize, Fall 2019" available on the EPFL – Babyfoot website.

To test these readings, we have recorded the following measures for every recorded ball position along 5 random trajectories (Fig. 12): $T(\text{sec})$, $X_{ball}(\text{mm})$, $Y_{ball}(\text{mm})$, $V_X^{Yann}(\text{mm}\cdot\text{s}^{-1})$, $V_Y^{Yann}(\text{mm}\cdot\text{s}^{-1})$.

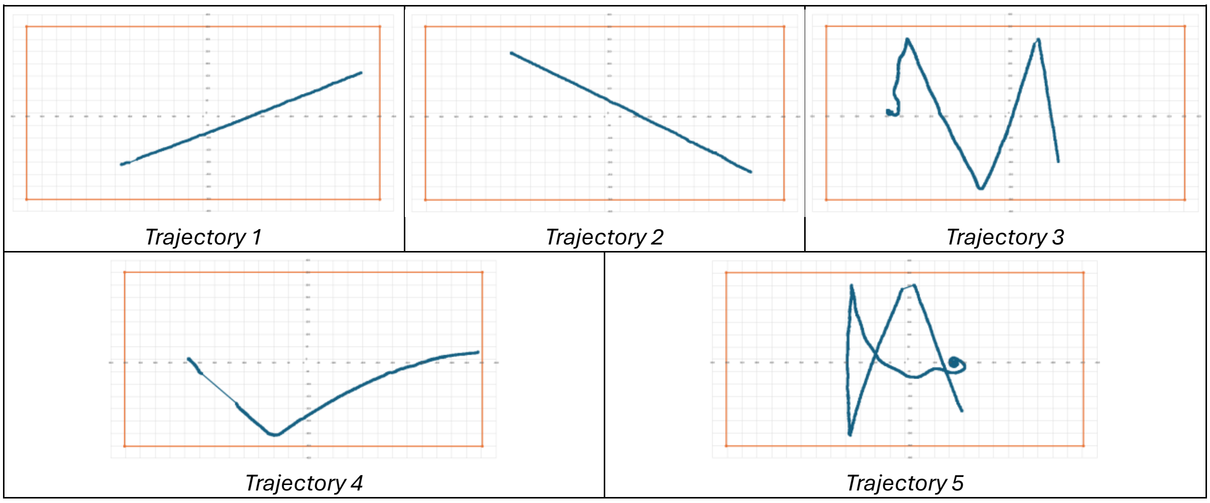



*Figure 12: Studied ball trajectories.*

Note that here we are interested in evaluating the directional accuracy of $V_X^{Yann}$ and $V_Y^{Yann}$: if the ball at a time $T_0$ is registered at a position $(X_{ball,0}, Y_{ball,0})$ with a speed along the X axis of $V_{X,0}^{Yann}$ and along the Y axis of $V_{Y,0}^{Yann}$, then we can anticipate it's position at $T_1$ using the following formula

$$\begin{pmatrix} X_{ball,1,pred}^{Yann} \\ Y_{ball,1,pred}^{Yann} \end{pmatrix} = \begin{pmatrix} X_{ball,0} + (T_1 - T_0)V_{X,0}^{Yann} \\ Y_{ball,0} + (T_1 - T_0)V_{Y,0}^{Yann} \end{pmatrix}$$

From there, to estimate the directional accuracy of $V_{X,0}^{Yann}$ and $V_{Y,0}^{Yann}$, we calculate the length of the orthogonal rejection of the vector going from $(X_{ball,0}, Y_{ball,0})$ to $(X_{ball,1,pred}, Y_{ball,1,pred})$, from the vector going from $(X_{ball,0}, Y_{ball,0})$ to $(X_{ball,1}, Y_{ball,1})$ (Fig. 13). By applying this reasoning at every point of a trajectory, we can evaluate how much the direction we predict the ball to move in deviates from the actual direction it moves in (based on the registered position). This is how we evaluate the directional accuracy of $V_X^{Yann}$ and $V_Y^{Yann}$: the shorter the orthogonal rejection is, the more accurate the speed readings are. With Yann's speed estimations we obtain an average orthogonal rejection of 1 $mm$ from one position to the next when the ball is in movement.

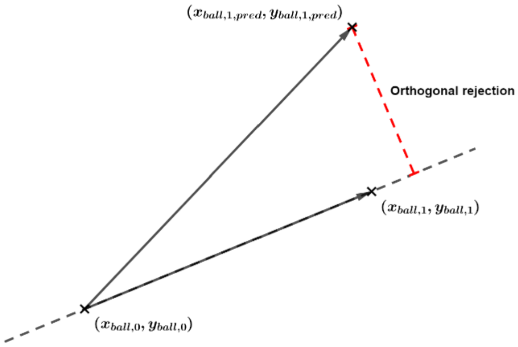



*Figure 13: Schematic to explain how we evaluate the directional accuracy of speed readings.*

