FINAL REPORT

DBB111 - CREATIVE MECHANICAL DESIGN, ENGINEERING AND MANUFACTURING (BASIC)

27-01-2022
Quartile 2

Petr Dobiáš
Susan Draaijer
Aloysia Prakoso
Maartje Pirée
Leah van de Sande

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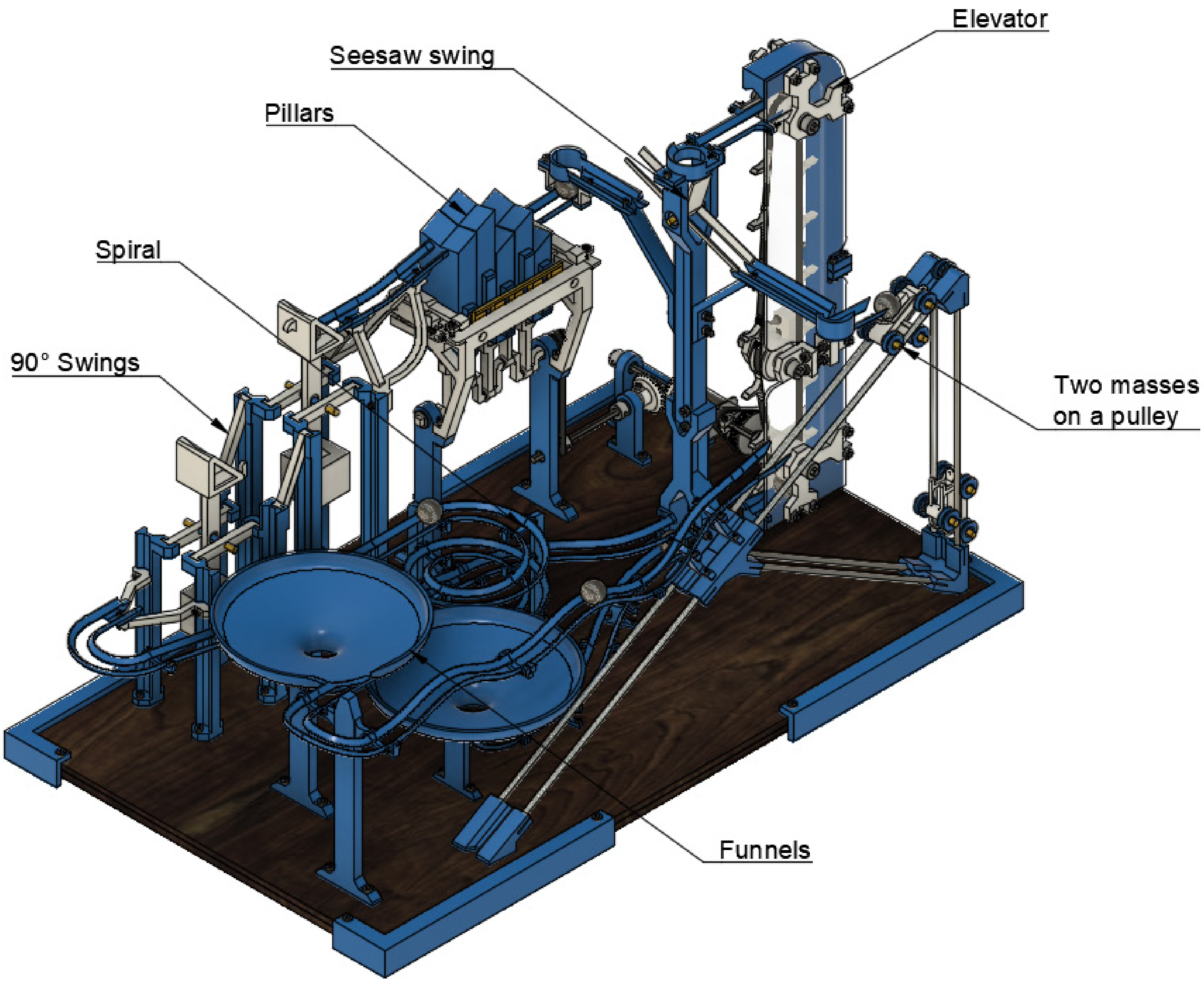
1. INTRODUCTION

The following pages document a collection of various interconnected mechanisms that together form a “marble machine” designed to move solid 20mm steel balls. The whole system is motorised, which allows it to run in a continuous loop indefinitely. Whenever a ball reaches the lowest point in the system and has lost its energy, it gets elevated back to the initial position and the cycle continues...

2. COMPLETE ASSEMBLY

Figure 1 displays the complete assembly, where the individual components will discuss the function and design of each component individually.
The machine consists of 7 distinct mechanisms through which the steel balls travel. The ball's path begins at an elevator, where it is lifted to the starting position, then it is guided to a "seesaw swing", which creates a junction between two different paths.
The first possible path leads to a mechanism called "Pillars" and continues to "90° swings". Then the path curves 180° and the ball travels back to a rail spiral which leads directly back to the elevator.
The other path leads to a mechanism referred to as "Two masses on a pulley", where the ball takes a short ride on a cart. Afterwards, it travels along bumpy rails which curve into a pair of funnels. The funnels then lead back to the elevator, closing the loop.



3.1 RAILS

A model of rails designed to allow for easy adjustments of shape to suit our need of guiding the ball between individual components.

CONCEPTION

As the whole project revolves around the movement of marbles, having a well-designed system of rails on which the ball moves is crucial. Specifying how the rail comes into contact with the ball as well as the overall shape of the cross-section was one of the first tasks to be completed. Starting the modelling work with this particular design was important as it would later be used in some form in all other components, whether completely integrated or just to make attachment points for an entrance/exit rail. Having this model available for everyone as a reference greatly helped reduce compatibility issues, as everyone had an idea of how the components will be connected.

DEVELOPMENT

The theory is that in order to make the ball move with minimal friction, the surface area of the rail touching the ball should be minimised. An ideal cross-section shape could therefore be a sharp point that is touching the ball. However, since we are working with plastic, such sharp point would get easily blunted or otherwise damaged. Therefore, the idea was to make the contact surface be flat, so the ball touches tangentially as opposed to trying to match the shape of the ball with a curve.

Knowing the diameter of the ball, the first step was to sketch 2 tangent lines running diagonally at 45° degrees to the horizontal. Then, as seen in figure 2, the dimensions were specifically chosen to be round numbers, with the width and height of each rail being 5mm and the separation between them 10mm. This was intended

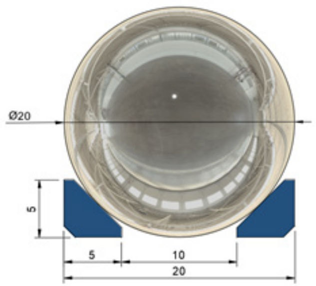


Figure 2: The rail cross-section

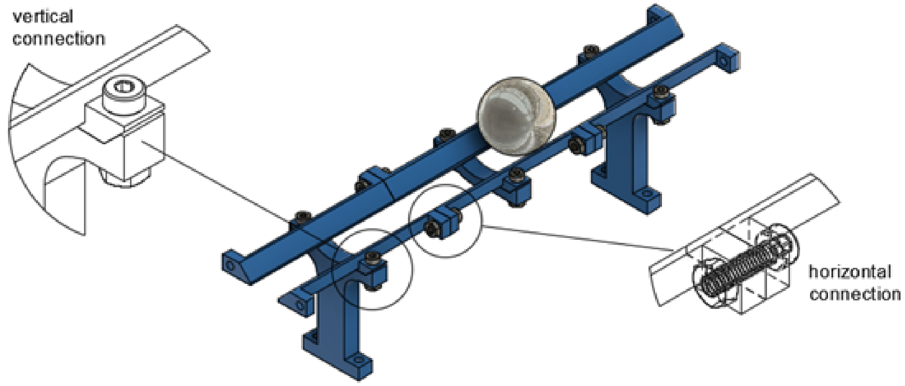


Figure 3: The rails.

to make further work with the rails as effortless as possible. The edges are chamfered in order to again make manufacturing (3D printing with a 0.4mm nozzle) easier and the product slightly less prone to damage.

The rails features two types of connection points as shown in figure 3. The vertical connection connects the rails to a pillar or a spacer (figure 4). The horizontal connection connects two rail

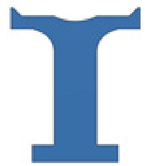


Figure 4a: Rail pillar.

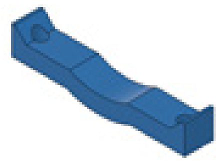


Figure 4b: Rail spacer.

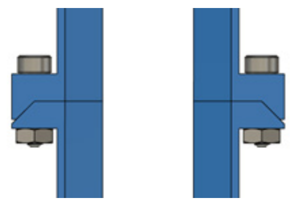


Figure 5: Top-down view: rail connection with a 45° kink


Figure 6: rail connection, hole + slot

segments or attaches the rail to another object. Both connections use M2x8mm screws. The vertical connection also has a 45° kink at the outer edge, which is meant to help constrain rotation on the vertical axis. Thus, all 6 degrees of freedom are constrained.

Initially, this kind of kink was also featured in the horizontal connection (figure 5). However, upon a closer look, this arrangement would make it difficult to exactly align the rails so that the connection is smooth. Therefore, a simpler solution was chosen, where the kink is removed and one of the holes is a slot (figure 6) so that the parts can be manually aligned while assembling the rails and tightening the bolts.

FINAL DESIGN

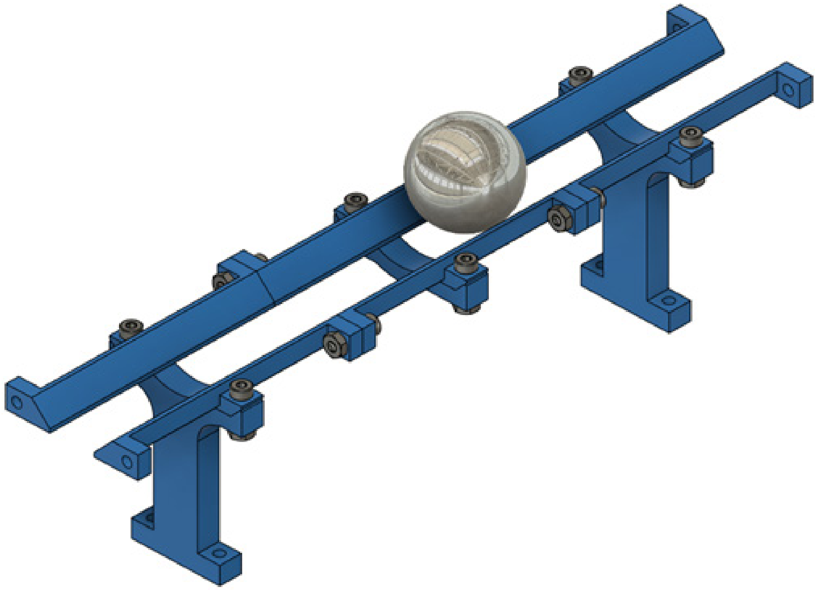


Figure 7: The final design of the rails.

