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Identification of Sources of Variation in the Initial Conditions of the Ball for Shots with the Tech United Soccer Robots

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Identification of Sources of Variation in the Initial Conditions of the Ball for Shots with the Tech United Soccer Robots

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Abstract

Tech United is a team that focuses on innovation in the field of robotics through soccer robots and healthcare. During games, the soccer robot passes the ball to teammates or shoots on goal. When multiple shots are taken by the Tech United soccer robot using the same settings, the ball does not land in the exact same spot every time. Variation is undesired in the shot, as the autonomous robots cannot calculate explicitly where the ball will land. This impedes the robots to shoot accurately. This report focuses on the identification of sources of variation in initial conditions of the ball when shots are taken by the Tech United Soccer Robots. The two potential sources of the variation in the initial conditions of the ball that are investigated in this report are the ball handling and the ball orientation.

Experiments are done by shooting the ball multiple times for different scenario's, calculating the initial angle and velocity of the ball from the measured trajectory. From the results, the standard deviation, and thus the variation, can be determined. It can be concluded that the ball handling has a significant effect on the variation in the shot. This is expected since the ball handling wheels are controlled using only their own height as an input and contradict the ball motion when shooting. A variation in the voltage of the ball handling motors or in the height of the ball handling wheels causes the ball handling to interfere differently with the ball, causing a variation in the initial ball conditions.

The ball orientation is expected to be a source of variation since the ball has inconsistent parameters over its surface like the stiffness of the surface. The ball is made from hexagonal surfaces, stitched together. The hexagonal planes and the seams have different properties, that is why the parameters of the ball are inconsistent over its surface. The two most varying contact area's on the ball are tested with, being the middle of the hexagonal surface on on the ball and the intersection of seams. The initial velocity of the ball with the lever tip hitting the ball in one of these two areas have been compared to see if the initial velocity of the ball is significantly different. The tests show that the orientation of the ball does not have a significant effect on the initial velocity of the ball, as the average velocity for the different contact area's is very similar. However, the test result showed that the standard deviation of the shots taken on the intersection of seams is lower than for the shots taken on the middle of the hexagonal planes. This means that the shots taken on the intersection of seams show less variation in the initial ball conditions.

Contents

1 Introduction

Tech United is a multidisciplinary team of students, PhD students, employees and alumni of the Eindhoven University of Technology, mostly from the Control System Technology group. This team innovates in the field of robotics trough robot soccer and healthcare. Soccer is a popular sport all over the world, playing soccer with robots is an ambitious challenge for students in the field of software and mechatronics [1].

The soccer robots of Tech United compete in the Middle Size League, organised by the RoboCup Federation. In the form of a tournament, this is a soccer league where two teams of five robots play soccer autonomously, communicating over a wireless network. The robots make every decision by themselves, the only human element in the games is the referee. The intention of RoboCup is to promote robotics and artificial intelligence research. The eventual goal of RoboCup is to defeat the human soccer world champions by 2050 [2].

The soccer robots of Tech United are called TURTLEs. The main features the TURTLEs require to play soccer are that they can drive in every direction, grab the ball using a ball handling system and have a shooting mechanism to pass or shoot the ball. The TURTLEs use cameras to see the environment around them.

To defeat the human soccer world champions by 2050, accurate and consistent passes to teammates and shots on goal are important requisites. Currently, the passes and shots lack a considerable amount of consistency. Due to the introduction of variation, the passes and shots do not follow the aimed trajectory. This is especially the case with lob shots. Variation is a problem for the soccer robots. Even though the robots are calibrated before the games, the variation can not be fully resolved by the calibration. The controller of the robots cannot cope with variation when aiming as it is impossible to predict the variation beforehand.

To increase the consistency of the shots, the variation in the shots has to be decreased. However, currently the variation and its causes are not fully understood. Therefore, sources of variation have to be found. After the identification of the sources of variation in the initial conditions of the ball for the shots of the Tech United soccer robots, the variation can be addressed.

Eliminating all variation is unrealistic. However, it is believed that the variation still can be decreased significantly. To do so, the most influential sources on the variation have to be found. In this report, sources of variation in the initial ball conditions for shots taken by the Tech United soccer robots are identified and tested on its significance.

2 General mechanics

In this section, the general mechanics of the most important elements of the soccer robot used for shooting are explained. These are the shooting mechanism itself and the ball handling.

2.1 Shooting mechanism

The TURTLEs are equipped with a shooting mechanism to shoot or pass the ball during games. This shooting mechanism consists of multiple components, namely the capacitor, solenoid and the lever. In Figure 2.1, a schematic overview of the shooting mechanism with its relevant components is shown. Element I is a fixed pivot point. At connection II, the lever is attached to a string which can lift point II up and down. Therefore the height of the lever tip IV can be adjusted. With a different height of the lever tip, the contact point with the ball is different as well, thus changing the initial angle α_0 of the ball. This way, the robot can aim the ball at a certain angle when shooting or passing. At III the solenoid is connected to the lever with a sliding connecting. A solenoid is an actuator assembly with a sliding ferromagnetic plunger inside the coil. By applying power, the plunger shoots out of the solenoid. This gives speeds to the lever tip, resulting in the initial velocity of the ball v_0 directly after impact.

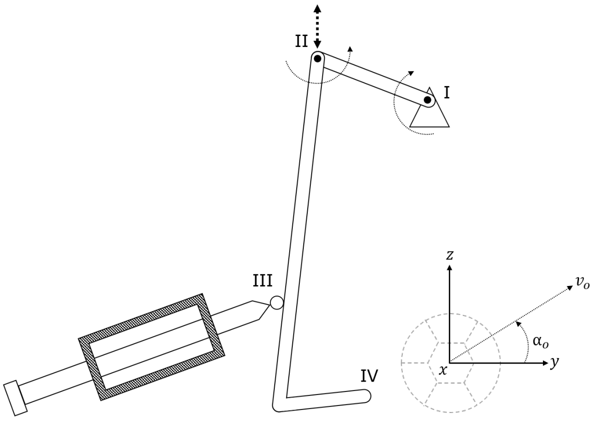


Figure 2.1: Schematic overview of the shooting mechanism.

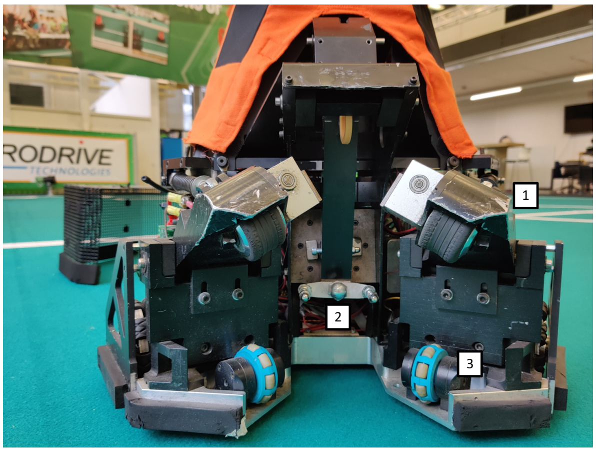


Figure 2.2: Front side of the soccer robot where 1 is the ball handling, 2 is the lever tip and 3 is a passive wheel.

2.2 Ball handling

The TURTLEs have a ball handling to grab the ball when receiving or intercepting a pass, prevent the ball from rolling away while dribbling and to position the ball for a pass or shot. The ball handling of the TURTLEs consist of two constructions, one on each side of the robot. This can be seen in Figure 2.2 at number 1. The ball handling mounted to the robot with a pivot axle and a spring. The pivot axle makes sure the ball handling can move upwards a bit, so the ball can move inside the robot further. The spring is used to have the rubber wheels push onto the ball, so contact will not be lost. The ball handling has a controlled motor to drive the rubber wheels. These wheels spin inwards, because of which the ball will be pulled into the robot when making contact with the wheels. The ball handling is used by the soccer robots to catch the ball when receiving a pass, keep the ball with it while moving and makes sure the shooting mechanism can make contact with the ball when shooting or passing.

3 Sources of variation

The variation in the initial ball conditions of the shots taken by the TURTLEs can have a broad amount of causes. The challenge is to find the most influential causes. Previous research is rehearsed before two hypotheses are put up about the most significant sources of variation.

3.1 Previous research

Various studies are performed into the reproducibility of the Tech United soccer robots. Reproducibility means that the accuracy of the shot is high, i.e. the robots can aim precisely, and that the consistency in the shot is high. The variation in the shot has to be low for the consistency to be high. Accuracy is not a focus is this report, only the variation in the initial ball conditions.

The hardware as well as the software have been investigated. This report is focused on the hardware only, thus a summary of the previous research about the hardware will be given. Multiple variables have already been ruled out to be the source of a significant variation in the shot. In his research [3], C. Kengen showed that the capacitor voltage and lever height show consistent behaviour during shooting. Therefore it is concluded that the variation inside the robot caused by these variables are individually too small to measure accurately to correlate to the variation in the shot. The lever velocity also has been inspected. The lever velocity showed significant variation over different shots. However, this variation could not be correlated with the variation in the initial ball conditions. If this is to be investigated, the lever velocity should be measured more accurately.

Along with the outruling of multiple variables, it was concluded in in [3] that the initial lever position did account for a significant variation in the initial ball conditions. The initial lever position matters since the lever has only that much space to accelerate before hitting the ball. If less space is available, the lever tip cannot transfer the energy generated by the solenoid as efficient as when the lever is pulled back before shooting. The lever did not fall back to the same position after each shot. Because of this, the lever did not start of the same position when shooting. A set of repelling magnets were implemented to generate a force backwards at the end of the plunger's stroke, as well as a set of passive magnets to hold the plunger at its initial position once it is moved backwards. Doing so, the variation in the shot was decreased significantly. The standard deviation for lob shots at a duty cycle of 100% and a lever height of 100% was decreased from 0.32 m/s to 0.08 m/s for the initial velocity and from 1.06°to 0.49°for the initial angle.

In [4], J. Senden recommended that the force between the ball handling wheels and the ball should be incorporated in the software. The output voltage of the potentiometers is nearly linear with the ball handling angle. Still, there is a variation in the output voltage and the ball handling angle. That indicates that the force exerted by the ball handling wheels onto the ball is inconsistent as well. The ball handling thus may have an influence on the variation in the initial ball conditions

In the same research is is shown that the ball pressure has great influence on the initial ball conditions. The relative ball position with respect to the center of the robot showed an error as well, but this problem can be resolved by calibrating the software and will not be further investigated in this report.

I. Franklin looked at the use of spin for bouncing balls [5]. She introduced angular velocity to drastically change the path of the ball when bouncing. Currently, no spin is introduced intentionally. Spin could introduce a variation in the path of the ball, if the spin is significant. However, the angular velocity of the ball is small thus in this report, the initial velocity and angle of the ball are the analysed initial conditions, the angular velocity of the ball will not be considered.