*We determine the orthogonal rejection by doing the following:*

1. *First and foremost, we determine the equation of the line going through the points* $(x_{ball,0}, y_{ball,0})$ *and* $(x_{ball,1}, y_{ball,1})$*:*
$$ax + by + c = 0$$
*Where* $a = \frac{y_{ball,1} - y_{ball,0}}{x_{ball,1} - x_{ball,0}}$, $b = -1$ *and* $c = y_{ball,1} - ax_{ball,1}$.
2. *From there we can determine the shortest distance from* $(x_{ball,1,pred}, y_{ball,1,pred})$ *to the line previously defined i.e. the orthogonal rejection of the vector going from* $(x_{ball,0}, y_{ball,0})$ *to* $(x_{ball,1,pred}, y_{ball,1,pred})$*, from the vector going from* $(x_{ball,0}, y_{ball,0})$ *to* $(x_{ball,1}, y_{ball,1})$ *:*
$$distance\ \left(ax + by + c = 0, (x_{ball,1,pred}, y_{ball,1,pred})\right) = \frac{ax_{ball,1,pred} + by_{ball,1,pred} + c}{\sqrt{a^2 + b^2}}$$

*Please note that normally the numerator is usually taken as absolute value. However, in our scenario, I believe it is more interesting to take into consideration the "sign of the distance" to really identify the estimation model's accuracy.*

### ii. Other speed estimation methods

After, reviewing the results from the above analysis, I have tried to develop my own estimation of the position and speed (+ acceleration but results weren't conclusive) of the ball at time $T_1$ given its previous positions at time $T_0, T_{-1}, \dots$ .

#### 1. Test 1:

My first idea was to use:

- A first retrograde finite difference formula to estimate the acceleration of the ball:
$$A_{ball,0}^{MG} = \begin{pmatrix} A_{X,0}^{MG} \\ A_{Y,0}^{MG} \end{pmatrix} = \frac{\begin{pmatrix} X_{ball,0} \\ Y_{ball,0} \end{pmatrix} - 2 \cdot \begin{pmatrix} X_{ball,-1} \\ Y_{ball,-1} \end{pmatrix} + \begin{pmatrix} X_{ball,-2} \\ Y_{ball,-2} \end{pmatrix}}{\Delta T^2}$$
- A second retrograde finite difference formula to estimate the speed of the ball:
$$V_{ball,0}^{MG} = \begin{pmatrix} V_{X,0}^{MG} \\ V_{Y,0}^{MG} \end{pmatrix} = \frac{\begin{pmatrix} X_{ball,0} \\ Y_{ball,0} \end{pmatrix} - \begin{pmatrix} X_{ball,-1} \\ Y_{ball,-1} \end{pmatrix}}{\Delta T}$$

and thereby estimate the position of the ball using the following kinematic equation:

$$POS_{ball,pred1}^{MG} = \begin{pmatrix} X_{ball,1,pred1}^{MG} \\ Y_{ball,1,pred1}^{MG} \end{pmatrix} = \frac{1}{2} A_{ball,0}^{MG} \Delta T^2 + V_{ball,0}^{MG} \Delta T + \begin{pmatrix} X_{ball,0} \\ Y_{ball,0} \end{pmatrix}$$

2. Test 2:

My second idea was to use the previously estimated acceleration $A_{ball,0}^{MG}$ as well as Yann's estimation of the speed $V_{ball,0}^{Yann}$ to estimate the position of the ball using the following kinematic equation:

$$POS_{ball,pred2}^{Yann/MG} = \begin{pmatrix} X_{ball,1,pred2}^{Yann/MG} \\ Y_{ball,1,pred2}^{Yann/MG} \end{pmatrix} = \frac{1}{2} A_{ball,0}^{MG} \Delta T^2 + V_{ball,0}^{Yann} \Delta T + \begin{pmatrix} X_{ball,0} \\ Y_{ball,0} \end{pmatrix}$$

3. Test 3:

My third idea was to neglect the impact of the acceleration term and estimate the position of the ball using only $V_{ball,0}^{MG}$ as done previously with Yann's readings:

$$POS_{ball,pred3}^{Yann/MG} = \begin{pmatrix} X_{ball,1,pred3}^{MG} \\ Y_{ball,1,pred3}^{MG} \end{pmatrix} = V_{ball,0}^{MG} \Delta T + \begin{pmatrix} X_{ball,0} \\ Y_{ball,0} \end{pmatrix}$$

4. Test 4:

In the context of this task M. Salzmann also recommended taking more than two points to estimate $V_{ball,0}$. That's to say to not necessarily only use $(X_{ball,-1}, Y_{ball,-1})$ in the calculation of the speed:

$$V^{CS/MG}{}_{ball,0} = \begin{pmatrix} V_{X,0}^{CS/MG} \\ V_{Y,0}^{CS/MG} \end{pmatrix} = \frac{\begin{pmatrix} X_{ball,0} \\ Y_{ball,0} \end{pmatrix} - \begin{pmatrix} X_{ball,-i} \\ Y_{ball,-i} \end{pmatrix}}{i \cdot \Delta T}$$