In Figure 7 above, the final design of the rails is shown. This particular model was actually never used in the final design. However, pieces of it were often copied and modified and served as a basis for rails of different shapes or were implemented into other components that interact with the ball.

3.2 ELEVATOR

The elevator is the main component that allows the complete assembly to function continuously. This is done by elevating the steel ball from the lowest point to the highest point and resetting it back to its starting position. It is powered by a motor and uses a conveyor-belt-like system to convey the steel ball upwards where it enters a separator referred to as the 'seesaw swing', which sends the ball to two different paths.

CONCEPTION

There were multiple ideas on how the elevator would function that eventually led to the final general concept which was sufficient to start developing in CAD.

The initial idea was to create a conveyor belt with grooves in it as shown in figure 1. The belt would be rotated using a motorised pulley, and the grooves would have plates sticking out of it, allowing the steel balls to rest on it and eventually be pulled upwards.

The belt was also intended to be completely 3D printed, where smaller components (on the right of figure 8) are used to increase the flexibility of the belt. However, within this design, there were too many degrees of freedom, where the ball could roll left, right and forwards, ultimately creating a risk of it falling off the plate. Therefore, a new design had to be created where there is only one degree of freedom, vertically upwards.

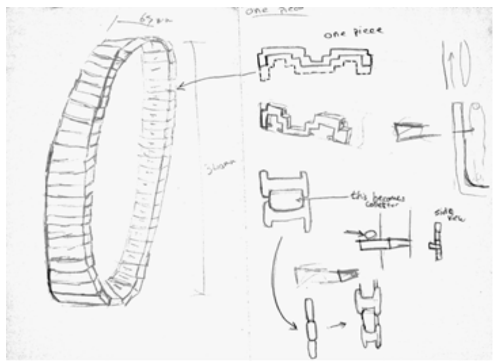


Figure 8: The initial idea of the elevator mechanism.

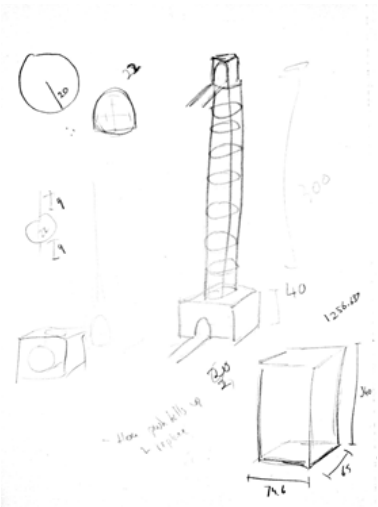


Figure 9: The second elevator concept.

Figure 9 demonstrates a new design that only allows one degree of freedom. The design functions where a large sum of steel balls get inserted into it, and with a motor the steel ball will be pushed upwards, and then another ball enters underneath it. Eventually, this causes the balls to go upwards and be ejected. The issue with this design is the quantity of balls needed to have only one ball ejected, which causes the total mass inside the system to accumulate and become too heavy. This can be demonstrated by a simple equation: "number of balls" • "mass of the ball" = "total mass inside the system". As the total mass inside the system increases, the downwards force increases (as dictated by F=ma). the upwards force that is generated by the motor to allow the balls to shift upwards also needs to increase. This was initially uncertain, as we didn't know how powerful the motor would be. Another issue is that obtaining enough balls would be costly, especially since most of them would be idle inside the elevator. Therefore this idea was scrapped.

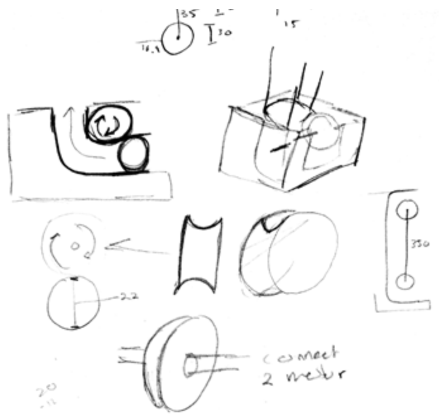


Figure 10

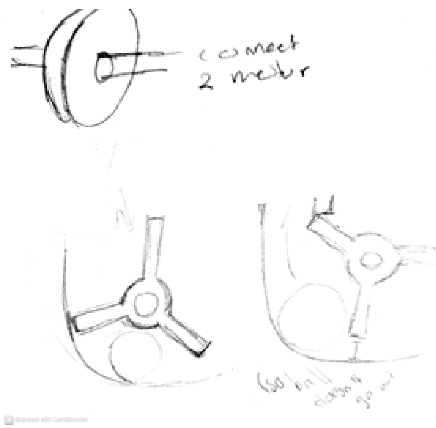


Figure 11

The concept in figure 10 still included the design in figure 9, however, the method in which the ball would travel upwards was adapted. The ball would travel upwards through the frictional force between the wall, the ball and the pulley. However, this still did not fix the issue of the total mass inside the system being too large.

Figure 11 shows the main component of the final concept being the method in which the ball travels upwards. The design shows a pulley that rotates allowing the ball to travel upwards. This design still included the initial idea in figure 9 and 10, and combines them. However, the new idea (not displayed in the figure) works where the balls being raised does not depend on the number of balls in the system (unlike in figure 9). In this situation the elevator can have one or multiple balls passing through in one go, without affecting each other. The sketches in figure 10 and 11 also do not include the use of a belt, which will be implemented to carry the ball from the bottom of the elevator to the top.

DEVELOPMENT

Whilst developing this component, a lot of alterations were made. The alterations were to guarantee that the ball would pass through the system the way it was intended to. This means that it has to exit at a specific location and must continuously travel upwards (not slipping and falling downwards).

Figure 12a demonstrates the most primitive form of the elevator. It contains transparent panels on either side (which can be better seen in figure 12b), and a base structure that the ball must travel upwards onto. The curve was produced through the use of circles, where the circles are placed up at a 45degree angle from the rectangular base of the sketch, which was to assure that the curvature would fit nicely with the rotation of the ball,

Figure 12a & 12b

where the ball doesn't have an coarse path to travel. The dimensions were simply determined with the maximum height allowed for the project.
Figure 13 shows the digitalization of the sketch drawn in figure 11. The idea was that the flaps would push the ball upwards, which would be placed in the top and bottom circles of the sketch in figure 10. This design would then be powered by a motor to rotate, the issue being there was no method in which the ball will continue it's upwards path as there was no continuous upwards force.

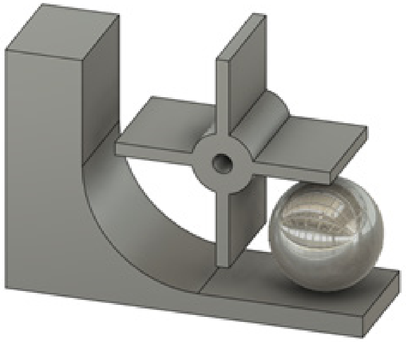


Figure 13

Figure 14

Figure 14 shows further adjustments to the design, where instead of having the design in figure 7, it was removed and replaced with a placeholder. Furthermore, an indent was created in the base which results in limiting the degrees of freedom in the system. This then means that the steel ball will go along a straight path, and doesn't shift left or right, meaning that the displacement along the horizontal-axis for the input will be equal to the displacement along the horizontal-axis for the output (both being approximately 0).

To replace the placeholders in figure 14, a pulley was created as shown in figure 15a. This is done so that a conveyor belt can be placed in the system, which will push the steel ball against the base, making it rotate and travel upwards. The pulleys were based on the following video: "How to create a GT2 timing pulley in Fusion 360 - Cad Tutorial, 2019," where the parameters were adapted to fit the measurements of the elevator (Anon, 2019). However, the design was not perfectly appropriate for the function, which led to its final form in figure 15b. The teeth were shortened to 6mm in its total length, to make sure the belt couldn't shift along the horizontal-axis. To reduce the chance of the belt slipping off the pulley, a rim next to the teeth was added to the design. A chamfer was applied to these inner edges to help reduce the friction of the belt and the sides of the pulley as well, or else the belt might follow the shape of the pulley and temporarily deform. The design in figure 9a has a total width where it exactly touches the transparent side panels of the component (Figure 16), which unnecessarily increases the friction, ergo, to mitigate the friction with the acrylic panel, the side of the pulley was extruded inwards except for a small extrusion that touches the plastic bearing.

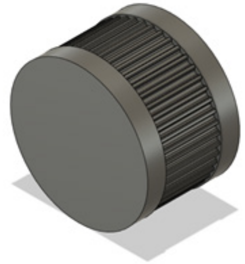


Figure 15a: initial design of the pulley.

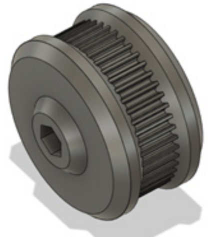


Figure 15b: improved design of the pulley.

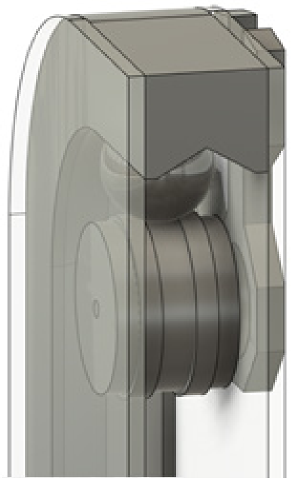


Figure 16

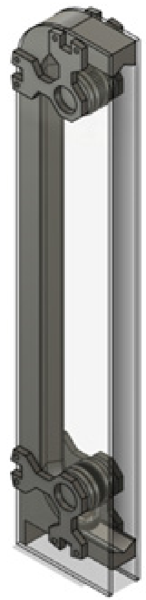


Figure 17

Figure 17 displays the addition of pulley holders on both the top and bottom. This was done to attach the panel to the base as well as having space for the addition of bearings. Figure 17 also includes new panels, which still need to be changed mainly as the bottom of the panel now overlaps the wooden board. In this version of the elevator as well, the belt isn't tensioned yet, which means that the steel balls have a high risk of slipping, which is to be solved by the addition of a third, tensioning pulley.