Although the variation in the initial ball conditions has been decreased because of adjustments made in the hardware, variation is still present in the initial ball conditions when shooting. Other sources of variation have to be identified to find out where this variation originates from. The accumulation of small variations can cause a significant variation in the initial ball conditions, but the most influential variables have to be found first to effectively decrease the variation.

3.2 Potential sources of variation

There are plenty elements in the robot that could contribute to the variation in the initial ball conditions of the shots. The challenge however is to find the most significant elements. Small variations can aggregate to be significant, but these are harder to correlate to the variation in the shot and simply less effective to focus on when aiming for a more consistent shot. These small variations could be found in the pressure of the ball, temperature of the coil, hysteresis in the lever, wear in the bearings, mass distribution of the ball, the rope with which the height of the lever is set, capacitor voltage, torsion in the shooting mechanism, force generated by the solenoid and so forth. As said, these variations are expected to be small, accumulated they will introduce a significant variation in the initial ball conditions.
To decrease the variation effectively, the variables that introduced variation the most should be found first. Hypotheses can be put up for the variables that are expected to have a significant impact on the various of the initial ball conditions of the shot. The following two hypotheses are made:

1. The ball handling has a significant effect on the variation in the initial ball conditions of the shot
2. The orientation of the ball has a significant effect on the variation in the initial ball conditions of the shot

To elaborate on the two hypotheses, both are reasoned individually. Here, the hypotheses are explained and relevant research papers are reviewed.

3.2.1 Ball handling

Because of how the ball handling works, as explained in Section 2.2, the ball handling pushes onto the ball, exerting a force onto it. In addition to that, the wheels pull the ball inwards when the robot passes or shoots the ball, which counters the shooting motion of the ball. The force the ball handling exerts on the ball can differ between shots, as shown by [4]. Additionally the ball handling wheels may not grab the ball at the same height, because of which the power applied by these wheels is not the same. Concluding, the interference with the motion of the ball may not be constant for every shot. The inconsistency in the interference can cause various in the initial ball conditions.

3.2.2 Ball orientation

The ball used in the RoboCup Middle Size League is, just like normal soccer balls, manufactured by stitching together hexagonal planes, placed over a rubber interior. The properties like the stiffness and damping factor of the hexagonal surfaces and seams are different. Properties of the ball thus are not homogeneous over its surface and can differ locally. The properties of the ball determine how the ball deforms during interaction with the lever tip. Since the contact area with the lever tip on the ball is relatively small, the local properties of the ball matter. Different orientation of the ball and thus a different contact area with the ball can cause a different deformation of the ball as the properties of the ball are not the same. A different deformation of the ball causes the ball to have different initial conditions, being the initial angle and velocity. The lever tip hitting the ball at a different area thus could cause a variation in the initial conditions of the ball.
D.S. Price found in 2006 that deformation of the ball upon impact with a plane can be characterised by the inbound orientation of the ball [6]. In 2007 he found that the distorted shapes at maximum deformation are caused by a combination of the strain distribution in certain directions by the multiple layers of material of the hexagonal surfaces and the presence of the stiffer skeletal effects of the seams [7]. This suggest that the largest differences in deformation of the ball can be found between the lever impacting in the middle of a larger hexagon plane and an intersection of seams.

4 Testing

Testing is done with TURTLE three and a separate test setup. Down below, first the measurement equipment is explained, followed by the test setup. All tests have been performed in the building of Tech United, Impuls, located on the campus of the TU/e. After that, the data processing is explained.

4.1 Measurement equipment

During testing, different types of measurement equipment are used. The used measurement equipment are the OptiTrack system, a high speed camera and a piezoelectric element. All three systems are elaborated on in this section.

4.1.1 OptiTrack system

The OptiTrack system is a motion capturing system capable of tracking objects in six degrees of freedom [8]. The twelve cameras send out discrete infrared wavelengths. The infrared light is reflected back to the cameras by markers placed on the object desired to track. To do so, these markers have to be highly reflective. The OptiTrack system can track spherical markers more accurately, but on a ball that is shot away, they will fall off after every shot. Flat markers are used in the experiments as these can endure multiple tests. The material used for these markers is the Reflective Adhesive Tape of Salzmann, produced using 3M reflective material.

To make the markers, the tape is cut in circles with a diameter of 20mm. This size is chosen so the marker is big enough to be tracked, but not too big to reduce accuracy. A total of seventeen markers are put onto the ball in an asymmetric manner. The markers can be seen in Figure 4.1. The asymmetry is important, as the software would not be able to distinguish the orientation of the ball if the markers are placed symmetrically. Seventeen markers is more than the recommended amount of markers by OptiTrack, which is between seven en thirteen. However, since the object to track is a ball, not all markers are visible at all times. That is why more markers are used. With not all markers visible, calibrating the object in Motive for the software to recognize the ball is a challenge. The calibration of the ball is done in multiple steps. The ball is put on the field and an object is made in Motive with all the visible markers. Then the ball is rotated very slightly, until another marker that has not been added yet is visible. Because the camera can see most of the other markers that are added to the object already, it is still able to know the orientation of the ball. The new marker is added at the right relative position with respect to the other markers on the ball. If the ball is rotated too much, the OptiTrack system does not recognise the orientation of the ball anymore since it cannot orientate the object due to a lack of corresponding markers. Slowly, the ball is rotated and the newly visible markers are added until all seventeen markers are included in the object. Then, the middle of the ball, the location which coordinates are tracked by the software, can be accurately placed using the spherical pivot placement in the builder plane.

Settings of the tracking software Motive are changed to be enable tracking flat markers. In the application settings, the circularity of the markers is changed as the marks are flat and the spherical filter is removed. The threshold and exposure of the cameras are changed in the camera settings to have the software recognise the markers as well as possible. The sample frequency of the system is adjusted as well to retrieve more accurate data. In Table 4.1, the used settings can be seen.

Setting	Value
Filter Type	"None"
Circularity	0.00
Exposure	$110\mu s$
Threshold	120

Table 4.1: OptiTrack settings.

4.1.2 High speed camera

The used high speed camera is the AOS Promon U1000. This camera can tape video at high frame rates. Two aspects limit the frame rate of the camera, the recorded resolution and the illumination of the environment. The used frame rate is 500 fps with a vga resolution of 800x600. The exposure of the camera is turned all the way up, but to provide enough light a 300W Specilights LED is aimed at the ball. This way, the ball is visible enough at high frame rates to see deformation of the ball when in contact with the lever.

4.1.3 Piezoelectric element

The test setup contains a piezoelectric element from Kistler, the 9251A [9]. This is a three-component force sensor, of which only the z-direction is connected in the setup. The piezoelectric element is placed behind the solenoid in order to measure the force of the solenoid acting on the rest of the frame. The measured force can be converged to find the force of the lever on the ball.

4.2 Test setup

A test setup is made to create the same situation as with the TURTLE, only without lever of the shooting mechanism and the ball handling. This is done to have to orientation of the ball as the only variable, but still mimics the situation the TURTLE has when shooting at the same shape of the lever tip is used. Furthermore is can be seen if the lever mechanism introduces a variation in the initial ball conditions by comparing the shots with the TURTLE and the test setup. However, the EBox limits the power of the solenoid in the test setup. The initial velocity of the ball is way lower, because of which the situation cannot be compared directly and the variation introduced by the lever mechanism is not investigated in this report.

The test setup contains a solenoid similar to the ones that can be found in the TURTLE. It has a capacitor and a high voltage module to power the solenoid. To measure the power going through, as a checkup, a multimeter is attached to the capacitor. For the power supply, a BaseTech BT-305 is attached and set to 24.0V. To operate the setup, a Simulink model is used, which sends signals to the setup through a SMF Ketels EBox. Using the PWM input of the model, the duty cycle of the solenoid can be set, controlling the intensity of the shot.

To be able to have to setup shoot at different angles, the angle of the solenoid can be adjusted with the slits in the metal planes, as can be seen in Figure 4.1. Changing the angle also changes where the lever tip hits the ball. To make sure the lever tip hits the ball directly through the center of the ball, the plateau where the ball is put on can be translated horizontally and vertically. A thin ring is fixed onto the plateau, therefore the ball is at the same initial position on the plateau for all shots and does not roll off the plateau during testing.

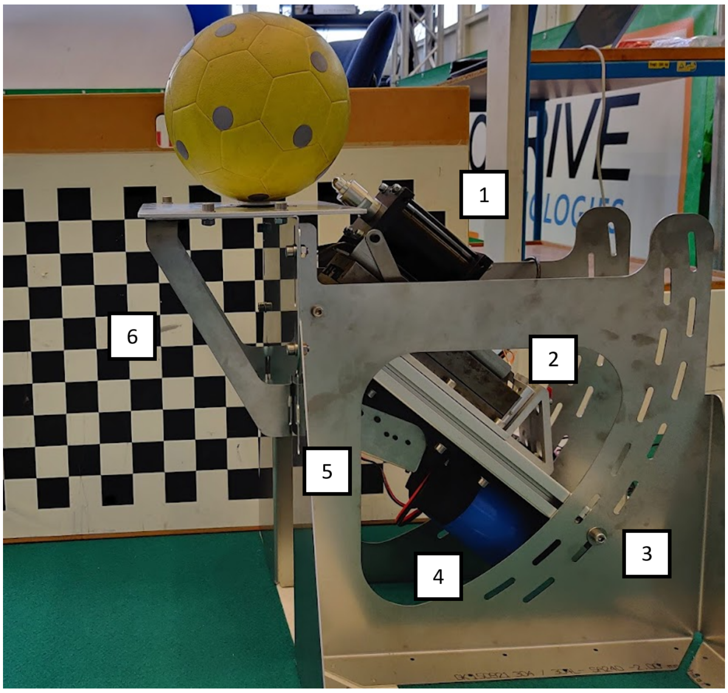


Figure 4.1: Test setup with ball where 1 is the solenoid, 2 is the piezoelectric element, 3 are the slits to set to angle, 4 is the solenoid, 5 is the high voltage module and 6 is the movable plateau.

During testing, both the TURTLE as well as the test setup are positioned against the white line at the right hand side of the field. This is done since the OptiTrack system can measure only half the field properly because of the way the cameras are mounted. This position is preferable to get accurate results from the OptiTrack system. The test setup is operated with a Simulink model and the robot is operated using an interface provided by Tech United.

4.3 Data processing

Data processing is important to execute correctly for the results to be valid. The data is preprocessed for the trajectories to start at the same position and time. Only the usefull data is selected, excluding the data before the shot is taken and the data after the ball has travelled five meters, excluding the bounces and making sure the OptiTrack can still measure the ball accurately. This is done for the fitting with the equations of motion to be accurate. After that, the initial velocity and angle of the ball are calculated from the measured trajectories. With the initial ball conditions known, the variation in the initial conditions can be compared between the tested situations.
The measurement with the OptiTrack system starts before the ball is shot. The time stamps are real time, meaning that they differ each measurement. The OptiTrack position data is translated in such way that the initial position of the ball is zero for the x-, y-, and z-direction and the trajectory is set to start at $t = 0$. This way, the trajectories and the initial angle and velocity can be compared.