5. Results

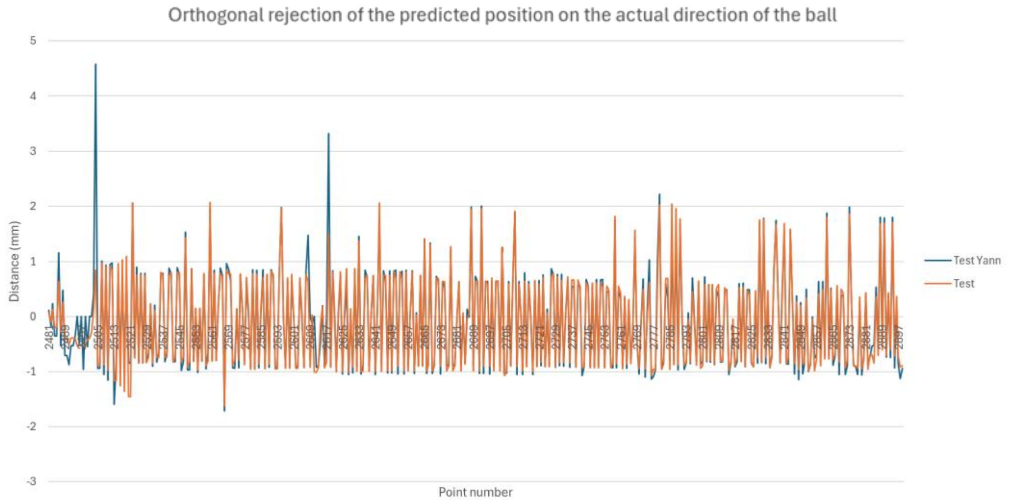
After evaluating the directional accuracy for each model (Fig. 14) as we did previously with Yann Morize's in section II. A. i., we observe that the most reliable and accurate speed reading is the one where the speed is defined as it is in test 4, with $i = 19$:

$$V^{CS/MG}{}_{ball,0} = \begin{pmatrix} V_{X,0}^{CS/MG} \\ V_{Y,0}^{CS/MG} \end{pmatrix} = \frac{\begin{pmatrix} X_{ball,0} \\ Y_{ball,0} \end{pmatrix} - \begin{pmatrix} X_{ball,-19} \\ Y_{ball,-19} \end{pmatrix}}{19 \Delta T}$$

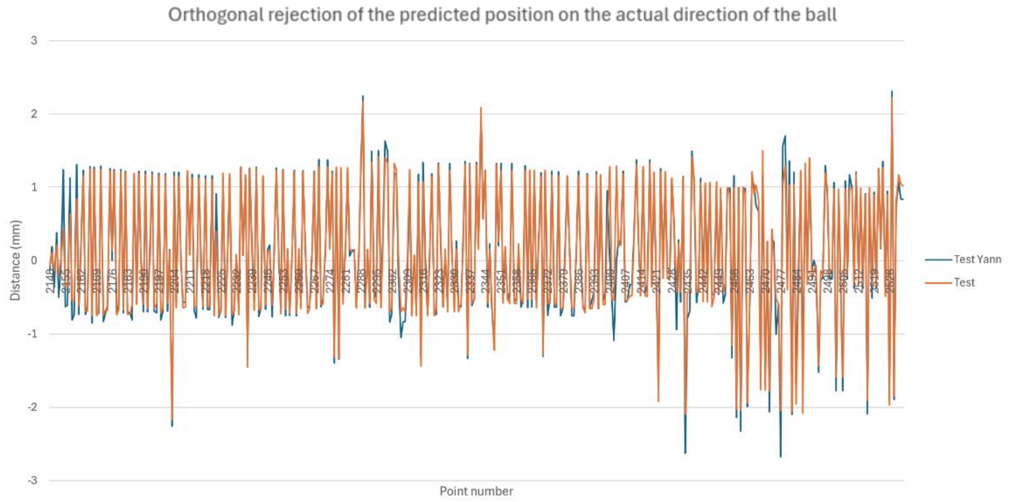
On average, for a given trajectory of approximately 4000 recorded positions, this model is 3% more accurate than Yann's.

That being said, it is important to note that given the method we have used to evaluate the accuracy of the speed estimation, this evaluation depends on the accuracy of the ball's position readings themselves. Therefore, I have chosen not to change the method of estimating the speed of the ball for two reasons. First, the relative improvement is marginal, only 3%. Second, I believe that Yann's measurements were taken in a potentially more stable environment for the cameras. Indeed, during the semester, I was working alongside Mr. Keusch who was working on calibrating the cameras which can cause minor changes in the camera's setup and positioning. These adjustments could have introduced uncertainties or variations in the values recorded during my data collection. This is why I believe that it is best to stick with Yann's method for now and change the speed estimation method later, if need be, when we are satisfied with the camera's readings and calibration.