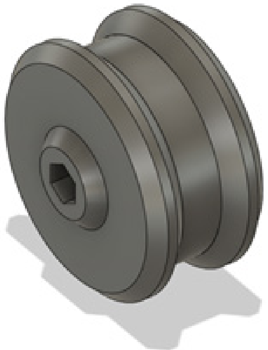


Figure 18: Tensioning pulley, toothless.

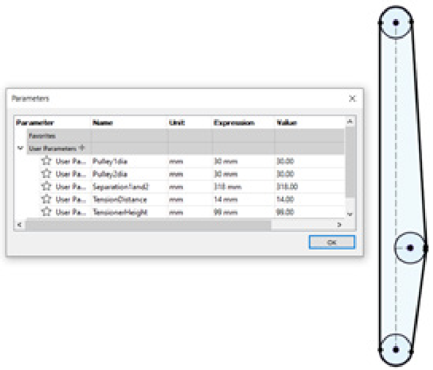


Figure 19: The belt model with adjustable parameters.

The third pulley's (figure 18) approximate position was determined by pseudo calculations made using Fusion 360 (figure 19).

The pseudo calculation gave us a rough estimate of the position of the tensioning pulley. However, to be able to precisely adjust the tension and account for the inaccuracy of the length of the belt, the tensioning pulley's position was designed to be adjustable. This is done (visible in figure 20) with the use of 4 screws, each of which features 2 nuts - one for tightening the screw and the other for adjusting the distance between the pulley and the base.

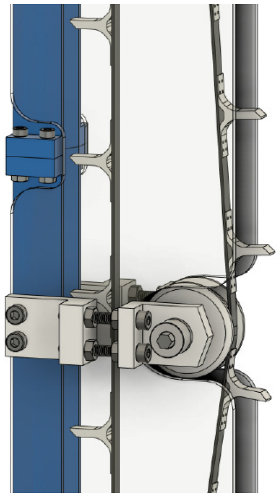


Figure 20: The tensioning pulley.

In figure 21 it is evident that the base is quite tall, reaching a full 40cm in height, which is too large to be printed in one piece with the available 3D printer. As a solution, the base was split in half, where 2 screws are on each side connect the two components.

The final changes of this component made are primarily located at the pulleys. A bearing and metal securing collars were added on both sides of all of the pulley holders (as shown in figure 22 and 23), where the bearings fit with a minimal gap

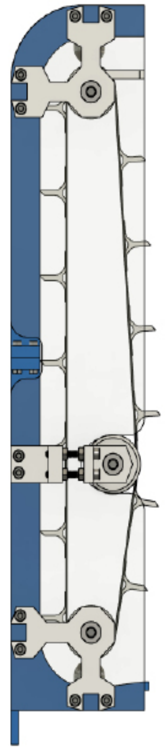


Figure 21: Full side view of the elevator.

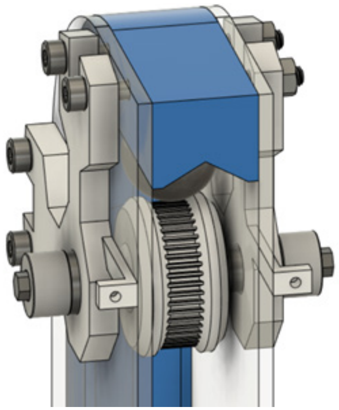


Figure 22: close-up of the elevator exit.

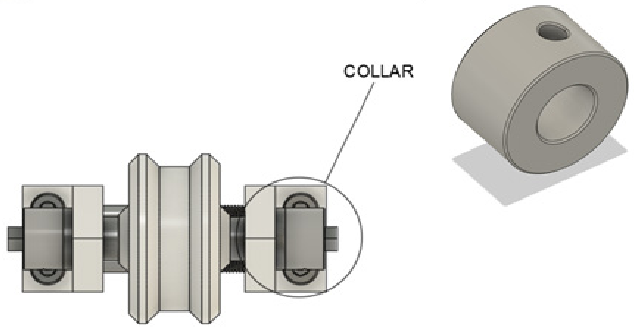


Figure 23: close-up of the pulley axis.

FINAL DESIGN

Figure 24: Final design of the elevator mechanism.

3.3 SEESAW SWING

The seesaw swing determines which of the two routes the steel ball enters. Whenever a steel ball passes through, the direction (left or right) that the ball travels switches as the weight of the steel ball pushes the seesaw down on either the left or right side. The flap at the pivot point allows the ball to slide onto the elevated part of the seesaw, pushing it downwards and opening up the other side for the next steel ball. The balls therefore change paths in an alternating fashion.

CONCEPTION

Figure 25 exhibits the initial sketch of the component. Initially, the seesaw swing included a funnel, however that funnel was not necessary, as there are more efficient ways to guide the ball. In this initial sketch, only the seesaw was depicted, with no concept created on how the piece would be held.

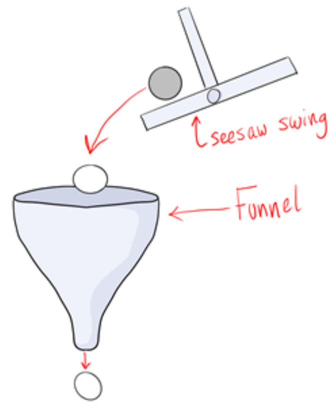


Figure 25: Sketch of the seesaw swing.

DEVELOPMENT

To start off the design as intended in the sketch in figure 25, the 3D modelling began with the base of the seesaw without any connector pieces to hold it as shown in figure 26.
To create a functional swing, a pivot point had to be created in the centre of the design, which to implement a bar in the centre was created as shown in figure 27. The difference between the centre beam in figure 26 and 27 is that in figure 26 the beam was fixed, and the beam in figure 27 is connected to a base that allows it to freely rotate along the pivot point.

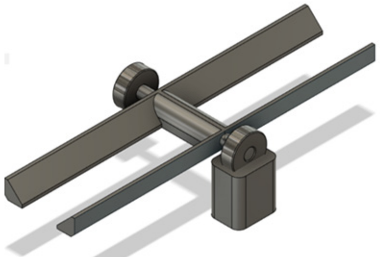


Figure 27

Figure 26

The seesaw is fixed onto the rod shown in figure 28, which is held together through friction. The rod goes into the bearings which allow for it to rotate with a low coefficient of friction, causing the seesaw to rotate with it. The movement along the horizontal-axis was prevented through the implementation of spacers, which are simple plastic tubes.

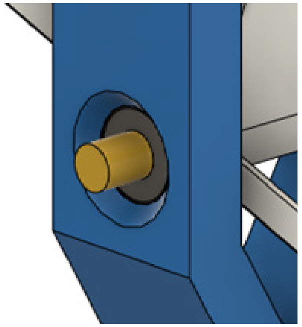


Figure 28

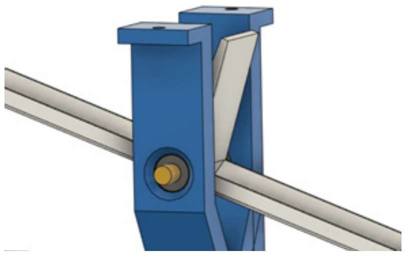


Figure 29

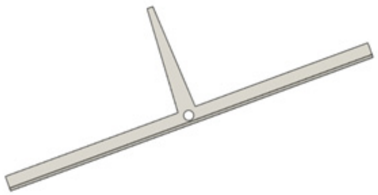


Figure 30

With regards to the method of switching the route of the ball from left to right into the next components, the use of a divider (figure 29) will be implemented. When the ball lands on one side of the seesaw, through the weight, it pushes the seesaw down on the given side, and the other end gets elevated. The elevated side also then presents an opening with the divider, allowing for the next steel ball to pass through there (as seen in figure 29). Furthermore the bar in the middle had to be rather long, as to prevent the balls from rolling over onto the wrong side.

To prevent the seesaw from rotating too far, a type of blockage had to be made. The initial idea, as shown in figure 31, was an extension that spanned from one rail to the other. This version used unnecessary material, and thus a second concept was formed. This concept was later refine to have the rails attached to to the main pillar as seen in picture of the final product

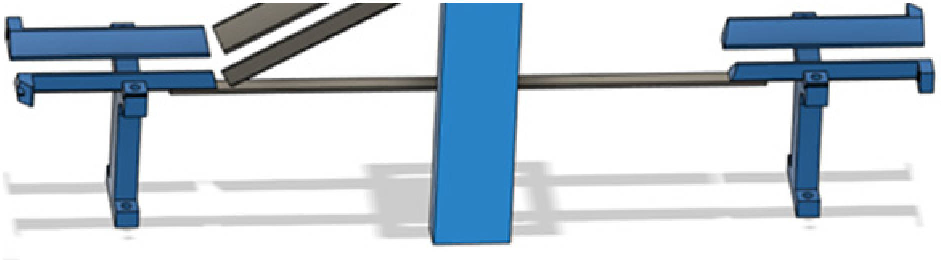


Figure 31

To control the movement of the ball, a sloped ring was formed above the seesaw (figure 32). This allows the ball to fall perfectly on the open end of the seesaw. The ring was then attached to a larger pillar component, which is to hold the entire seesaw swing contraption. The pillar, due to its large size, is separated into two pieces (figure 33). The upper piece slides into the bottom piece and can be tightened in place without any play with the bolts that are inside slotted holes. The whole component is visible in figure 34.

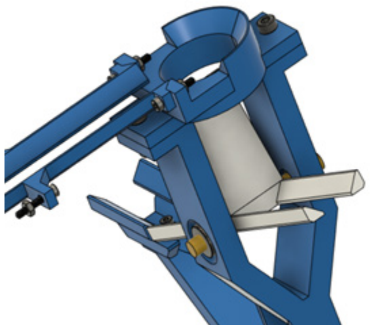


Figure 32

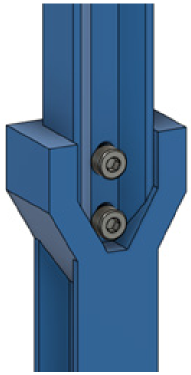


Figure 33

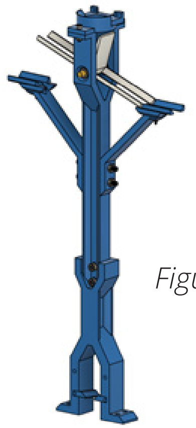


Figure 34

FINAL DESIGN

Figure 35: Final design of the seesaw swing mechanism.