Consider an example trajectory as seen in Figure 4.2. The velocity components which are used in the data processing are defined by showing the velocity component in the z-direction and the projected velocity component in the x-y plane. The equations of motion of the ball, which is a mass with an initial velocity under influence of gravity, neglecting air resistance, are given by Equation 4.1.

$$
\begin{aligned}
x &= v_{x,0}t + x_0 \\
y &= v_{y,0}t + y_0 \\
z &= v_{z,0}t + z_0 - 0.5gt^2
\end{aligned}
\tag{4.1}
$$

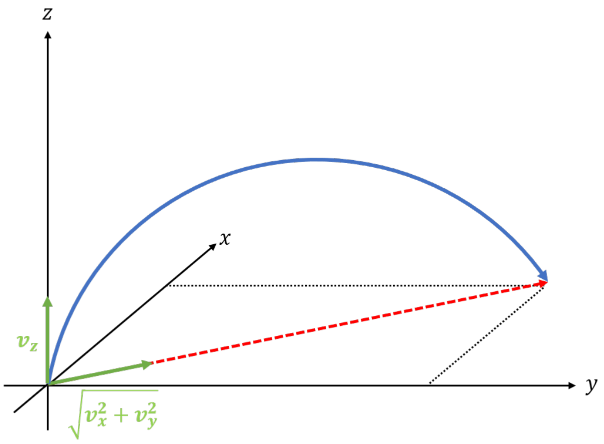


Figure 4.2: Theoretical trajectory.

With the initial values of x_0, y_0 and z_0 all equal to zero and the values of x, y and z known at sample time t, the initial velocity in all directions can be found. This is done by stacking the equations of motion over time and taking the pseudo inverse of the design matrix in Equation 4.2 and to determine the initial velocity component $v_{0,x}$, $v_{0,y}$ and $v_{0,z}$.

$$
\underset{x_0, v_x}{\arg\min} = \left\| \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} - \begin{bmatrix} t_1 & 1 \\ t_2 & 1 \\ \vdots & \vdots \\ t_n & 1 \end{bmatrix} \begin{bmatrix} v_x \\ x_0 \end{bmatrix} \right\|_2^2
\tag{4.2}
$$

The data gathered from OptiTrack contains datapoints of the ball still at its initial position before shooting. These are filtered out as only the trajectory of the ball is looked at. Furthermore, every datapoint after five meters from the robot or test setup is removed. This is done to ensure accurate measurements, as the OptiTrack system does not cover the whole field as explained in subsection 4.1.1. In the plotted trajectory data from Figure 4.3 the trajectories of the ball as measured by the OptiTrack system can be seen. The inaccuracies can be seen at the end of the trajectory in the left side of the figure. The measured position of the ball over time can be seen in Appendix A.

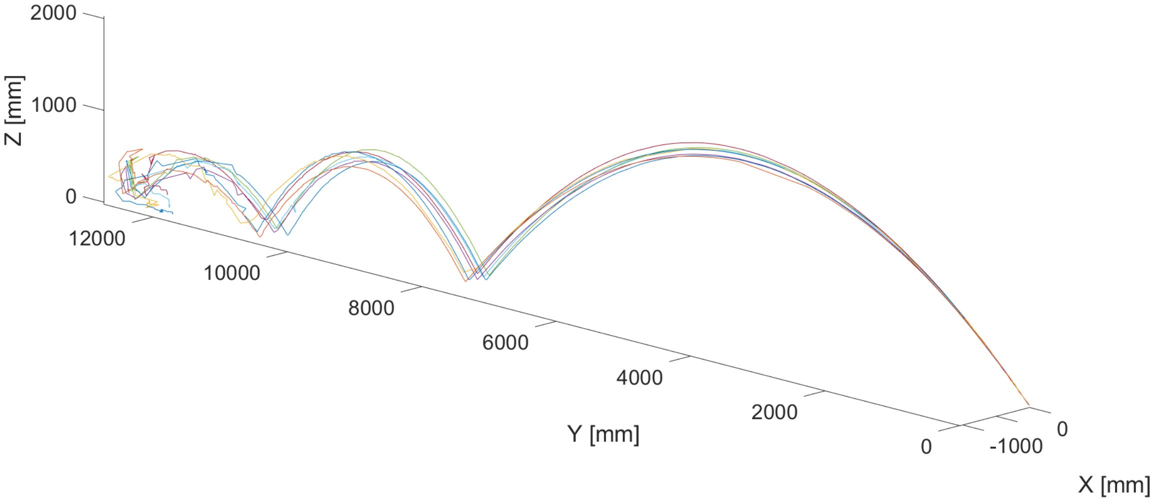


Figure 4.3: Trajectory of ten shots taken by the full robot with duty cycle $K = 40\%$ and lever height $L = 100\%$.

Knowing the initial velocity compounds, the initial velocity in the direction of the trajectory can be found using Equation 4.3, as well as the angle of the ball with respect to the ground, as can be seen in Equation 4.4.

$$v_0 = \sqrt{v_{x,0}^2 + v_{y,0}^2 + v_{z,0}^2} \tag{4.3}$$

$$\alpha_0 = \arctan\left(\frac{v_{z,0}}{\sqrt{v_{x,0}^2 + v_{y,0}^2}}\right) \tag{4.4}$$

By calculating the initial angle and velocity of every shot, the average and standard deviation at each setting can be calculated. The formulas of Equation 4.5 and Equation 4.6 are used for both the initial angle α_0 and the initial angle v_0. The variable N is the number of observations.

$$\alpha_{0,avg} = \frac{1}{N}\sum_{i=1}^{N} \alpha_{0,i} \tag{4.5}$$

$$\sigma(\alpha_0) = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N} \mid \alpha_0 - \alpha_{0,avg} \mid^2} \tag{4.6}$$

The standard deviations are essentially the quantification of variation in the shot. A low standard deviation means that the variation in the shot low is, therefore are the reproducibility and consistency of the shot high, which is desired. The actual values of the initial velocity and initial angle, the averages and standard deviation are shown in Section 5.2 for the ball handling and Section 6.3 for the ball orientation.

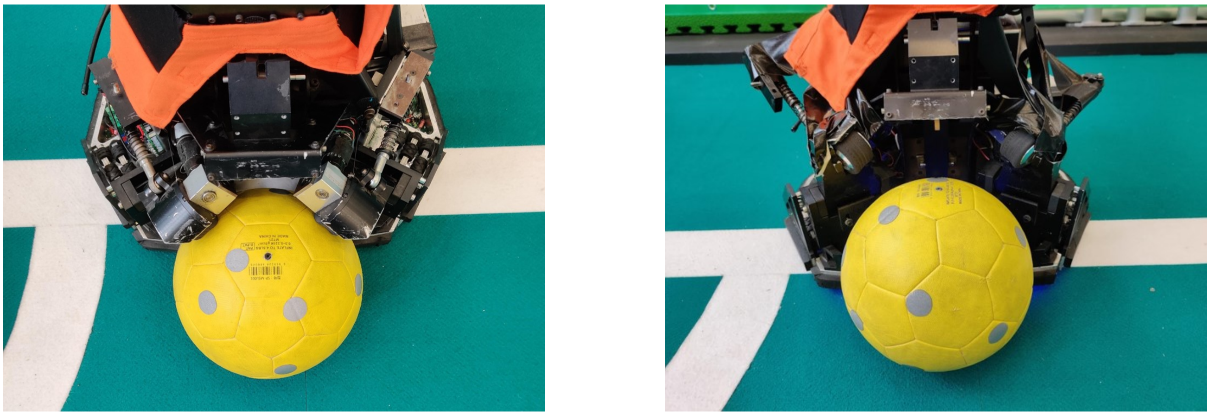
5 Ball Handling

The ball handling is expected to introduce a significant variation in the initial ball conditions. An experiment is set up to test the variation introduced by the ball handling. After that, the results of the experiment are discussed.

5.1 Experiment

The experiment to test hypothesis 1, stating that the ball handling has a significant effect on the variation in the shot, is done with TURTLE number three. When shooting with the robot, two variables in the settings of the software determine the trajectory of the shot. These are the duty cycle K and angle L, both variables vary between 0 and 100%. The duty cycle determines how powerful the shot is, thus relating to the initial velocity of the shot. The selected lever height is naturally related to the initial angle of the shot.

Shooting with different settings is useful as the variation may not be the same at different settings. During games, the desired shot is different for every possible scenario thus knowing the variation at different settings is favorable. Sixteen different settings are made out of four different settings for both the duty cycle K and lever height L with the values 40%, 60%, 80% and 100%. Values between 0% and 40% are not considered, as shots with these settings are improbable. Ten shots are taken at each setting. These shots have been taken with the full robot and the robot with the ball handling removed. This way, the difference between the variation in the shots can only be caused by the influence the ball handling has on the shots. The difference between the two situations can be seen in Figure 5.1. The ball is placed the same way every time for both situations, with the valve pointing upwards en the text of the ball directed to the robot.



(a) Robot with ball handling.

(b) Robot without ball handling.

Figure 5.1: Robot with and without ball handling.

5.2 Results

In this section, the results of the performed tests with the full robot and the robot without the ball handling are shown and discussed. The location of the first bounces are visualised at the end to show the spread caused by the variation in the initial ball conditions.

5.2.1 Average initial angle and velocity

Here, the average values of the initial angle and velocities are shown. For the values of the average initial velocity, the used unit is mm/s, the average initial angles are expressed in degrees.
In Figure 5.2 and Figure 5.3 respectively the average initial angle and velocity can be seen for different duty cycles and lever heights. The average values are calculated per settings over the ten shots taken.
It can be seen that increasing the duty cycle results in an increase in the initial velocity of the ball, which is expected. What is not expected is that the initial angle also changes when the duty cycle is changed. In Figure 5.3 it can be seen that the initial velocity shows also an unexpected occurrence, namely dependency on the lever height.