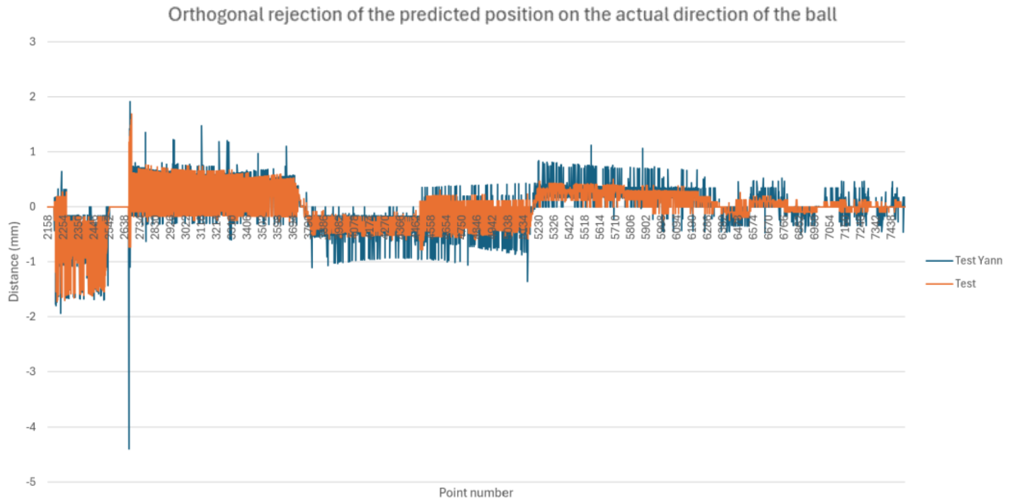
Nevertheless, this part of the project was a great way to explore different speed estimation techniques as well as the different ways to evaluate these techniques depending on our objectives.



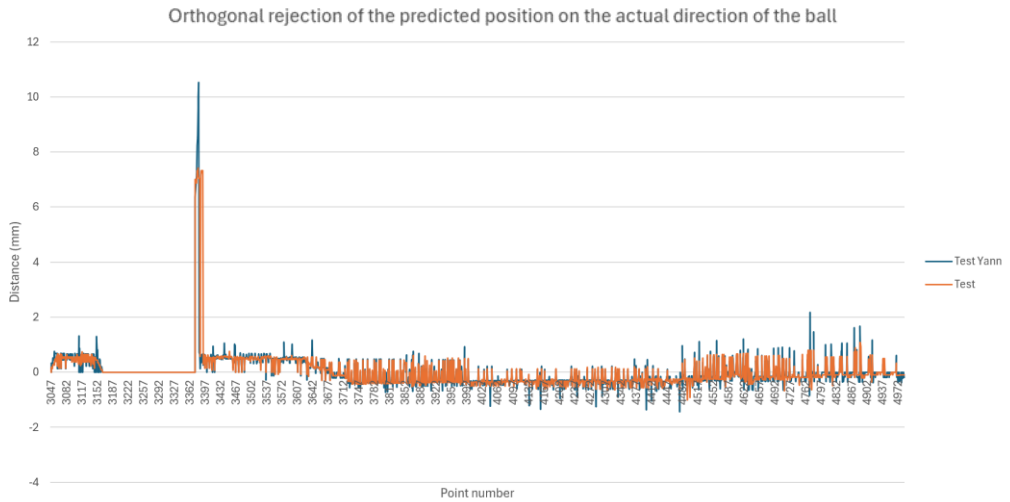

*Trajectory 1*



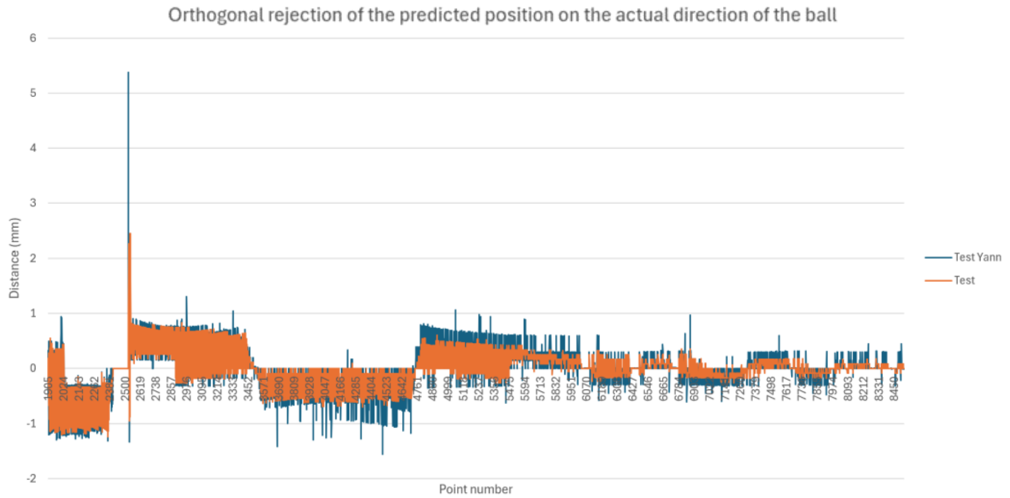

*Trajectory 2*




*Trajectory 3*




*Trajectory 4*




*Trajectory 5*

*Figure 14: Table of results for each trajectory. The blue curve shows the orthogonal rejection of the predicted ball position, using Yann's model, on the actual direction of the ball. The orange curve shows the orthogonal rejection of the predicted ball position, using the model from test 4 with* $i = 19$, *on the actual direction of the ball.*

# III. Real-time adaptation

At this stage, we know and understand how to make the ball move in a certain way i.e. vertical juggling, horizontal juggling, angled shots etc. We have also designed a few strategies that are able to adapt with the foosball's layout (ball position and white players' positions and rotations) given a specific situation (for example the blue strikers have the ball) i.e. the ***Summer_2023_Scan_Shoot_Straight*** strategy as well as the damping strategies etc.