3.4 POWER TRANSFER

The power transfer system is used to transfer power from the motor to the components "Elevator" and the "Pillars". The motor's power is transferred though a belt to an axis that is attached directly to the Elevator. To transfer power the Pillars, 90° bevel gears are used to transfer the force to an axis perpendicular to the initial axis, where another belt is used to rotate the crankshaft of the Pillars.

CONCEPTION

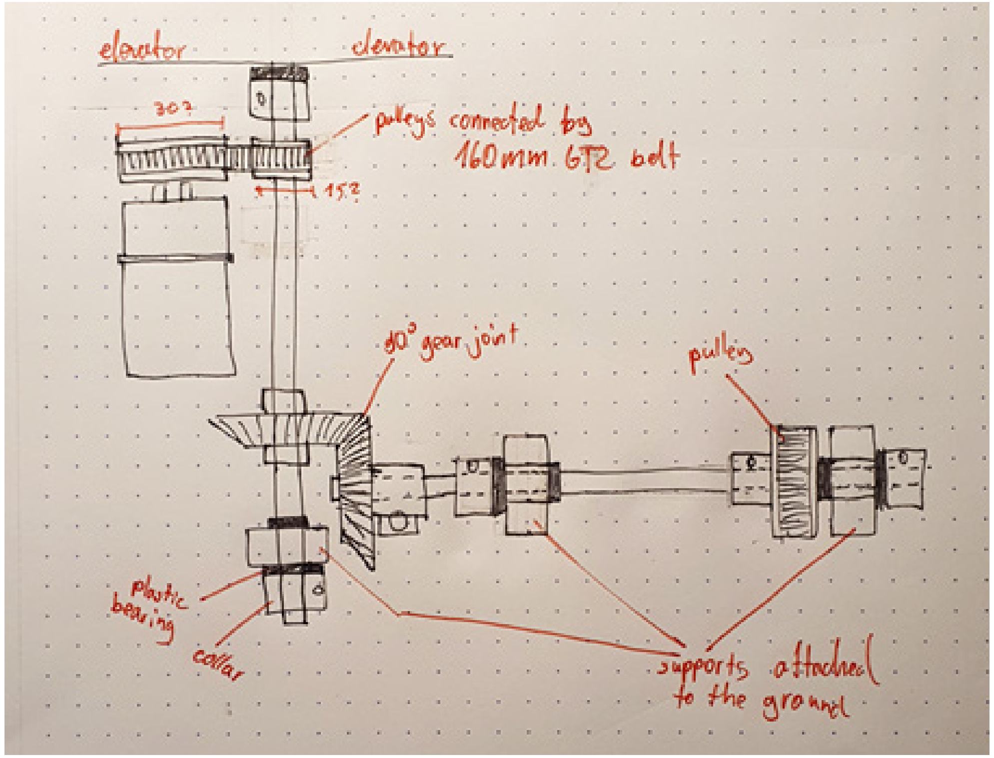


Figure 36: Initial proposal of the power transfer mechanic.

Figure 36 above displays the initial proposal that was almost completely replicated in CAD.

DEVELOPMENT

Figure 37 shows the entire component that transfers the force from the motor to the final, which will be broken down in parts A, B and C.

Part A - initial transfer from motor to hexrod:
To calculate the torque of the 15mm pulley (on the left) in figure 38, the ratio of the teeth is used:

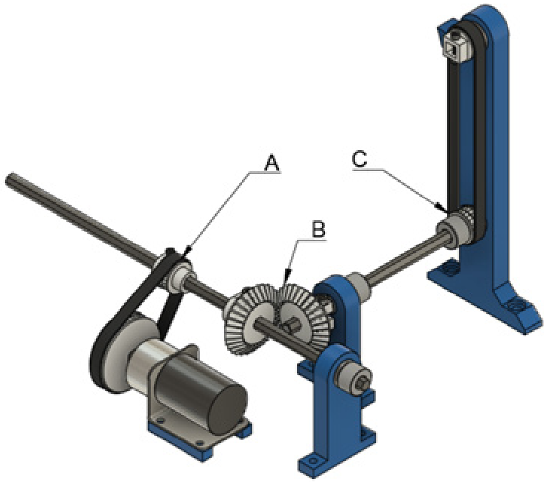


Figure 37: Entire component that transfers the force from the motor, broken down in parts A, B and C.

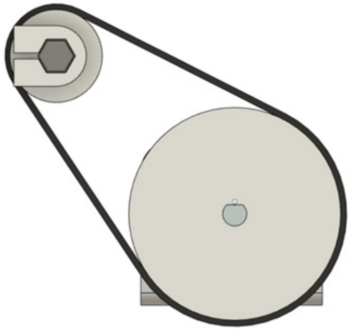


Figure 38: Part A - Initial transfer from motor to hexrod axis.

"Number of teeth in 35mm pulley" = 55
"Number of teeth in 15mm pulley" = 24
Therefore, the gear ratio is 2.29:1

The "maximum output torque" of the motor is 12Ncm, which is when a 12V is used. However the battery used is 9V, meaning the output torque is less. For simplicity, the torque of 9Ncm will therefore be assumed to find an approximation. However to make calculations easier, the newton centimetre will be converted to newton metre: 0.09Nm. Now using the gear ratio, the output torque of the 15mm pulley is 0.039m

In figure 39 the force gets transferred to the pulley inside the elevator. To calculate the torque of the pulley inside the elevator (32mm pulley) the gear ratio should be calculated:

"Number of teeth in 15mm pulley" = 24
"Number of teeth in 32mm pulley" = 47
Therefore the gear ratio is 1:1.95

This means that the torque in the 32mm pulley is 0.077Nm

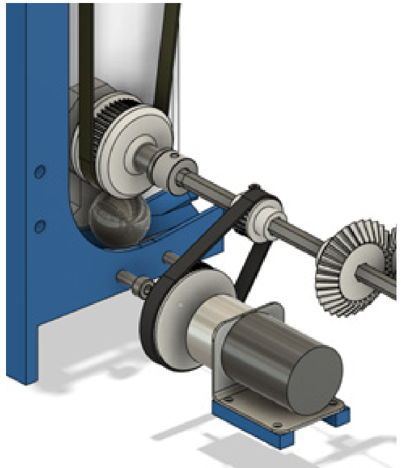


Figure 39: Connection to the elevator (side panel has been hidden)

Now to find out the amount of force needed for the elevator to counter the weight of one steel ball, F=ma can be applied:

Mass of steel ball = 33g = 0.033kg
Acceleration = g = 9.81ms^{-1}

Force = "Mass of steel ball" • "Acceleration"
F = 0.033kg • 9.81ms^{-1} = 0.324N

However, to determine whether the ball can be lifted upwards by the belt, the torque the ball exerts on the pulley needs to be determined.

The unit of torque is Newton metres, thus the force should be multiplied by the distance of the centre of the pulley to the centre of mass of the steel ball.

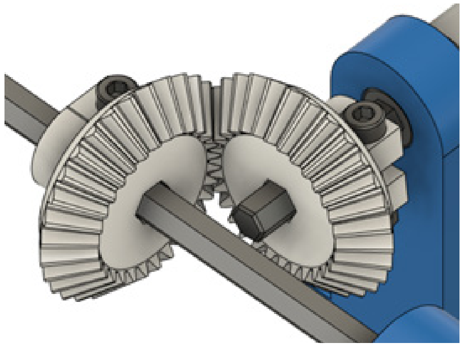
Force = 0.324N
"Radius of 32mm pulley" = 16mm = 0.016m
"Radius of steel ball" = 11mm = 0.011m

Torque = Force • (“radius of 32mm pulley” + “radius of steel ball”)
Torque = 0.324N • (0.016m + 0.011m)
Torque = 0.324N • 0.027m
Torque = 0.00864Nm
So, while the torque the motor exerts on the pulley is 7.7Ncm, the torque the ball exerts on the pulley is 0.86Ncm in the opposite direction.

The “torque of the 32mm pulley” > “torque needed to raise the ball”.

So, ignoring the weight of the belt, the frictional forces, the fact that some power is used by the other mechanism and other inefficiencies, it can be said that the motor is sufficiently strong to lift multiple balls, specifically ~9 balls.

Part B - 90° Bevel Gears:



While gears were avoided in the complete assembly, in this circumstance, to transfer power to a perpendicular axis, there aren’t any other simpler alternatives, which lead to the decision to implement a pair of bevel gears.

Figure 40: Part B - 90° Bevel Gears.

The first version of the bevel gear is shown in figure 41a. However when comparing the gear with gears found online made by others, the shape of the teeth did not seem to be optimal and thus could cause an increase in slipping and other errors. Rather than spending a lot of time in developing a gear, a gear was found online (Keskin, 2021) (figure 41b) and modified.

Part C - Transferring Torque to Crankshaft:

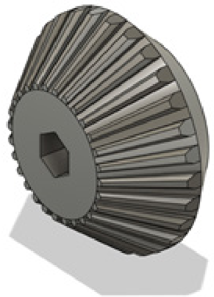


Figure 41a: Our original design.

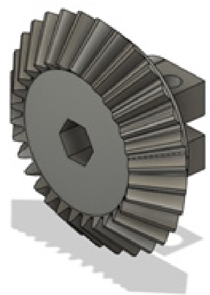


Figure 41b: Modified version of the bevel gear found online.

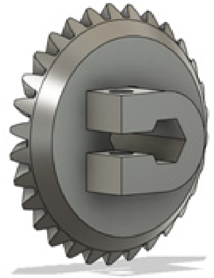


Figure 41c: Back-view of the modified bevel gear.

To transfer the torque vertically to the crankshaft of the “Pillars” component, two pulleys and a belt were inserted. The pulley sizes are equal to the “15mm pulley” in Part A, meaning that there is no change in gear ratio, thusly the torque is 7.7Ncm.

The following equation can be used to determine the length of the belt (Żuławińska, 2019):

Belt length =

$$[(D_L + D_S)\cdot\frac{\pi}{2}] + (D_L - D_S)arcsin[\frac{(D_L - D_S)}{2L}] + 2\sqrt{L^2 - 0.25(D_L - D_S)^2}$$

$D_L = D_S$ (as both pulleys are equal in size)
L = distance from the centre of one pulley to the other (which is pre-determined)

Now adapting the formula found online;
"Belt length" = $\pi(D_L)+2(L)$
D_L = 15mm
L = 94.1mm
"Belt length" = π(15mm)+2(94.1mm)

Final details:
Slots were created within the wooden board (figure 42a) that the motor connects to, along with the motor being elevated (figure 42b). As the belt's length was already predetermined, the position of the motor has to be adjustable in order to tension the belt. To accomodate this, the slots are made to allow the motor to shift, so that we can find the perfect belt tension while assembling and fix the motor at that position.