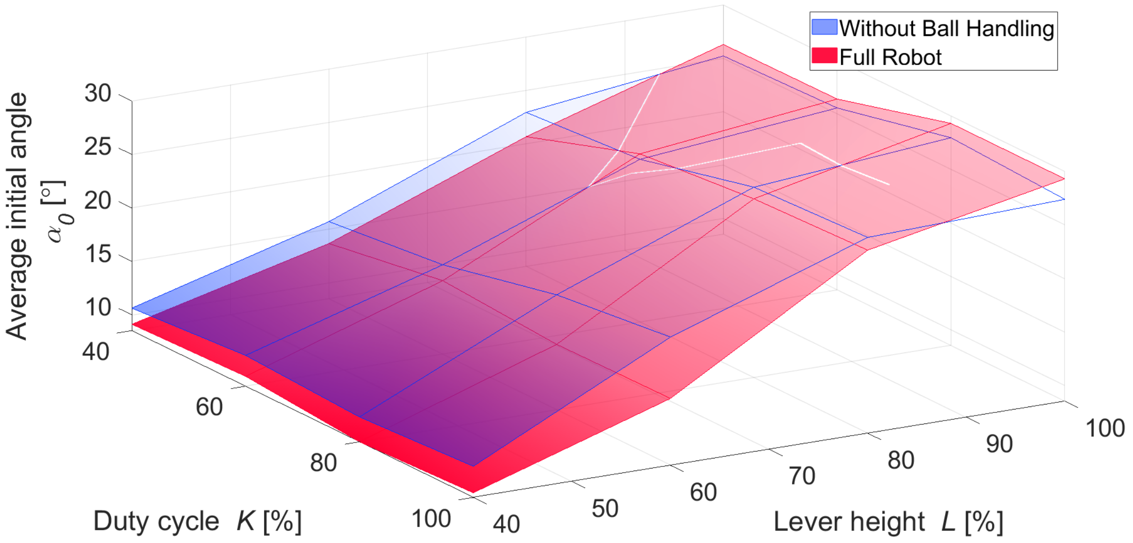


Figure 5.2: Average initial angle $\alpha_{0,avg}$ over duty cycle K and leverheight L.

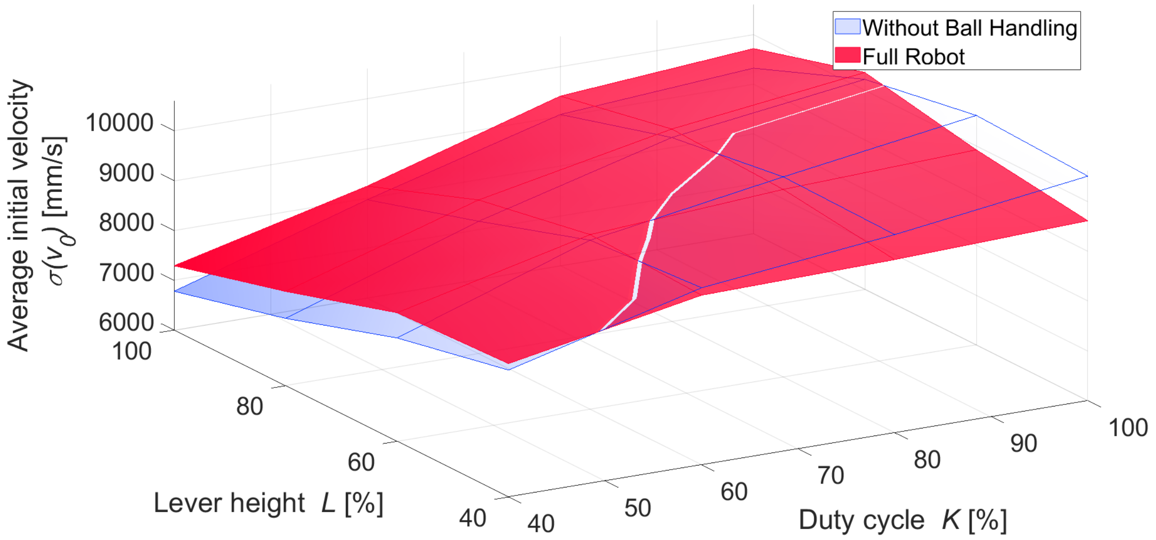


Figure 5.3: Average initial velocity $v_{0,avg}$ over duty cycle K and lever height L.

Here it can be seen that, next to the expected correlation between an increasing initial angle with an increasing lever height L, the initial velocity of the shot decreases when the lever height L is increased. A part of this occurrence can be explained by the mechanics of the shooting mechanism. The ratio between II to III and III to IV, as referred to as in Figure 2.1, changes when the lever height is changed. Changing this ratio means a shift in the power and velocity of the lever tip, thus introducing the unexpected occurrences of the duty cycle influencing the initial ball angle and the lever height influencing the initial ball velocity. Increasing the lever height L increases the ratio and thus decreased leverage, meaning the power exerted by the lever tip onto the ball is less. That is why the initial velocity decreases when the lever height L increases, as seen in Figure 5.3. However, this ratio cannot be correlated fully to the decrease in velocity. This decrease can be taken into account by the robot when choosing a shot. As long as the variation in the shot, talked about in subsection 5.2.2, is not affected because of the change in the ratio, it is not a complication.

5.2.2 Variation

The variation in the initial ball conditions of the shots is quantified by calculating the standard deviations of the initial conditions of the ball at the different settings. In Figure 5.4, the standard deviation of the initial angle over the duty cycle and lever height can be seen. The standard deviation of the initial velocity over the duty cycle and lever height can be seen in Figure 5.6. To better visualise the difference in the standard deviations, Figure 5.5 and Figure 5.7 are shown. The plotted percentage is the standard deviation of the robot without ball handling as a percentage of the standard deviation of the full robot. A negative percentage in these figures thus means that the standard deviation in the initial conditions of the ball is lower for the robot without a ball handling. Using the variation in the shots, the situation with the full robot and without the ball handling can be compared on its consistency. The lower the standard deviation, the less variation is introduced to the initial ball conditions, which is desired.
It can be seen that with increasing duty cycle K, the standard deviation of the initial angle decreases. For the initial velocity of the ball, the standard deviation of the robot without the ball handling is relatively similar over the different settings of the duty cycle. Overall it can be seen that the standard deviation of the full robot is higher than for the robot without the ball handling.

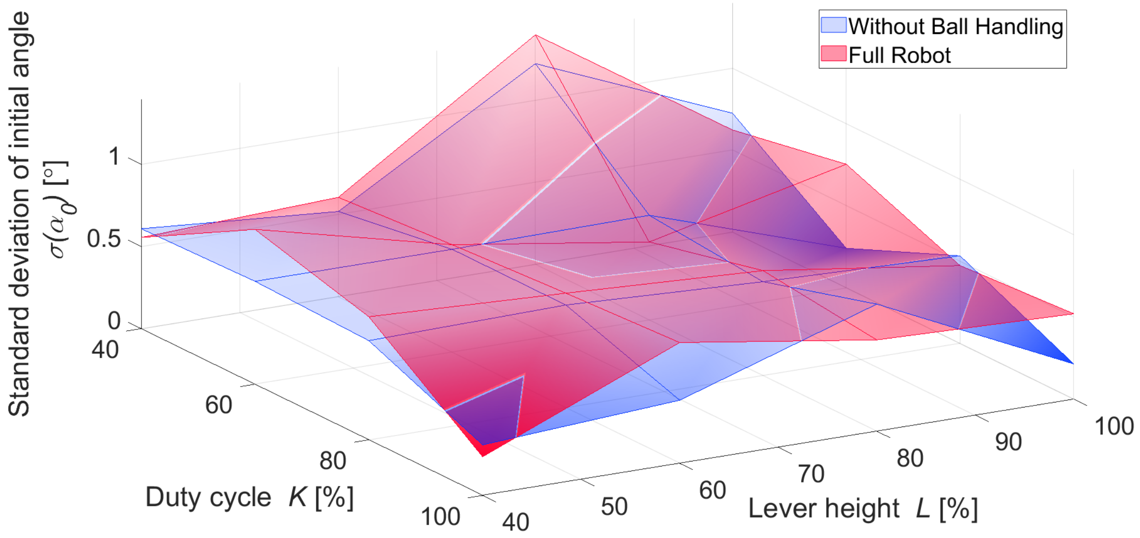


Figure 5.4: Standard deviation of initial angle $\sigma(\alpha_0)$ over duty cycle K and lever height L.

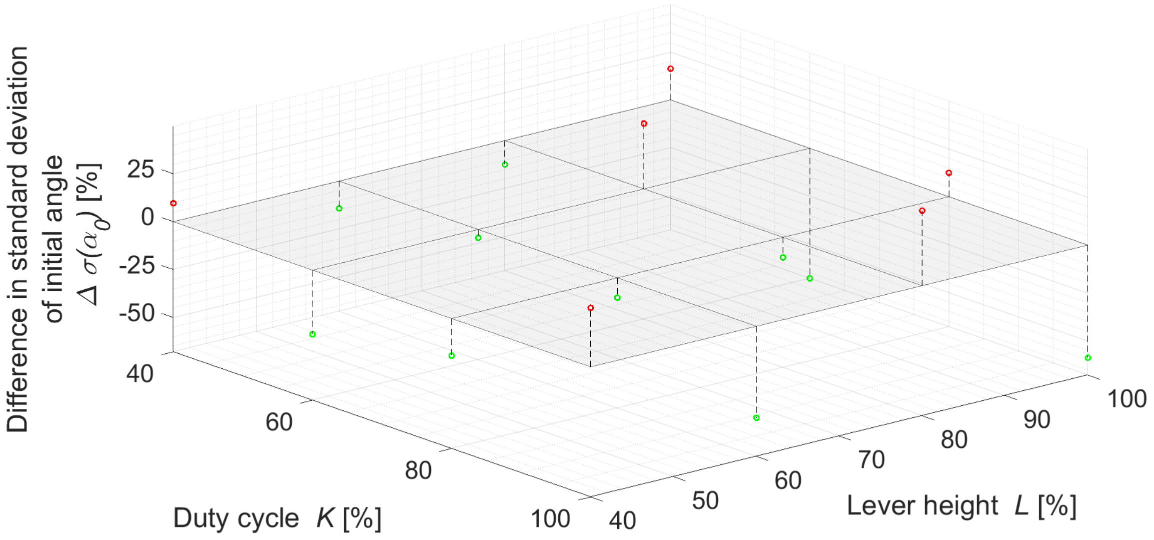


Figure 5.5: Percentage difference in standard deviation of initial angle over duty cycle K and lever height L.