However, it is very important to note that the efficiency and working of these strategies relies on accurate and consistent ball-position tracking and readings. This is one of, if not the, automatic foosball's biggest challenge: accurate and consistent ball tracking. Indeed, if the camera calibration is off by as little as $1\ mm$, the ball position readings can be offset by at most $6\ mm$! This leads to the need for manual adjustments in the strategies through the introduction of offset constants.

Luckily, I have been working alongside Guillaume Keusch during this semester, a Master student at EPFL, whose focus is on calibrating the camera. This calibration is, in my opinion, the last piece to the foosball-puzzle, even if it is the biggest piece yet: with precise and harmonious ball readings, the strategies will gain in robustness and autonomy – there will no longer be a need for any offset constants or even if there is, these will not need to be changed every time the camera moves just a little i.e. once established, they will remain unchanged.

Considering this need for robustness and adaptability in calibration, working on more sophisticated strategies is not currently the area where the most significant progress can be made. Please note that this doesn't mean that all the previously developed strategies will go to waste: independent VIs have been created to mimic each strategy considering their inputs (ball position etc.) as accurate and reliable, and therefore contain a limited number of constants, if any!

That being said, what we can work on for the time being is strategy navigation i.e. creating a decision tree to navigate efficiently and rapidly through strategies based on the foosball's real-time layout.

To do so we must understand what we can and cannot do with the ball given the foosball's pitch real-time layout. To do so, we will create a visualisation VI. Specifically, the objective here is:

- When the ball is within range of a blue player rod, show all the possible trajectories for passing the ball to another player rod, or shooting the ball, given the current layout (ball position and white players' position and rotation).
- When the ball is within shooting range of a white player, show the predicted ball trajectory if the player were to take the shot.

## A. Visualisation

### i. "When the ball is within range of a blue player rod" task

For now, the objective is to indicate to the user when the ball is in range of a blue player rod and if this is the case, all the possible trajectories for a pass to another specific player rod or a shot on goal given a real-time foosball layout (ball position and white players' position and rotation).

The first step of this strategy is to find the intersection of each of the white players foot with the plane parallel to the pitch's ground offset by the ball's diameter (see dotted blue line on Fig. 16). This requires not only to consider the white players' position along Y ("translational" position) but also how their positions vary along X when the players rotate ("rotational" position).

For representation purposes, we have simplified the players' geometry to a cuboid (see Fig. 15). Using this representation, we notice that the surface formed by the intersection between the plane defined previously and the players is a rectangle. Note that the dimension of this rectangle along the pitch's Y axis is constant as it equal to the players' width i.e. $21\ mm$. However, the dimension of the rectangle along the pitch's X axis varies with the player's angle (this dimension is shown in red on Fig. 16). We can determine this dimension using trigonometry (the calculations are not detailed here because they are tedious; you can however find more details about these calculations on the ***Player_foot_imprint*** VI).

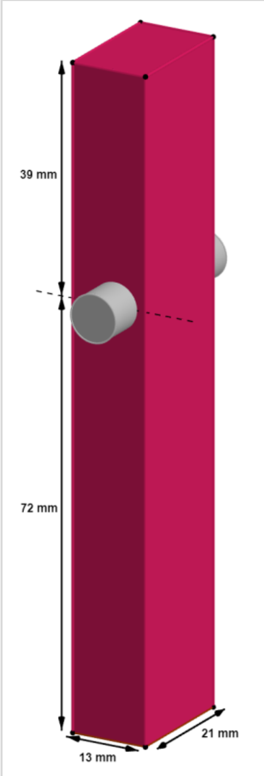


*Figure 15: Cuboid with the players' dimensions.*

From there we can apply these calculations to every rod and map out the surfaces (specifically the rectangles) where the top of the ball will be in contact with one of the players foot (Fig. 17) i.e. the intersection of each of the white players foot with the plane parallel to the pitch's ground offset by the ball's diameter.

Finally, by knowing where the ball cannot travel if we do not want it to be intercepted (i.e. the "intersection" rectangles) and by knowing when the ball is within reach of one of the blue players' rods, we can determine, based on a certain objective (i.e. shooting or passing the ball to a certain player), the feasible shots given the "translational" and "rotational" position of the white players, whilst considering different factors such as:

- The reachability along Y for shooting i.e. if the ball is within reach of a blue player and not only its rod (rod translation limits).
- The reachability along Y for receiving, if the objective is to pass the ball to another player.