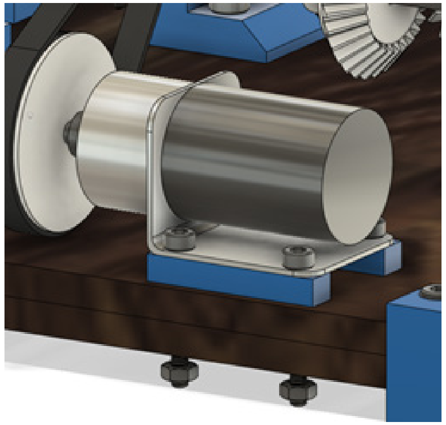


Figure 42a: the motor fixed to the board

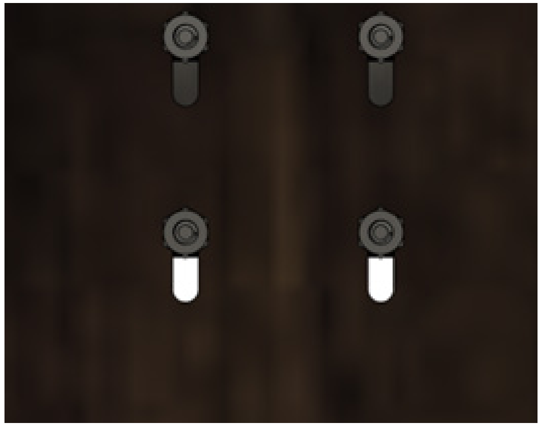


Figure 42b: bottom view of the motor attachment

FINAL DESIGN

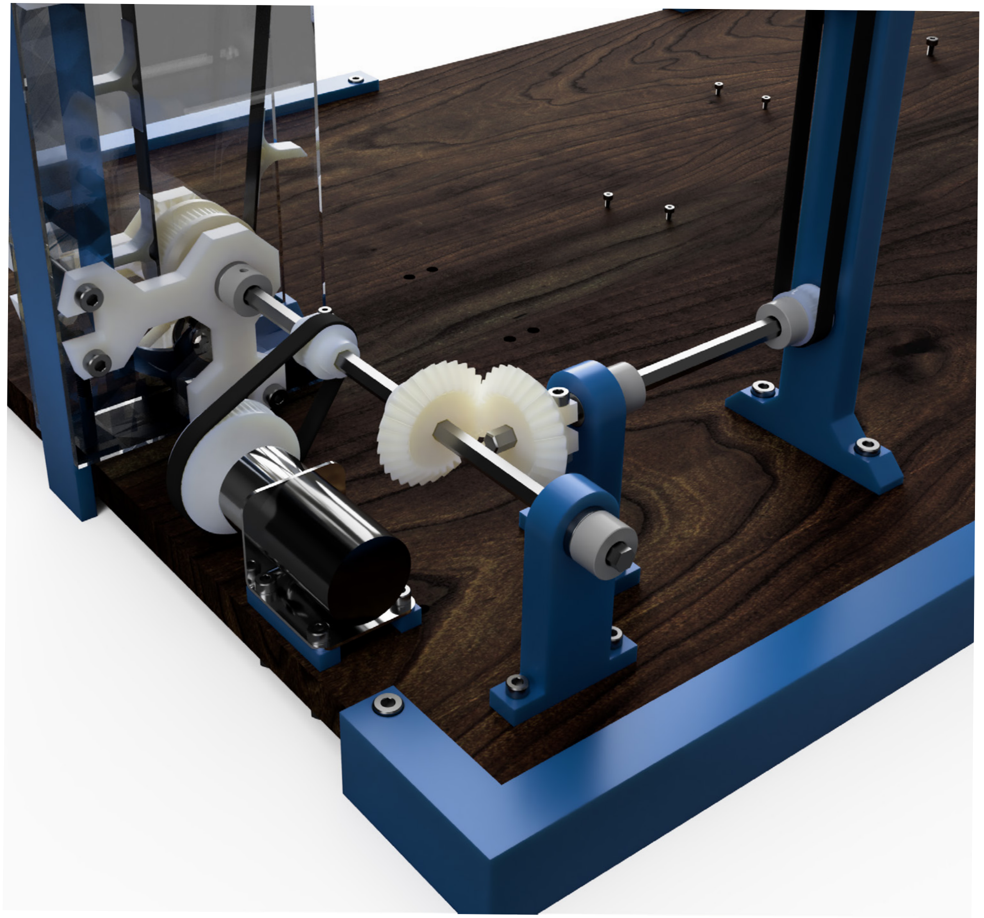


Figure 43: Final design of the power transfer mechanism.

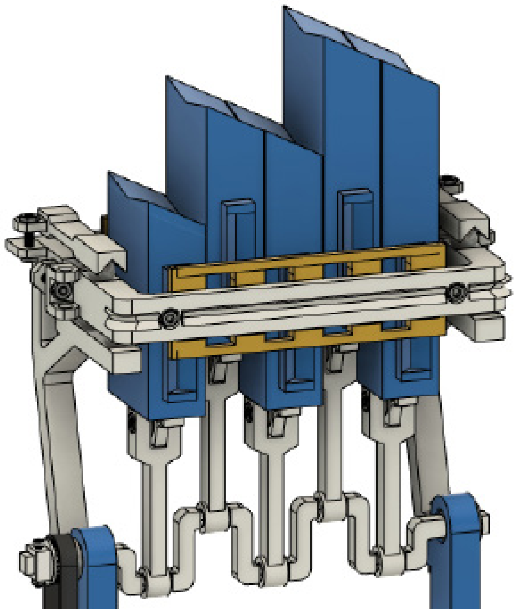
3.5 PILLARS

This mechanism consists of 5 pillars that oscillate up and down. This movement is driven by a crankshaft attached to the bottom of the pillars. The pillars change position in an alternating pattern. While one pillar moves from its minimal to its maximal height, the one next to it completes the opposite motion. With each 180° rotation of the crankshaft, the ball travels to the next pillar.

CONCEPTION

This mechanism was inspired by examples we found online, we tried to adjust it in a way that it uses the exact construction methods. Many examples online used a kind of rotating bar that depended heavily on the ability of the pillars to move back down by the force of gravity only. We decided we did not want to be too dependent on the weight of the pillars and the friction there might be in the ball slider mechanism on both sides of the pillars. This is why it was decided to use a kind of crankshaft that pushes the pillars up while also being able to pull them back down.

Figure 44: The final design of the pillars mechanism.



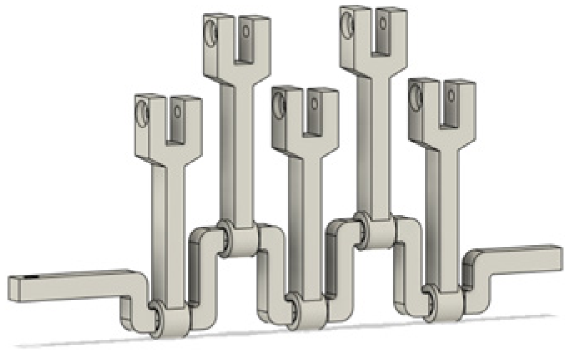


Figure 45: The crankshaft with 0.2 mm spacing between the horizontal and vertical beams.

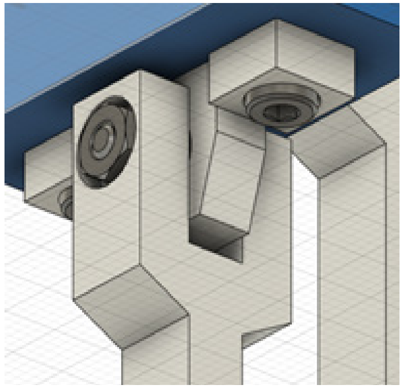


Figure 46 The rotational bearing connecting the crankshaft to the pillars.

DEVELOPMENT

There are five bars that oscillate up and down through a crankshaft which is rotated using power transferred from the DC motor that was addressed in section 3.4 - Power transfer. The crankshaft is printed in one piece using the 3D printer available at the university, with spaces of 0.2 mm in between the different bodies to allow them to move independently of each other (see Figure 45). Besides that, the top is connected to the bars with a rotational bearing, which also allows the bars to turn (Figure 46).
The hardest part in this mechanic is constraining the pillars so that they may move in only one direction, up and down on the z axis.

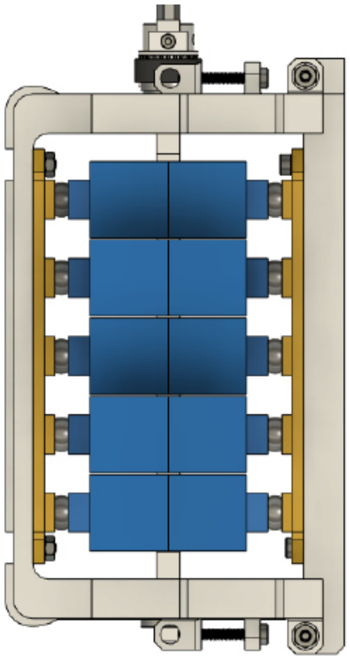


Figure 47: The ball slider mechanism consisting of balls and v-shaped bars on both sides.

The other 5 degrees of freedom are constrained with different methods. For constraining the pillars translation along the x axis, we used an elastic band that provides a horizontal force to the pillars, pressing them onto the other side, where ball sliders make sure there is limited friction for vertical movement of the pillars (Figure 47).

On one side of the pillars, there are two balls used in the slider and on the other side only one, to ensure that the pillars are not overconstrained and that rotation around the y axis is constrained. The sliders consist of these balls and a v-shaped bar on both sides of the balls. These sloped sides ensure the pillars are also fixed in terms of translational movement in the y direction, as well as the rotation around the z-axis and y-axis (Figure 48).

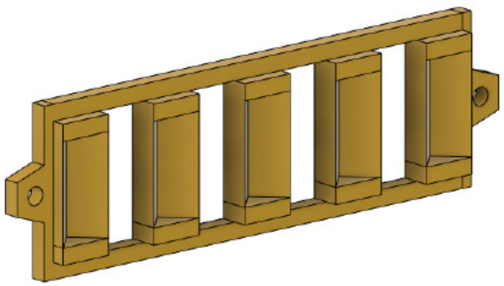


Figure 48: The v-shaped parts of the ball slider mechanism.