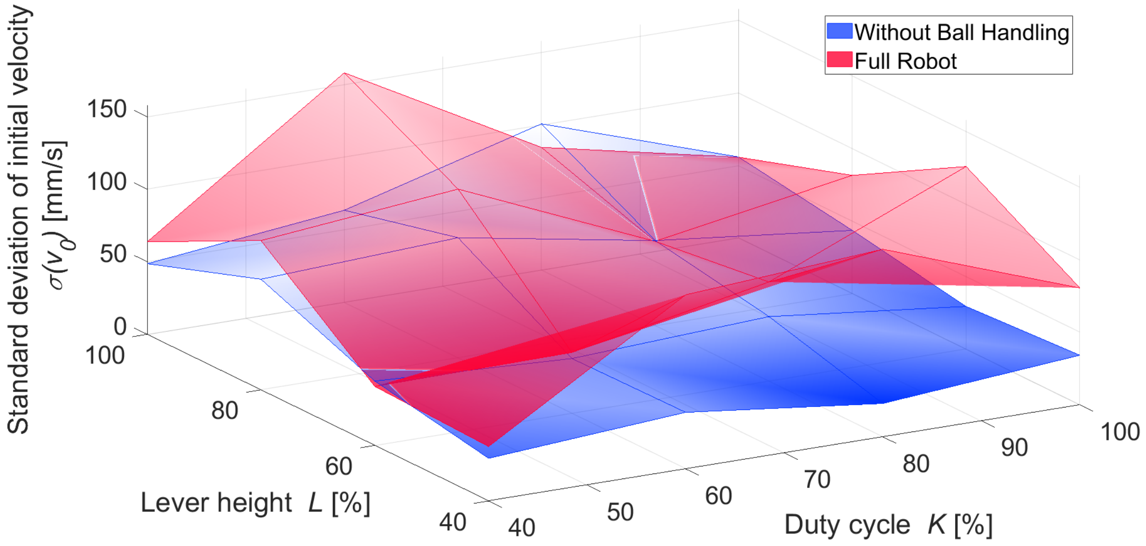


Figure 5.6: Standard deviation of initial velocity over duty cycle K and lever height L.

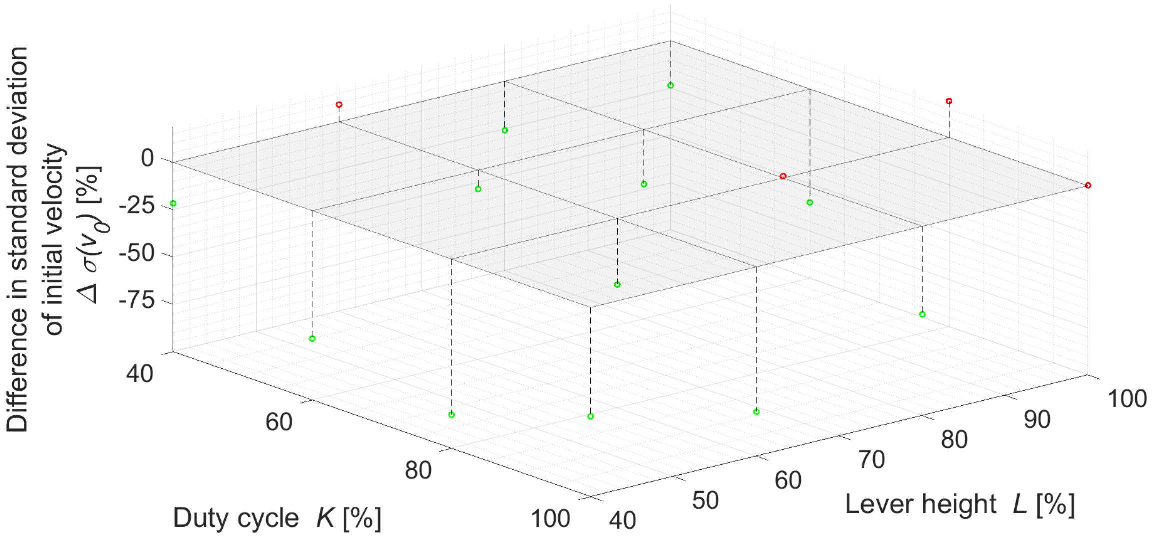


Figure 5.7: Percentage difference in standard deviation of initial velocity over duty cycle K and lever height L.

The standard deviation of the initial angle and velocity over lever height L can be seen as well in Figure 5.4 and Figure 5.6. Here again it can seen that overall, the standard deviation of the full robot is higher than for the robot without the ball handling. Furthermore it can be stated that the standard deviation of the initial angle increases with increasing lever height for both the full robot as for the robot without the ball handling.

5.2.3 Spread

The spread of the location of the first bounce is inspected to get familiar with the variation in the end point of the ball trajectories, being the first bounce. This end point can be estimated by calculating the location of the first bounce using the initial conditions of the ball gathered in the ball handling experiment. From these locations, a range in the y-direction can be calculated to compare the spread of the full robot and the robot without the ball handling. After that, the measured location is plotted and the results of the calculated location and measured location are compared.
To calculate the range of the location of the first bounce, air resistance and other phenomena due to the air like drag and the Magnus effect are neglected. This can be done since the linear and angular velocity are not sufficient for the phenomena to have a significant effect [10]. The equation of motion of Equation 4.1 is rewritten for the y-direction to find the location of the first bounce. This is the moment where $z(t > 0) = 0$. Using Equation 5.1, the distance from the start of the shot till the first bounce can be calculated.

$$y_e = \frac{2}{g} \cdot cos(\alpha_{0,avg} \pm \sigma(\alpha_0)) \cdot sin(\alpha_{0,avg} \pm \sigma(\alpha_0)) \cdot (v_{0,avg} \pm \sigma(v_0))^2 \tag{5.1}$$

To find the range where the ball will land according to the tests, the standard deviation of the setting is subtracted from or added to the average value of the initial angle and velocity. This way, the smallest and the largest range can be found. The total range over all settings of duty cycle K and lever height L then can be compared for the full robot and the robot without the ball handling. As a reference, note that the radius of the ball is 0.10 m.
For the full robot, the smallest range found by Equation 5.1 is 0.24 m and the largest range is 0.71 m. This account for 8.44% and 24.33% of the distance of the corresponding trajectories. For the robot without the ball handling, the smallest range is 0.22 m and the largest is 0.49 m. This accounts for 4.54%

and 12.42% for the distance covered by the corresponding trajectories. The ranges mean that the robot without the ball handling is up to $0.71 - 0.22 = 0.49$ m more accurate than the full robot.
The measured spread of the first bounces can be seen in Figure 5.8. The first bounces of all the shots taken with the TURTLE are visualised here. Note that for every figure the values of the x-axis is the same. This way, the values can be compared easier. The range of the y-axis is the same for every duty cycle setting, thus per row of figures. The measured spread is very close with the calculated spread. Furthermore, the difference in spread at the specific settings as shown with the standard deviation before is visualised here. It can be seen that the spread for the robot without ball handling is smaller that the spread for the full robot for most settings, meaning that the variation in the initial ball conditions is lower for the robot without ball handling. Additionally it can be seen that all shots have a slight deviation to the left side. This is expected to be caused by the calibration of the TURTLE.

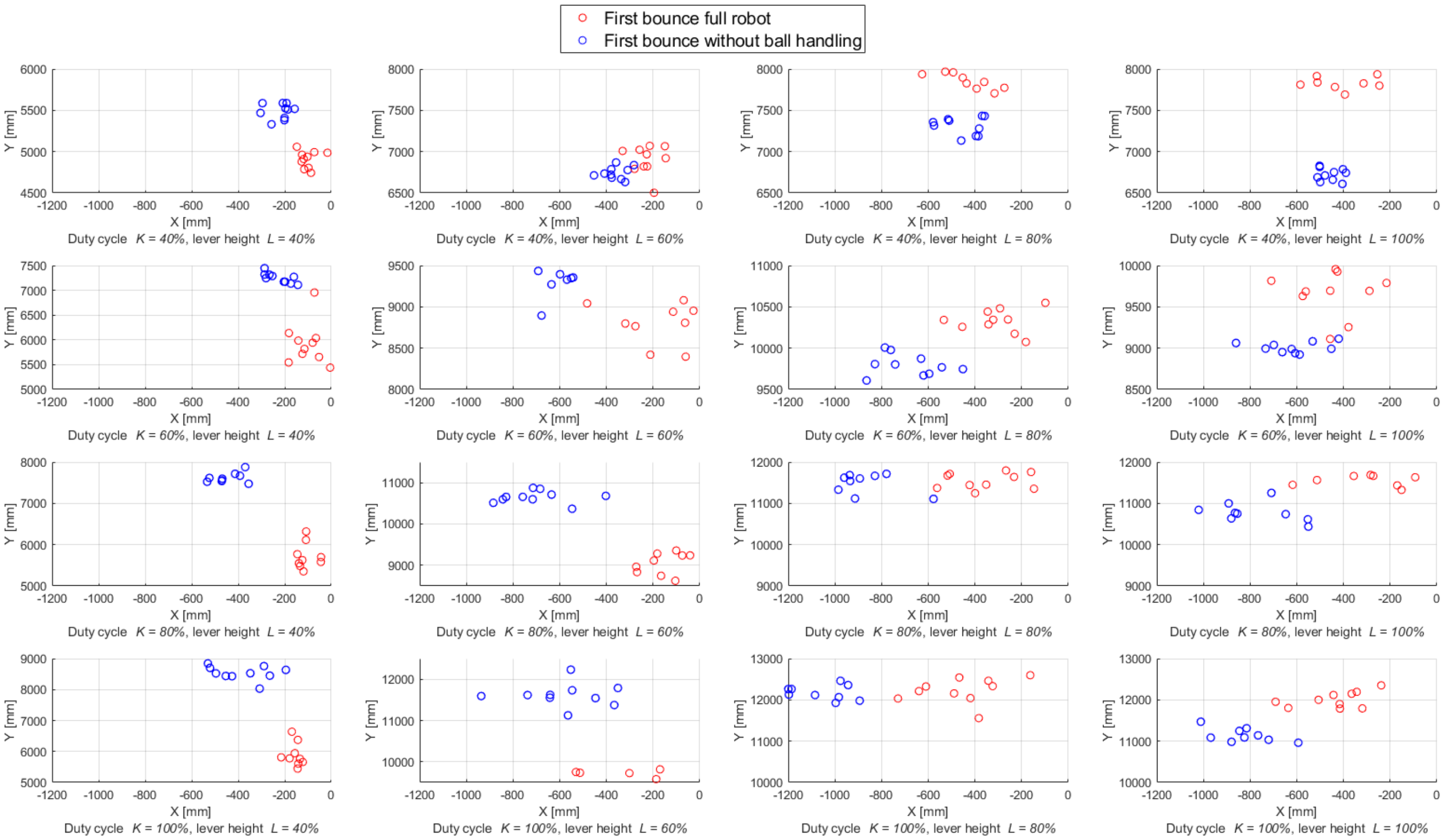


Figure 5.8: Location of first bounces of all test with the full robot and the robot without ball handling

Concluding, removing the ball handling from the robot during shots is beneficial for the variation in the initial ball conditions. The standard deviation can be decreased up to 0.106 m/s for the initial velocity and up to 0.51° for the initial angle. The range of the first bounce location of the ball can be decreased up to 0.49 m.

6 Ball Orientation

Variation due to the ball orientation can be estimated based on a physical model. The model to do so is explained first. After that, the experiment setup is shown. The results from the experiment is discusses at the end of the section.