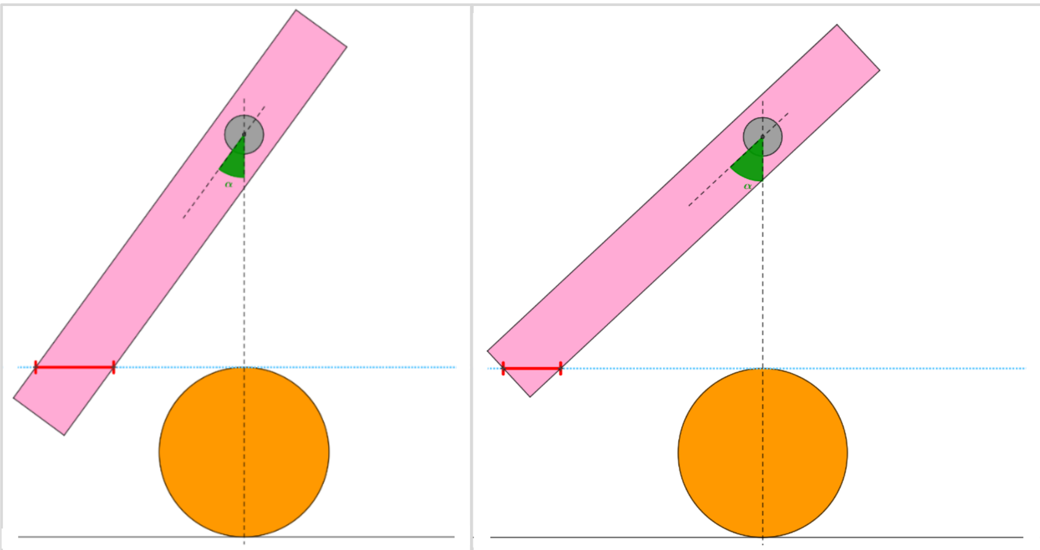


*Figure 16: Schematic showing how the dimension along the pitch's X axis of the "intersection rectangle" varies with a player's angle.*

From this VI we can also determine the safest shot i.e. the shot trajectory that stays the furthest away from any of the opponent players, as well as show the ball's trajectory. No pictures have been included to illustrate all these options because it is more fun for the reader to test all these out for himself directly on the foosball's main VI!

Note that uploading this visualisation VI to the foosball's main VI and connecting it to the various real-time variables (ball coordinates, player positions and angles) shined a light on the fact that the values recorded by the laser sensors for one same angle changes depending on the Y-position of the white players' bar. In my opinion, this variability may come from the fact that some of the players' bars are possibly slightly warped. This causes the position of the laser pointer on the 3D printed piece at the end of each bar to change as the bar translates, thus causing irregularities. To resolve this issue, using a "data collecting" type VI, I was able to plot the neutral angle curve (player in the low position) as a function of the Y position, for each rod (Fig 18). Finally, by utilising linear interpolation, the ***Opponent_initial_ang_finder*** VI is able to determine any rod's neutral angle for any position along the Y axis, thereby allowing us to properly incorporate the visualisation VI.

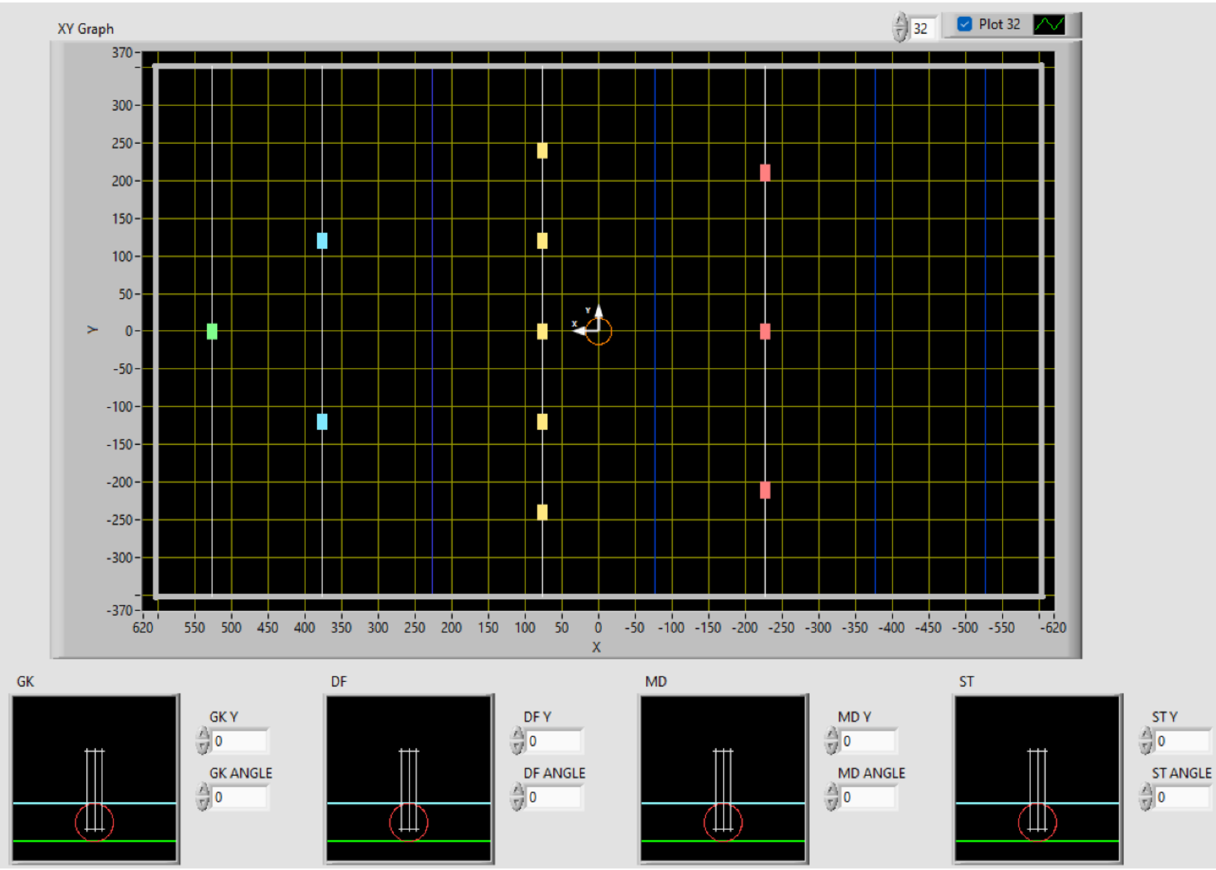



*Figure 17: Screenshot of the visualisation indicators on the front panel of the **All_players_foot_imprint** VI. The rectangles show where the top of the ball will be in contact with one of the players' foot i.e. the "no-go" zones.*