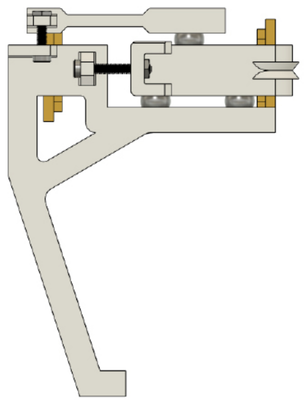


Figure 49: The ball slider setup, with two balls below and one ball on top.

To keep sliding piece in place, another ball slider setup was needed, as shown in figure 49. With two touch points from below, and a force from above, the part is limited to only one direction of movement. The force pointed downwards is a result of the elasticity of the 3D printed plastic. In this part of the mechanism, we used bolts in two places, to ensure force is adjustable to the elasticity of the elastic band and the bendability of the 3D printed material.

FINAL DESIGN

Figure 50: Final design of the pillars mechanism.

3.6 90° SWINGS

The mechanism features two swings. When a ball arrives to the first swing, it starts pivoting until it reaches the second swing and locks into it. The ball then continues to the second swing and the first returns to its original position. After the second swing pivots, the ball continues its journey along the rail.

Figure 51: The final design of the 90° swing mechanism.

CONCEPTION

This mechanic is designed differently in terms of assembling methods. While the other mechanisms use bolts and nuts to join different parts together, in this design, it was the goal to experiment with a bolt-less design while still constraining the component as well as possible. This way, it will be observed whether this type of construction will allow for play and whether parts designed in such a way can be a viable alternative to using traditional fasteners.

DEVELOPMENT

The mechanic consists of two rotating parts with a kind of a "cup" on top, and a cube at the bottom. The cup will hold the ball in place, using sloped sides that keep the ball from accidentaly falling off sideways (Figure 52). As the ball rolls from the rails onto the cup, the momentum of the ball cause the part to start pivoting. In the same way, the second part will rotate when the ball is passed on from the first to the second rotating part (Figure 53).

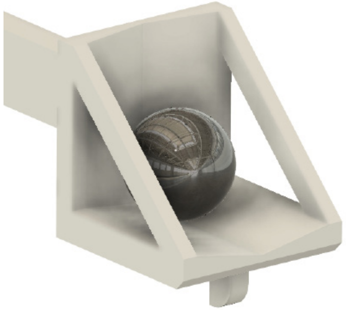


Figure 52: The sloped sides keep the marble in place.

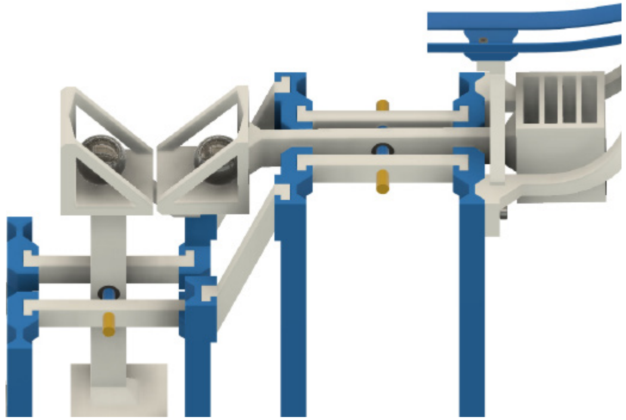


Figure 53: The parts can rotate to pass on the marble.

After the ball passed on from a rotating part to the rails for example, the weight of the box on the other side of the rotating part causes the part to return to its original vertical position.

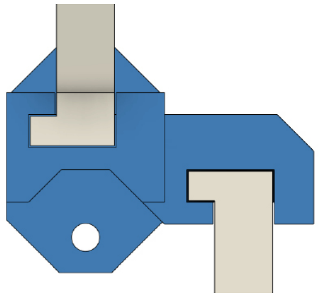


Figure 54a: The L-shaped connection.

The mechanic uses the vertical pillars to keep all parts in the air. As shown in Figure 4, the horizontal beams are connected to the vertical pillars using an L-shaped end that fits perfectly in the hole in the blue pillar (Figure 54). In this way, the vertical bar is constrained in all directions, by the blue pillar and the force of gravity from above.

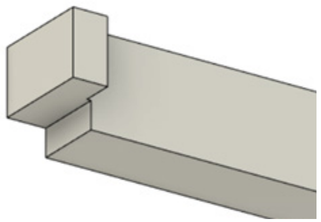


Figure 54b: The L-shaped connection.

The rotating parts can move using a ball bearing that is connected to the part and a vertical beam, in order to keep the friction there as low as possible (Figure 56).

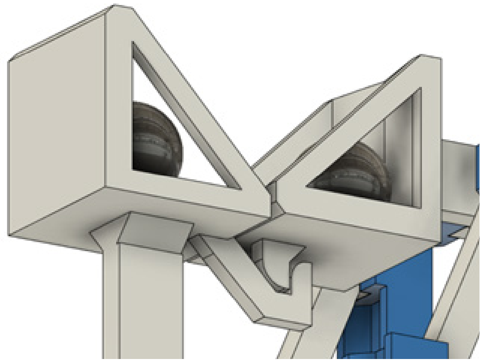


Figure 57: The rotating parts with the hook that connects them.

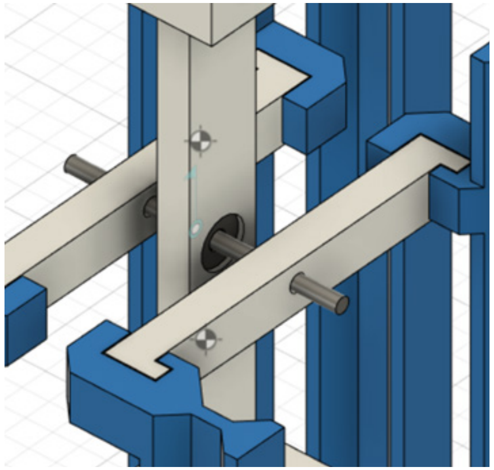


Figure 56: The rotating part that is able to move due to a rotational ball bearing

The two swings feature a little hook that allows them to lock together for the brief moment when the ball is passing on from one to the other (Figure 7). When the ball leaves the first swing, it starts pivoting back to its original position, releasing the lock. This prevents the swings from pivoting too far and dropping the ball.

Furthermore, as seen in figure 8, the blue pillars have an I-shape crosssection, which ensures the pillars resist shear stress in both dimensions, but do not require unnecessary material.

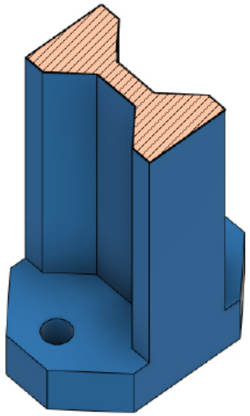


Figure 58: Section analysis of the pillar shows the I shape cross-section.

Center of mass analysis:
Herein lies the key to understanding why this mechanism works. Without the ball, the centre of mass of the swing lies just beneath the pivot point (figure 59a). In order for that to be the case, the shape and weight of the swing, especially the cube part, was carefully considered. As a result, the swing is completely upright while waiting for the ball to arrive.
When that happends, the centre of mass changes. Due to the significant weight of the solid steel ball (32.8 grams). the centre of mass shifts to above the pivot point and slightly to the right (figure 59b). As the net acting force has a small yet significant horizontal component the swing will begin pivoting, even without the momentum of the ball, which on its own would have sufficed to initialize the pivot motion.

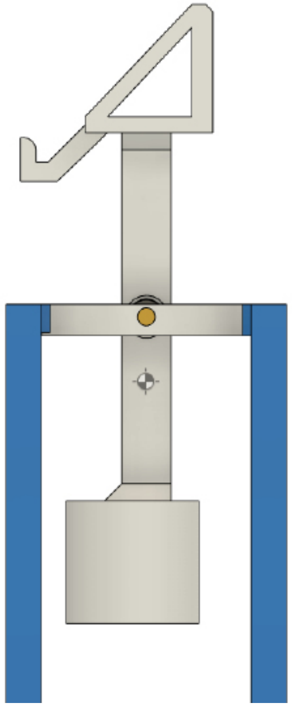


Figure 59a: The swing's centre of mass without the ball lies directly beneath the pivot point.

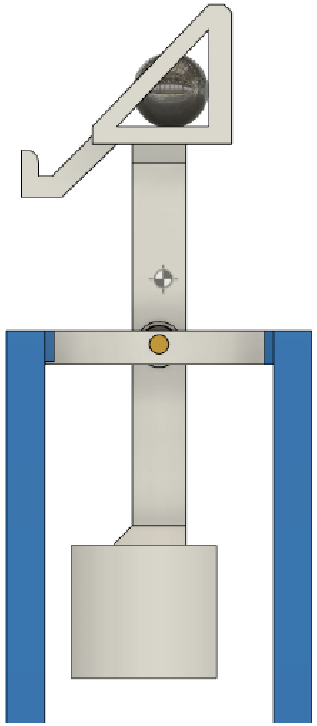
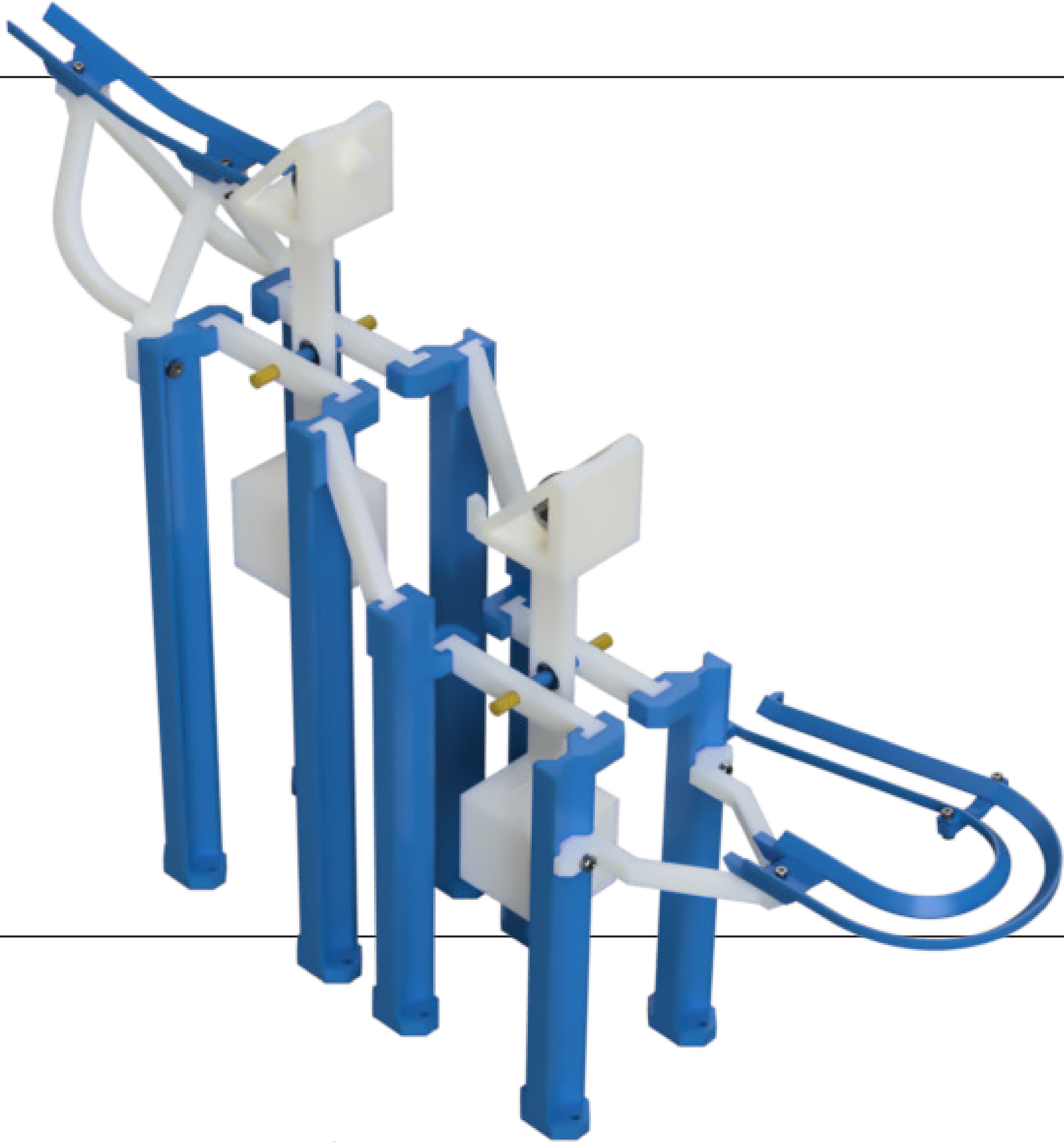