6.1 Model

As explained in subsection 3.2.2, variation in the initial ball conditions are expected to be caused by the orientation of the ball. The orientation of the ball determines the stiffness as the contact area with the lever tip is changed. A model can be made to calculate the differences in the ball velocity due to a change in the stiffness in the ball. With this model it can be estimated if variation in the stiffness has a significant effect on the ball velocity. The interaction between the lever and the ball can be simplified to a model where two masses are combined with a spring and a damper, as can be seen in Figure 6.1. This model is a simplified model, since it does not take slip or energy losses due to deformation in consideration. Furthermore, it is assumed that the lever is infinitely stiff. The lever has an estimated initial velocity to describe the actual situation more accurately. The spring and damper constants are representing components, since in reality, there is an infinite amount of parallel springs and dampers over the surface of the ball. The model is only valid while the lever tip is in contact with the ball. That means that for the Simulink model, the end velocity during contact with the ball is the initial velocity of the ball flight after shot by the lever tip.

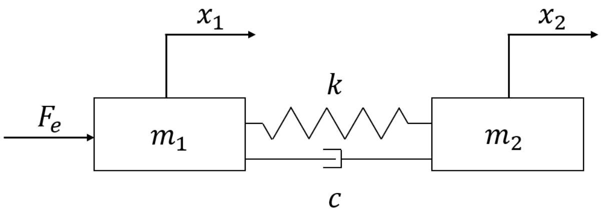


Figure 6.1: Two masses-spring-damper model where F_e is the external force of the solenoid, m_1 is the lever mass, m_2 is the ball mass, k is the spring stiffness and c is the dampingcoefficient.

Now, the free body diagrams of the two masses can be used to derive two equations. These equations are the force balances of the bodies to get the acceleration over time during the contact between the lever and the ball. Note that just like in Figure 6.1, 1 is associated to the lever and 2 is associated to the ball. In these equations, F_e is the external force on the lever exerted by the solenoid.

$$F_e - k(x_1 - x_2) - c(\dot{x_1} - \dot{x_2}) = m_1\ddot{x_1} \tag{6.1}$$

$$k(x_1 - x_2) + c(x_1 - \dot{x_2}) = m_2\ddot{x_2} \tag{6.2}$$

A Simulink model can use Equation 6.1 and Equation 6.2 to simulate the position, velocity and acceleration of both the lever and the ball over time. The parameters F_e, k, c, m and initial conditions can be fed into a Simulink model. These parameters are chosen to represent the actual situation [11], but are not exactly the same and thus may deviate from the actual situation. The data from the piezoelectric element, talked about in subsection 4.1.3, can be used to fit the parameters to the actual situation. This has not been done in this research and is left as a recommendation for future research.
The stiffness k can be varied to see the effect of variation in the stiffness of the ball on the initial velocity of the ball when shooting. Simulation data is gathered for a stiffness k with a 50% until a 150% deviation from its original in increments of 5%.

The Simulink model is cut off at the moment the difference in position between the lever tip and the ball is zero again. This is the exact moment on which the ball losses contact with the lever and starts its flight. The end velocity of the ball in the simulation thus is the initial velocity of the ball in the flight. As can be seen in Figure B.2, the cut off time is not the same for every simulation. Since the stiffness influences the deformation of the ball, the deformation is longer for lower stiffnesses and shorter for higher stiffnesses. However, this has to be the case as the cutoff moment has to be the time when the ball and the lever tip lose contact. This time thus is different for the 21 simulations.

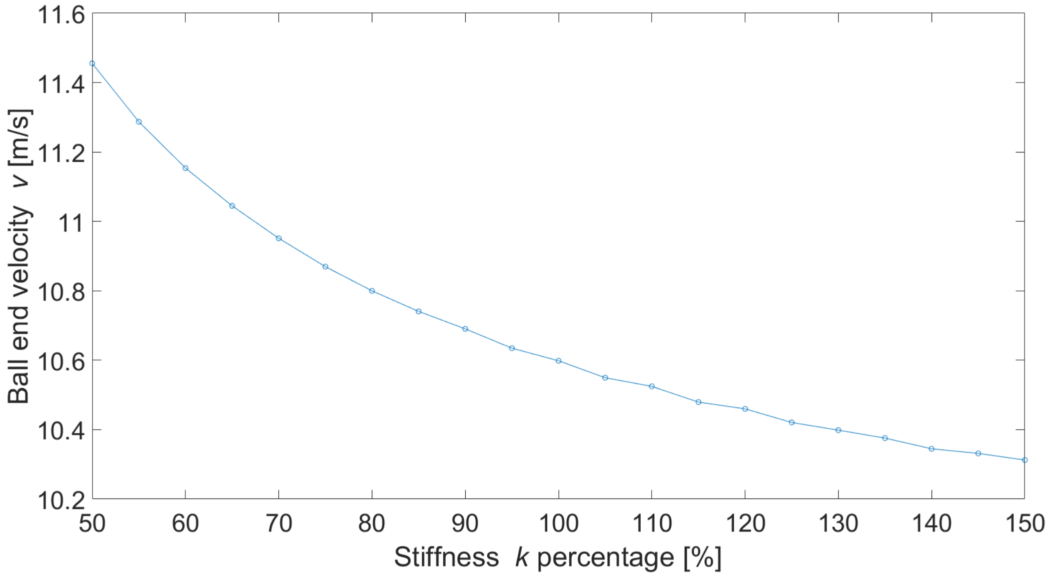


Figure 6.2: Simulated end velocity over percentage of original stiffness k value. A references line has been drawn through the datapoints.

In Figure 6.2 it can be seen that the end velocity increases exponentially when the stiffness is decreased. The difference between the end velocity at stiffness k of 50% and 150% is significant, namely 10.78%. If the stiffness of the ball differs this much in reality, the orientation of the ball does introduce a significant variation and should be taken into account.

6.2 Experiment

For the second hypothesis, the experiment about the effect of the orientation of the ball on the variation in the initial ball conditions for the shot is performed using the test setup. With this setup, the orientation of the ball can be controlled better. This is since the test setup can hit the ball through the center, which can not be done by the robot at all angles. The contact area with the ball can be chosen properly as well, another element that is difficult with the TURTLE. The high speed camera can record the impact better as there are no other parts of the robot covering sight.
The initial velocity of the ball is gathered by shooting the ball at different orientations. The contact area between the lever tip and the ball can be chosen by changing the orientation of the ball. The chosen contact area's are the middle of a larger hexagonal plane and the intersection of seams, as can be seen in Figure 6.3.
At two different duty cycles, under an angle of 45°, the ball is shot ten times at the middle of the hexagonal surface as well as at the intersection of the seams. The used PWM inputs are 1650 and 1800, which correspond to duty cycles of 67.3% and 79.7% respectively according to [5].

(a) Middle of hexagonal surface (b) Intersection of seams

Figure 6.3: Orientation of the ball at the test setup.

6.3 Results

In this section, the average velocities of the shots with the test setup are inspected. The difference between the average velocities of the shots with the contact area in the middle of the hexagonal surface and the intersection of seams is expected to be the maximum variation in the shots caused by the orientation of the ball. Next to that, the standard deviations when hitting the ball at the middle of the hexagonal surface or at the intersection of seams might be different. This could show that the variation introduced by the contact with the ball is different at the two considered spots on the ball.

6.3.1 Average velocity

The data gathered by the OptiTrack system is processed as explained in Section 4.3. The initial angles and velocities of the ball are calculated and noted with the corresponding standard deviations in Table 6.1.

Setting PWM area	**Average initial angle** °	**Standard deviation** °	**Average initial velocity** mm/s	**Standard deviation** mm/s
1600 Seams	29.119	0.895	5446.2	62.2
1600 Surface	30.915	1.195	5511.9	70.9
1850 Seams	29.867	0.928	5508.4	41.5
1850 Surface	29.916	1.286	5452.5	80.1

Table 6.1: Average initial angle and velocity of different contact area's and PWM settings.

The difference between average initial velocities of the area's at the two PWM settings is 1.20% and 1.02% for 1600 and 1850 respectively. This means that the difference in the initial velocity due to the contact area and thus the ball orientation is rather small. The difference in the average initial angle when hitting on the surface compared to the seams is 1.796° for a PWM of 1600, but for a PWM of 1850 just 0.049°. The two differences are not in the same magnitude, therefore it is concluded that more tests at varying PWM settings are required to find a correlation between the ball orientation and the initial angle.
Comparing this to the result from the Simulink model indicates that the stiffness does not range as

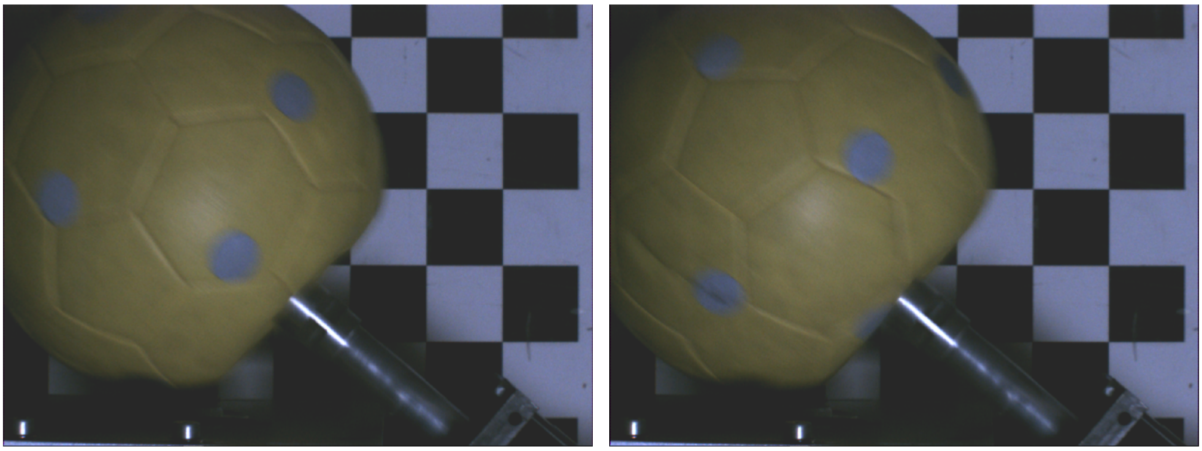
broad as 50% and 150% over the surface of the ball. The range of the stiffness is rather smaller, namely between 90% and 115%, the range where the difference in initial ball velocity is about the same. Do note that the parameters have not been fitted, so the data from the Simulink model differs from the situation of the test setup.

What is noticeable however is that the standard deviation of the shots taken onto the seams are constantly lower that the standard deviation of the shots taken on the surface. This true for both the standard deviation of the angle and velocity at the two PWM settings. It is expected that the stiffer intersection of seams can distribute the external force of the lever in a more consistent manner. This cannot be verified by the Simulink model since the simulation will give the same output every time for the same inputs. The difference in the standard deviations is significant, meaning the variation in the shot is smaller. That indicates that hitting the intersection of the seams is beneficial for the TURTLEs. However, more PWM settings will have to be tested to confirm the lower standard deviation when the ball it hit on the intersection of seams compared to the middle of the hexagonal surface.