*Figure 18: Plots of the neutral angle (player in the low position) as a function of the Y position of each white player rod.*

### ii. "When the ball is within shooting range of a white player" task

Moving on, the objective is now to indicate to the user when a white player is in control of the ball and, if this is the case, the most likely ball trajectory if the player were to shoot the ball in his current position.

For this visualisation task, the first thing we must do is update the ***curve_fitting_2nd_order_with_roots*** VI to do the opposite of what it currently does which means tweaking the VI so that it is able to find the angle a ball is shot at given a Y-offset and a X-offset from the ball. This has been done in the ***curve_fitting_2nd_order_with_roots_UPGRADED*** VI where you can choose the task you wish to perform:

- "ANGLE + X-OFFSET -> Y-OFFSET": Given a known shooting angle and an X-offset, find the required Y-offset.
- "Y-OFFSET + X-OFFSET -> ANGLE": Given a known Y-offset and X-offset, find the angle at which the ball will be shot at.

From there, we can now implement this to the ***All_players_foot_imprint*** VI!

# IV. Calibration related work

As mentioned previously, during this semester I was working alongside Guillaume Keusch whose goal was to improve the camera's calibration and accuracy. As part of this task, Prof Salzmann and Mr Keusch suggested using the players' positions to calibrate the camera. To contribute to this task, I decided to compare the camera-perceived positions of the players with their actual positions set by the motors responsible for their translational movement.

To do so, I have recorded the position of the ball at specific locations around each player (Fig. 19). For these measurements (Fig. 20), the player rods were all set to the position 0 and with an angle of 180° i.e. foot down.

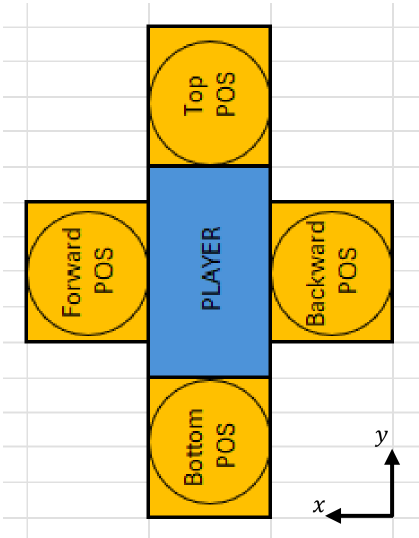



*Figure 19: Locations around each player where the ball's position was recorded.*

To fill in the "Calculated" column in Fig. 20, the following calculations were used for each player:

$$X_{calculated} = \frac{X_{Forward}+X_{Backward}}{2} \quad \text{and} \quad Y_{calculated} = \frac{Y_{Top}+Y_{Bottom}}{2}$$