Figure 59b: The swing's centre of mass with the ball lies above the pivot point and slightly to the right,

FINAL DESIGN



3.7 SPIRAL

The spiral is a component created to have the steel ball travel downwards, and eventually reinstated into the elevator.

CONCEPTION

When conceptualising the complete assembly, there was some empty space available. To fill this space a spiral was decided to be implemented. The idea was mainly that it would be one of the final components before the steel ball reaches the elevator once again. The spiral is then also supported by pillars as shown in figure 60.

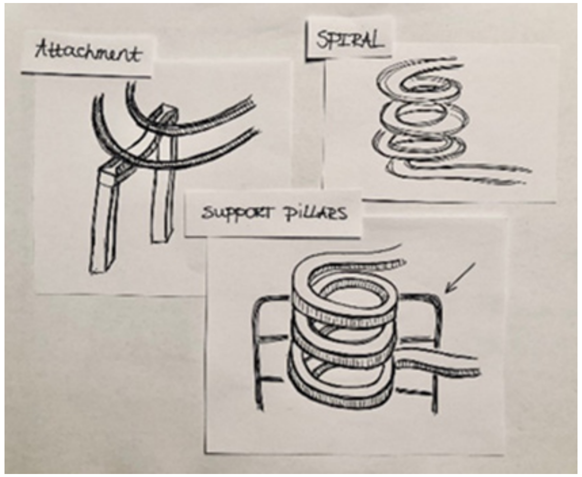


Figure 60: Sketch of the spiral mechanism.

DEVELOPMENT

The first step in developing the spiral was to begin with the rails. The original design is as shown in figure 61, where there is a solid piece which is representative of a slide. However when evaluating the design, it was recognized that there is a lot of unnecessary material used. To reduce the material used, the second version is based on the standard rails as seen in section "3.1 RAILS". This new version is shown in figure 62. Furthermore a concept in figure 61 that was not continued was the grey bowl at the bottom, this was discontinued as when placing the spiral in the complete assembly, the actual distance of the spiral to the bottom was established. This showed that the bowl took up space which was not available as it would mean the ball could not go further than that point. Rather than implementing the bowl, the spiral simply straightens out and leads to the elevator.


Figure 61

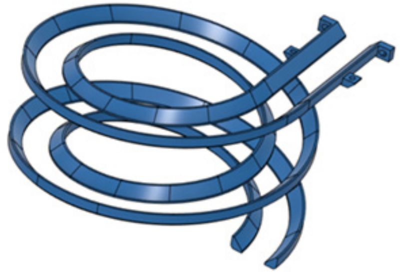


Figure 62

Up until now, the spirals were not only floating, but also disconnected from each other. If two separate pillars were to be added for the inner spiral and the outer spiral, the distances would not be maintained in the physical assembly, so to maintain this separation, one pillar was implemented that connected two parts of the spiral together (as shown in figure 63). Figure 64 displays how the pillar is attached to the spiral, being that there are extensions that contain a groove, the pillar then a component that perfectly locks into that groove, which is then further fastened with a screw. 3 pillars were implemented which stabilize the rail enough for it to carry the rather heavy ball.
The spiral is split at every point where the pillar is located. This was done to make 3D-printing simpler and reduce the amount of supports necessary.

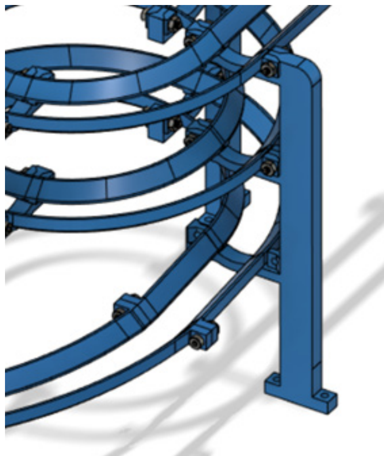


Figure 63

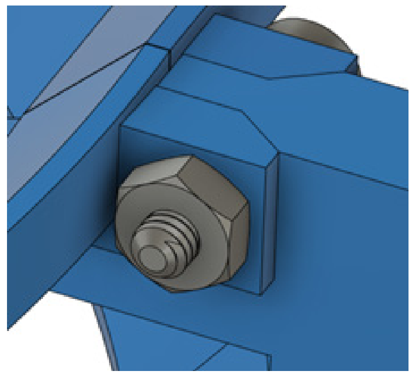


Figure 64

3.8 TWO MASSES ON A PULLEY

The two masses on a pulley (or simply "pulley carts"), are a mechanism inspired by the classic physics problem involving tension forces. As the steel ball enters a cart 1 that slides on two 30° rails, cart 1 becomes heavy enough to start moving and pull cart 2, which is suspended on a vertical rails, upwards. At the end of the ride, the ball gets removed from cart 1, which causes the vertical cart 2 to regain the upper hand and pull cart 1 back to its initial position.

CONCEPTION

Initially, the goal was to create a kinetic chain reaction that triggers only once. That made it possible to execute the following sketch, where the weight of one ball would start lifting another ball up. However, since we wanted our machine to function continuously, upwards motion like this was no longer possible, as the ball simply does not provide enough energy to the system for it to reset itself. Therefore, this idea was modified into a version where a cart would carry the ball a certain distance and then, after releasing the ball, be dragged back into its initial position.

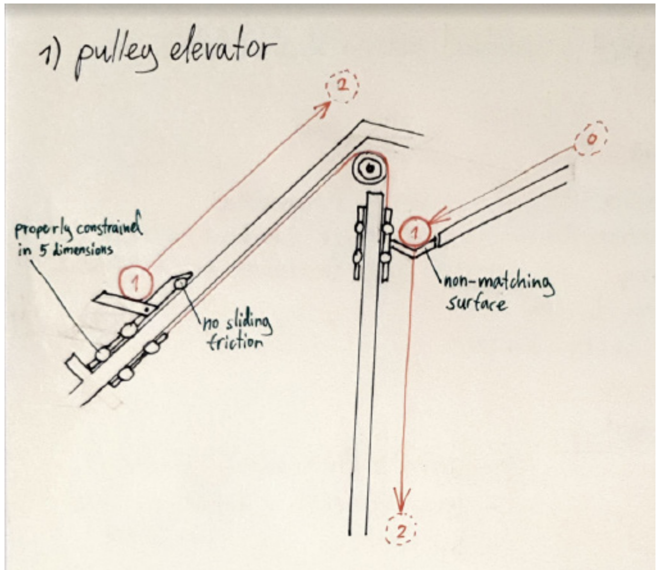


Figure 65: The initial idea visualised in a low-detail sketch

DEVELOPMENT

The carts are connected to eachother via a thin rope that is stretched across a pulley to minimize friction.

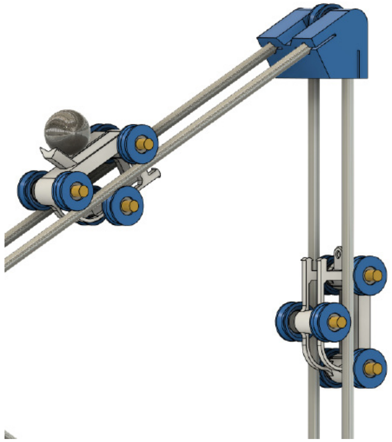


Figure 66: Closer view of the two carts.

The cart design

As seen in figure 67, there are three wheels on each side of the cart. Two pairs on one side and one pair on the other. This arrangement allows the cart to stay stable on the rail with only one degree of freedom.
The single pair of wheels is being pressured against the rail slightly by the very thin structure that holds its in place. Using the elasticity of the plastic, this part acts as a spring, eliminating play.
The wheel are simple 10mm bearings fitted with a plastic collar, which features a V shaped ridge that helps secure the wheel on the circular rail. Each pair rests on a shared 3mm steel axis and is secured on it with yellow endcaps.

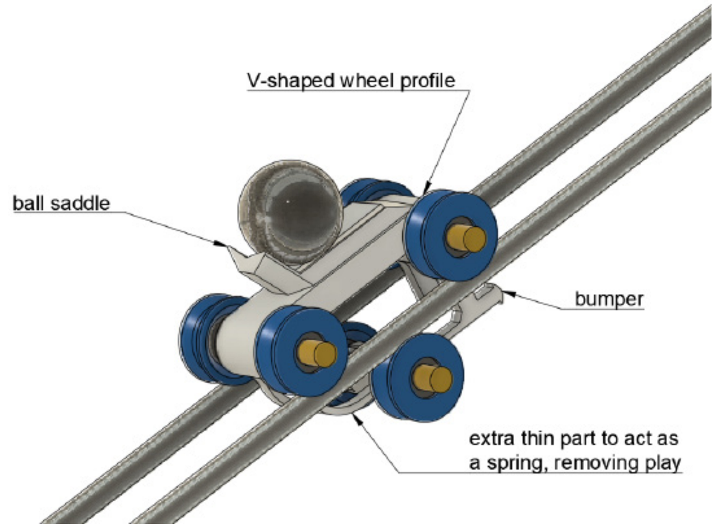


Figure 67: The ball-carrying cart close-up

Another feature of the cart are bumpers, intended to stop the cart against the flat part of the blue structural piece that hosts the pulley. The ball rests inside a V shaped saddle. This shape ensures the ball stays in the centre of the “seat”.