Using Equation 5.1 to find out the distance from the starting point of the shot to the first bounce with the values of Table 6.1, the lateral difference on the field can be found. This range is 0.155 m for a PWM of 1600 and 0.052 m for a PWM of 1850. This results in a difference of 5.90% and 1.96% respectively over the distance of the shot.

6.3.2 Deformation

The high speed camera footage is used to see whether the deformation of the ball at different orientation is significantly different. This is done by selecting the frame where the deformation is largest and compare these shots for the different ball orientations.



(a) High speed camera shot of the ball hit at the middle of the hexagonal surface with a PWM of 2000

(b) High speed camera shot of the ball hit at the intersection of seams with a PWM of 2000

Figure 6.4: High speed camera frames at maximum deformation.

The amount of deformation can be calculated by first determining the distance covered by the pixels. This can be done by using the black and white reference frame in the background. Taking the coordinates of the pixels at the corner of the squares, the distances covered by the pixels is known. This then can be used to calculate the distance covered by the flat deformed side of the ball, taking the pixel coordinate at the start and end of the deformation. The difference between the length of the flat side due to the deformation is 1.08% averaged over four measurements. This difference is about the same as the difference in the initial velocity of the ball, being 1.02% as stated in subsection 6.3.1. These values correlate and suggest that the orientation of the ball indeed has an insignificant impact on the average initial velocity of the ball for the current situation.

7 Conclusion and recommendations

The initial ball conditions of the shots taken by the TURTLEs of the Tech United robot soccer team show variations. These variations are a problem since it prevents the TURTLEs to shoot as accurate and consistent as possible. To identify the most significant causes of the variation in the initial ball condition, two hypotheses are drawn, repeated below. Plans to test the significance of the variation in the initial conditions are made and executed, after which the gathered data is processed and conclusions are made.

The two hypotheses on the sources of variation in the initial conditions of the ball are:

1. The ball handling has a significant effect on the variation in the initial ball conditions of the shot
2. The orientation of the ball has a significant effect on the variation in the initial ball conditions of the shot

The first hypothesis is supported. As elaborated in Section 5.2, the variation in the shot decreases significantly when removing the ball handling. The ball handling thus has a significant effect on the variation in the shot. The variation in the initial ball conditions for the robot without the ball handling is up to 0.106 m/s lower for the initial velocity and 0.51° for the initial angle.

The second hypothesis is rejected. In Section 6.3 it is shown that the difference between the average initial angles and velocities at different contact area's between the lever tip and the ball is insignificant. Therefore it can be concluded that the orientation of the ball has no significant effect on the variation in the shot in this situation. However, as D.S. Price showed in his research, the orientation of the ball does have an effect on the deformation of the ball. Since the deformation of the ball is what gives the ball its velocity, the orientation can have an effect, but in this situation it is found that the orientation of the ball does not results in a significant difference in the average velocity and angle of the shots.
What is found to be significant is that the standard deviation of the shots where the lever tip hits the ball at the intersection of seams is lower. From this it can be concluded that the variation in initial velocity of the shots can be decreased up to 48%, which is 0.038 m/s, and for the initial angle up to 22%, which is 0.35°, by hitting the ball on the intersection of the seams.

The first recommendation is to address the variation caused by the ball handling. The ball handling increases the variation in the shot. This is undesired and now the effect is shown, it could be resolved. A possible solution is to make the ball handling wheels move in the same direction of the ball at the moment the shooting mechanism hits the ball to not counter the motion of the ball. Alternatively, the ball handling can be pulled upwards just before the lever tip hits the ball. When timed correctly, the ball will still have the correct initial position. The ball handling will not touch the ball when shooting and thus will not interfere. As shown in Section 5.2, having the ball handling pulled upwards will decrease the variation in the shot.

The second recommendation is to perform the full robot experiment with more tests and settings to map the variation of the initial angle and velocity more accurately. If the first recommendation is already addressed or the mechanics of the shooting mechanism are altered, use that version of the robot. The settings that should be diversified are the duty cycle and the lever height. Using a mapping of the standard deviation at the different setting can aid the robot in selecting the optimal lever height and duty cycle to reach a desired location. Selecting the settings with a lowest standard deviation improves the chances to have to ball reach the desired location within a smaller range. The smaller range makes sure that the receiving robot can catch the ball easier or with a shot, improves the chances of scoring.
Next to that, shots can be taken using the test setup with the lever tip hitting the ball at multiple points at the hexagonal surface and the seams. The average initial angle and velocity can be retrieved, as well as the standard deviations, to get to know the variation over the whole surface of the ball. This way, the

impact of the orientation can be tested against the Simulink model at more contact area's.
The standard deviations should be looked at likewise. The experiments showed that the standard deviation is lower for the shots where the lever tip hits the intersection of seams. This however was only tested for two different PWM settings and should be validated by testing at more PWM settings.

The third recommendation is to redo the experiments with the ball orientation when the shooting mechanism is capable of providing a more powerful shot. It is expected that the local stiffness deviations will play a role at higher lever velocities, exceeding the current capabilities of the robot and its shooting mechanism. Note that when this the situation, aerodynamic effects might apply as well and if so, should be taken into account in the decision making of the robot when selecting the settings for a shot.

The fourth recommendation is to look at the lever mechanism. C. Kengen already showed that significant variation is present in the velocity of the lever. Beyond that, the influence of the lever mechanism on the variation in the initial ball conditions can be researched using the test setup worked with in the experiment of the ball orientation.

The last recommendation is to use the data from the piezoelectric element to fit the parameters for the Simulink model, obtaining the stiffness and damping variations over the surface of the ball. This way, the Simulink model can do a better job at representing the actual situation of the soccer robots, where the parameters of the ball are the same.

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A Trajectory

Here, the trajectory of the ball shot by the full robot using a duty cycle K of 40% and a lever height L of 100%. It can be seen that the data is showing inaccuracies after a certain time. The inaccuracy is caused by the OptiTrack not being able to track the ball over the whole field. At first, the orientation of the ball is measured incorrectly. This can be seen by the spikes in the data, meaning the coordinate of the middle of the ball is changed exactly the diameter of the ball. After that, the OptiTrack camera's simply cannot see the markers anymore.

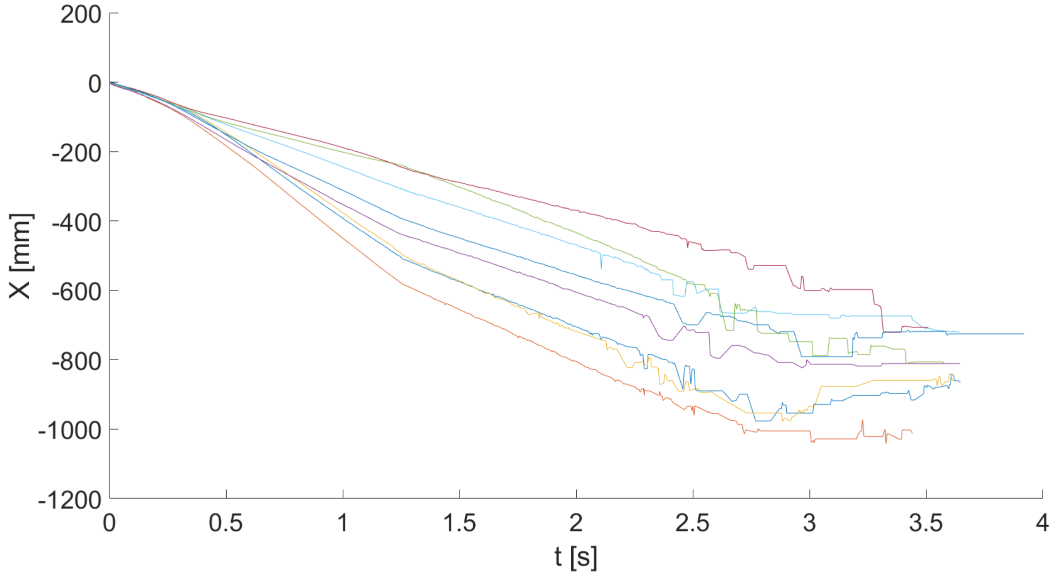

Figure A.1: X position over time of trajectory of ten shots taken by the full robot with $K = 40\%$ and $L = 100\%$.

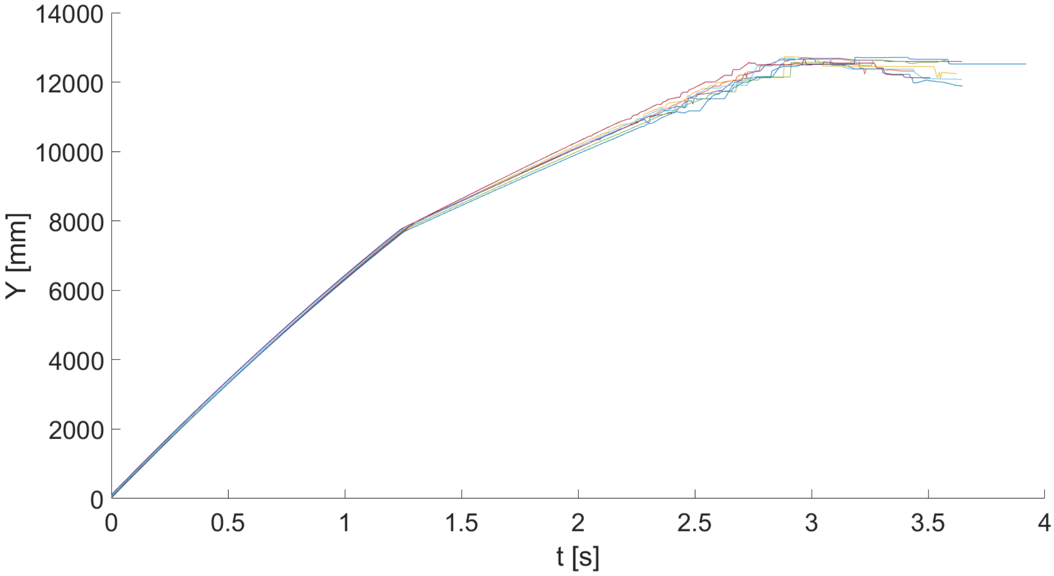

Figure A.2: Y position over time of trajectory of ten shots taken by the full robot with $K = 40\%$ and $L = 100\%$.