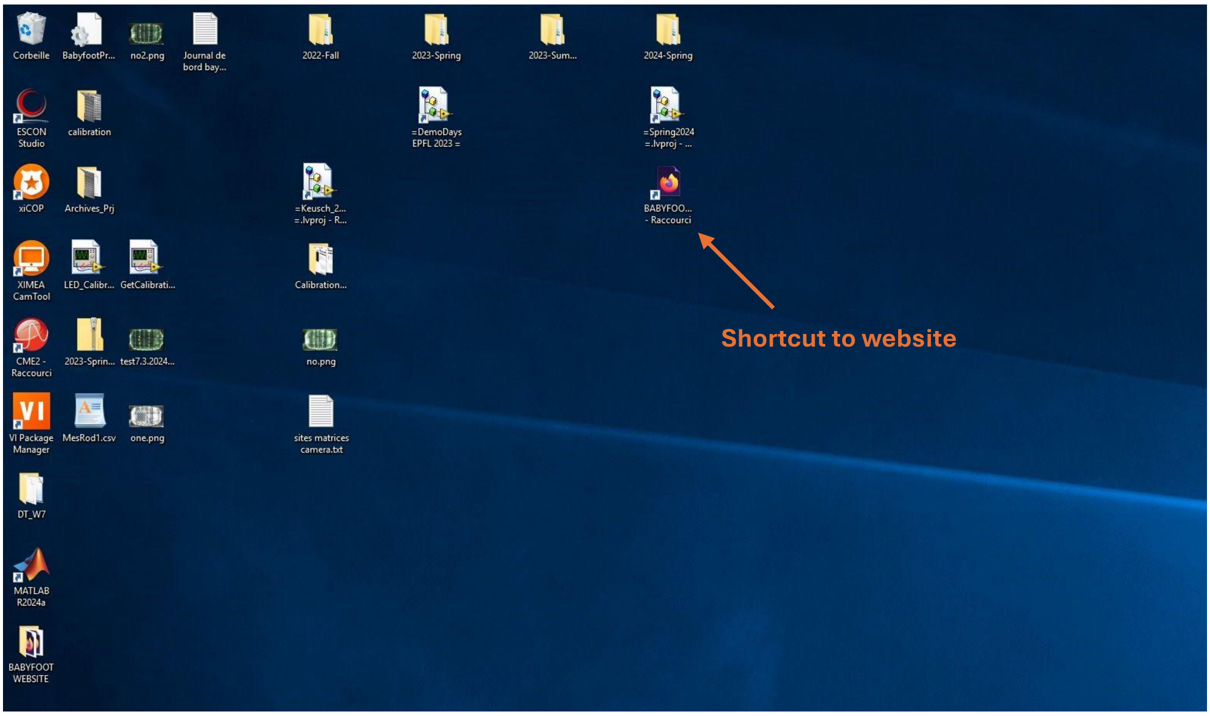
| PLAYER | Forward POS | | Top POS | | Backward POS | | Bottom POS | | Theoritical | | Caculated | | Error | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | X | Y | X | Y | X | Y | X | Y | X | Y | X | Y | X | Y |
| 1 TS | 246.58 | 208.54 | 232.57 | 237.58 | 198.95 | 208.87 | 232.92 | 182.64 | 226.5 | 210 | 222.765 | 210.11 | 3.735 | 0.11 |
| MS | 249.13 | -0.45 | 232.93 | 29.25 | 202.91 | 0.69 | 234.86 | -25.68 | 226.5 | 0 | 226.02 | 1.785 | 0.48 | 1.785 |
| 1BS | 251.35 | -205.87 | 235.63 | -177.15 | 205.99 | -207.12 | 237.89 | -236.29 | 226.5 | -210 | 228.67 | -206.72 | 2.17 | 3.28 |
| 2 TM | -54.35 | 223.94 | -73.05 | 251.99 | -100.02 | 222.37 | -72.51 | 196.8 | -76.5 | 240 | -77.185 | 224.395 | 0.685 | 15.605 |
| 1 TM | -56.31 | 118.53 | -72.25 | 143.36 | -100.32 | 116.78 | -72.24 | 89.32 | -76.5 | 120 | -78.315 | 116.34 | 1.815 | 3.66 |
| MM | -54.13 | 0.5 | -72.36 | 26.64 | -98.83 | -1.64 | -71.53 | -29.23 | -76.5 | 0 | -76.48 | -1.295 | 0.02 | 1.295 |
| 1BM | -53 | -119.49 | -71.04 | -92.88 | -96.6 | -120.59 | -71.02 | -147.67 | -76.5 | -120 | -74.8 | -120.275 | 1.7 | 0.275 |
| 2BM | -49.79 | -237.52 | -71.25 | -211.45 | -93.94 | -237.42 | -68.67 | -264.04 | -76.5 | -240 | -71.865 | -237.745 | 4.635 | 2.255 |
| TD | -355.11 | 110 | -374.34 | 136.43 | -400.73 | 110.35 | -374.75 | 82.37 | -376.5 | 120 | -377.92 | 109.4 | 1.42 | 10.6 |
| BD | -353.17 | -124.74 | -370 | -96.21 | -396.54 | -127.76 | -373.07 | -151.77 | -376.5 | -120 | -374.855 | -123.99 | 1.645 | 3.99 |
| GK | | | | | | | | | | | | | | |

*Figure 20: Table of the recorded ball's position at every location around each player. On the far right, in the error column, we calculate the absolute error between the camera-perceived positions of the players and their actual positions.*

Please note that no measurements were taken for the goalkeeper because the ball's position cannot be registered near that area.

# Website

As part of the automatic foosball project, easy access to comprehensive information is crucial for developing new strategies. To streamline this process, I have developed a locally hosted website on the foosball computer. This platform enables students to quickly access essential project details without the need to navigate through various interfaces or past reports. It centralises important information, making it more accessible and efficient for strategy development. Make sure to check it out!



# Next steps

We're making significant progress towards achieving a fully automated and functional foosball system. As we approach the final stages of development, there are a few key aspects of the foosball setup that I believe still require optimisation:

- Ball position camera readings: as mentioned previously, this is quintessential to allow the strategies to run smoothly as well as gain in robustness and in turn efficiency.

- Designated “ball angle VS Y-offset” graphs (Fig. 2) for every player: to enhance the precision of angled shots in our automated foosball system, it would be valuable to implement designated “ball angle vs. Y-offset” graphs for each player. Indeed, despite the apparent uniformity of all blue players, small variations in foot shape or the height of their rod can lead to unique characteristics in each player's shooting performance.

- Navigating through all the VIs autonomously and in real-time: One of the tasks I would have liked to work on more during this semester was the real-time adaptation involving the creation of a decision tree to navigate through various strategies. I was unable to complete this task due to a lack of time. That being said, I believe it was important to first develop as many strategies, and visualisation and indication tools as possible to truly understand the dynamics of the automatic foosball, thereby simplifying the development of the decision tree.