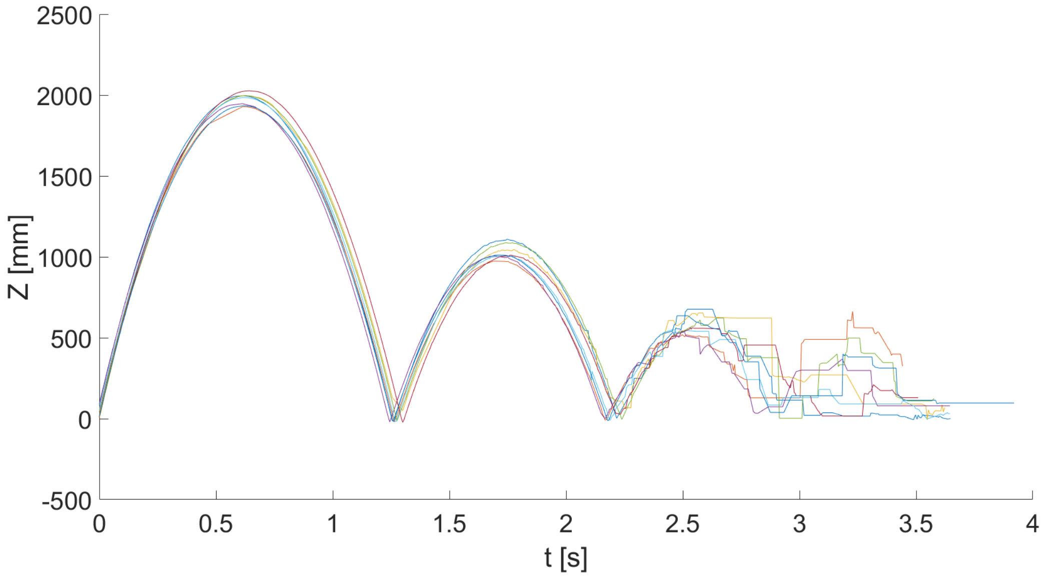

Figure A.3: Z position over time of trajectory of ten shots taken by the full robot with $K = 40\%$ and $L = 100\%$.

B Simulink model

The Simulink model can be seen in Figure B.1. Equation 6.1 and Equation 6.2 are implemented, using F, c, k, $m1$ and $m2$ as inputs from a Matlab script. The simulation is run for 0.05 seconds, which is more than the time the lever tip is in contact with the ball. The data is exported and saved, after which the data is cut off where the difference in position between the lever tip and the ball is zero. This is exactly the moment where the ball leaves the lever tip and starts it trajectory. The simulated velocity can be seen in Figure B.3. The simulated difference between the position of the lever tip and the ball can be seen in Figure B.2. The influence of a variation in the force on the end velocity of the ball can be seen in Figure B.4. Note that the difference in end velocity for the varying force is larger than for the stiffness.

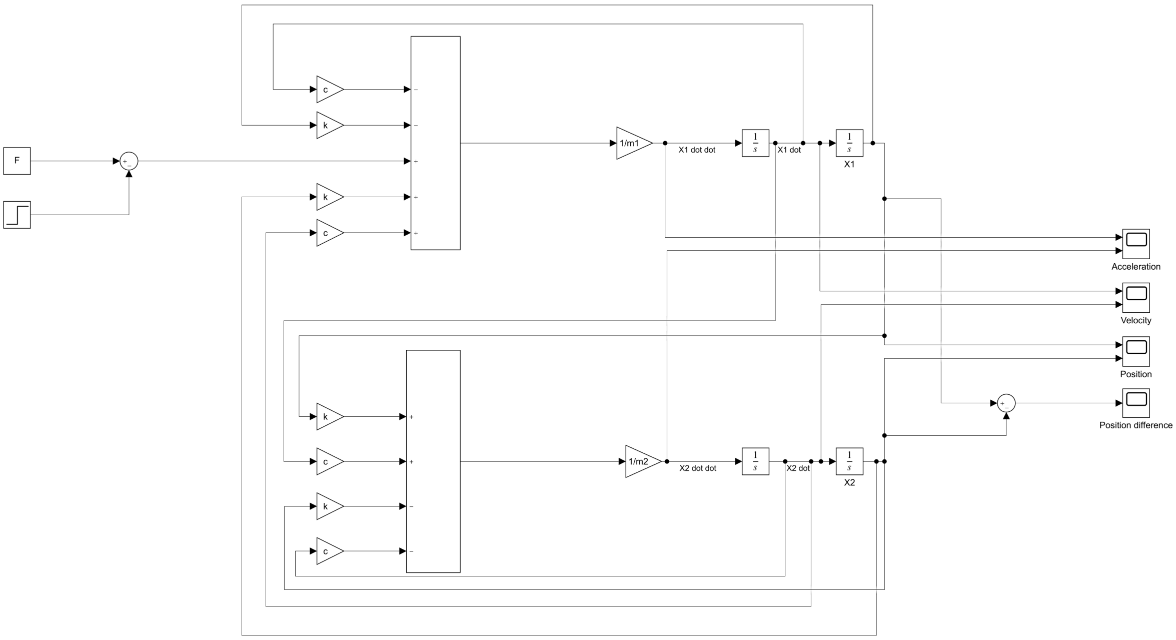

Figure B.1: Simulink model.

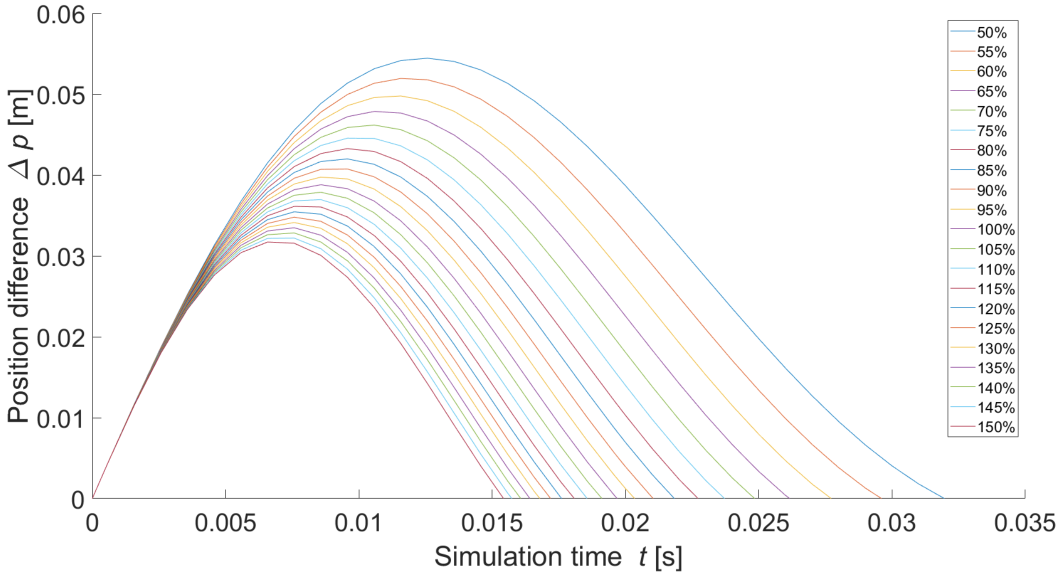

Figure B.2: Difference in position Δp between the lever tip and the ball over simulation time.

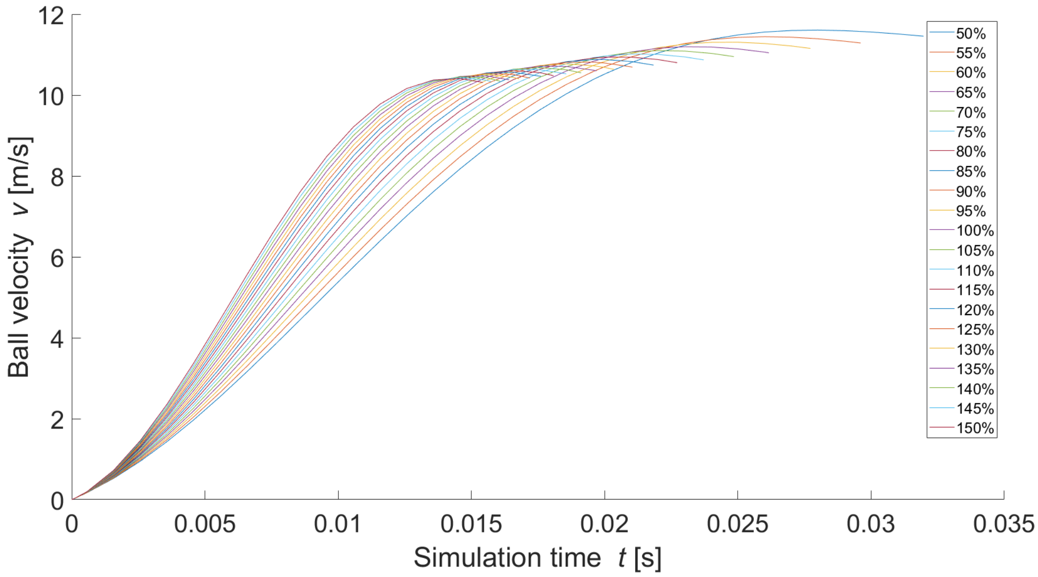

Figure B.3: Simulated velocity of the ball during contact with the lever tip for different stiffness percentages.

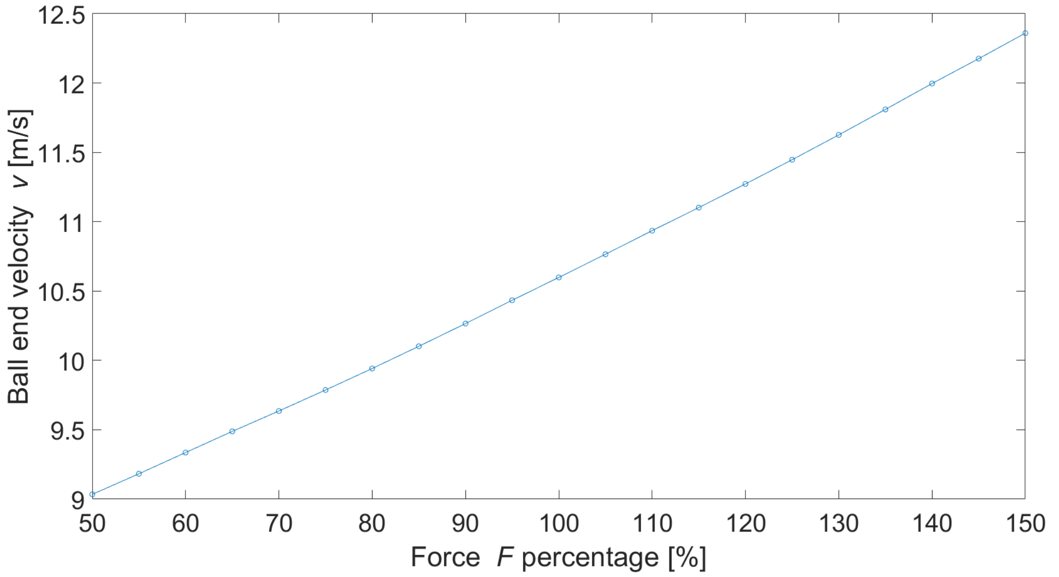

Figure B.4: Simulated velocity of the ball during contact with the lever tip for different force percentages.