The rail structure design

Originally, the 5mm steel rods were intende only as a means of guiding the carts. The fact that there was already a 60° angle between the two guiding rails, it became convenient to make use of the to construct the entire structure out of them. Thus, another two pairs of rails were added. First pair completes an equilateral triangle, creating a highly stable structure. The second pair continues parallel with the ball-carrying rail and provides a second point of contact with the ground plate (figure 68).

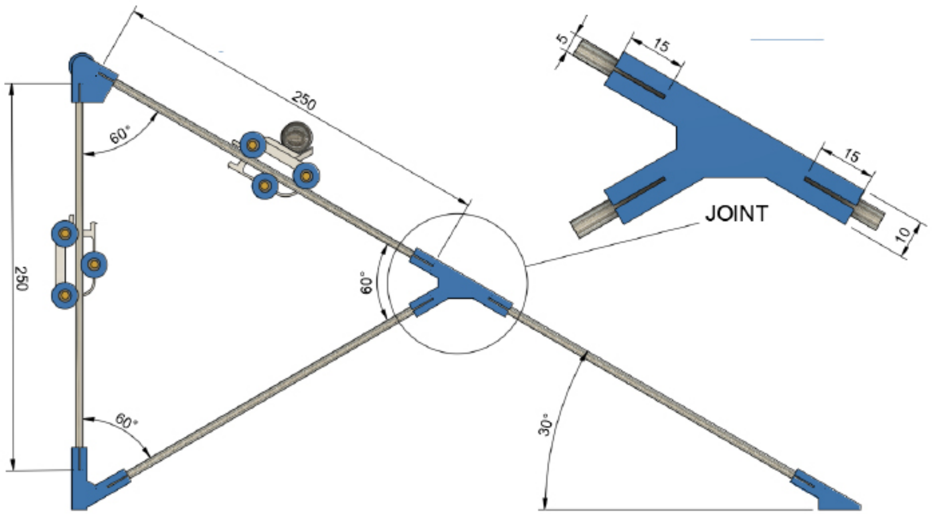


Figure 68: A drawing illustrating the structure of the rails

All the rails are connected with plastic connectors. A notable feature of these holders is the lack of bolts. Making use of the elasticity of plastic, these piece were designed with holes that have narrow slits, aiding in the necessary deformation to accomodate the steel rod and ensuring that the deformation stays only elastic, not plastic. The close up of this is seen in figure 69.

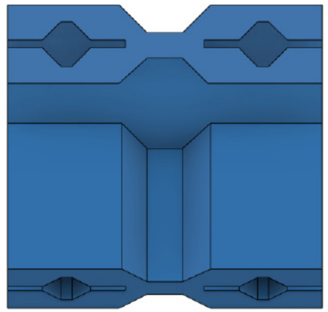


Figure 69: A close-up of the plastic connectors with bolt-less design

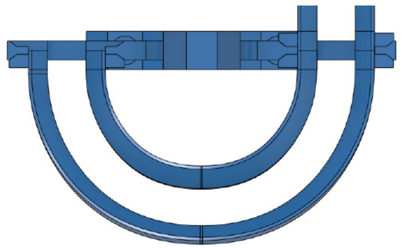
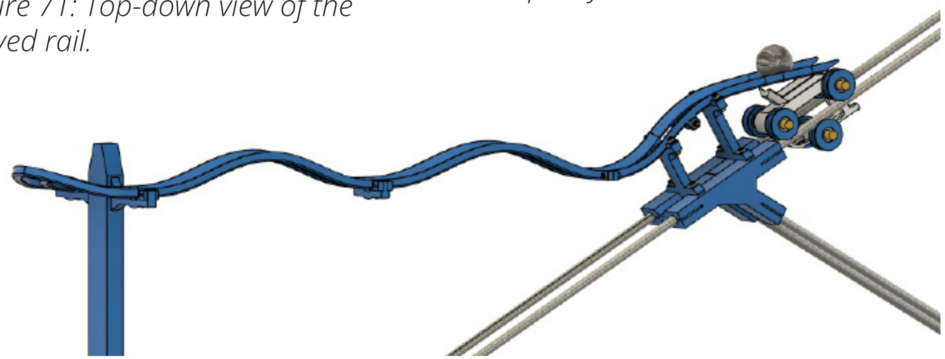


Figure 71: Top-down view of the curved rail.

The “snake” design

After leaving the cart, the ball travels along a rail referred to as “the snake” (figure 70). because of its resemblence. This design was inspired by a YouTube video titled “High road low road track race” by Bruce Yenny, which demonstrates the concept of kinetic and potential energy on a similar set of curved tracks (Yenny, 2014).
This rail ends with a 180° curve (figure 71) that guides the ball towards the component “the funnels”, which are the topic of the next section.

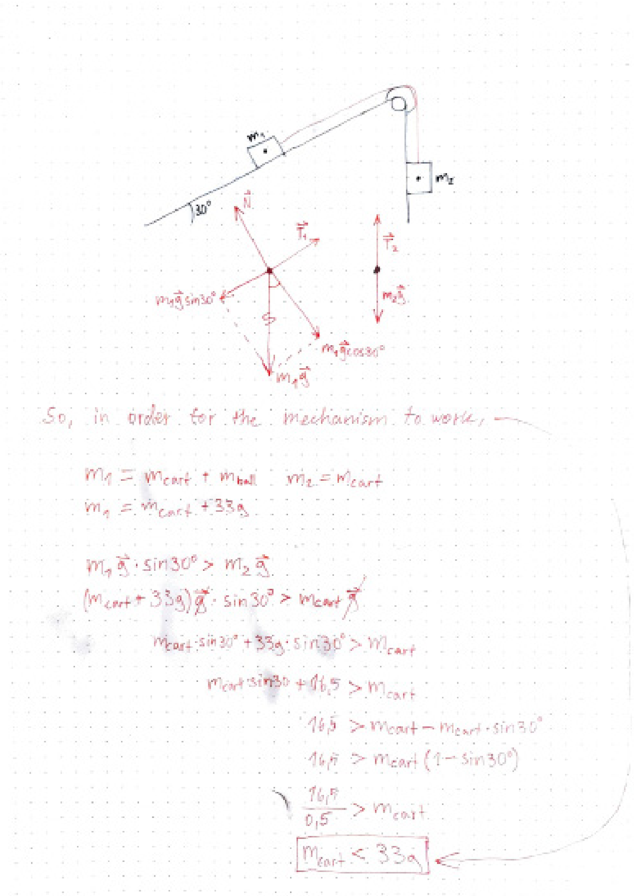
Figure 70: “The snake” rail that guides the ball after exiting the pulley cart



FINAL DESIGN

Figure 72: Final design of the carts mechanism.

Extra: pulley carts calculation
There is a certain limit to how heavy the carts can be while the mechanism still works. The heavier the carts, the less significant is the added mass of the steel ball. At a certain point, the mass the ball is simply not significant enough to tip the scales and move the carts.



To find this point, a simple calculation was conducted:
The results are rather anticlimatic, the mass of the cart must simply be lower than the mass of the ball. This could have likely been deduced even without the a full calculation. That said, this method could be used to find more information about the ideal masses of the two cart to achieve optimal balance.

3.9 FUNNELS

The two funnels are simple component which aims to guide the ball to perform a spiralling motion. A ball inside one of these funnels behaves very similarly to an orbiting object affected by the gravitational field of a celestial body. As the slope of the funnel increases exponentially, so does the centripetal force acting on the ball.

DEVELOPMENT

The main concern surrounding the funnel development is to sketch an appropriate curve that results in the desired movement of the ball. Making it too flat could results in the ball touching the outer rim for too long and a curve that is too steep would make the large area of the funnel essentially useless. Moreover, this is also highly influenced by the initial velocity of the ball. After a careful consideration and adjustments of the spline curve, the shape seen in figure 73 was chosen. Next step was just a simple matter of revolving this sketch along a vertical axis.

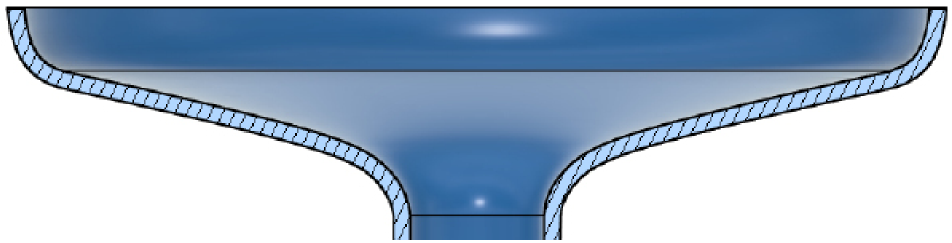


Figure 73: Cross-section of the funnel.

FINAL DESIGN

Figure 74: Final design of the funnels mechanism.

4. ASSEMBLING

INFILL

Within the software 'Cura', an open-source slicing software, there are many possibilities to slice the 3D model you would like to print. With different settings, the optimal result can be reached for the particular print you designed. For this project, the infill setting; the structure and shape of the material inside of a part, is chosen to be 'cubic' (Figure 75). When it comes to the strongest infill pattern that is relatively less time-intensive, the cubic setting comes out on top. The strength of the prints in this project is of importance because it must prevent 3D-printed parts from breaking both when assembling the entire assembly, as well as while the assembly is in use. Choosing this infill setting has proven to be effective, as the printed parts have not been damaged or broken throughout the project (Figure 76).

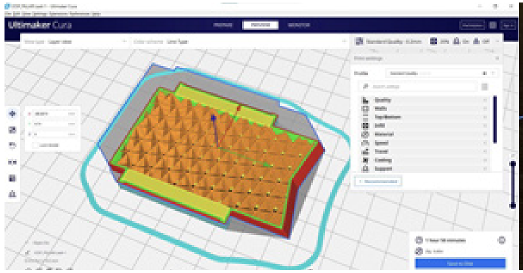


Figure 75

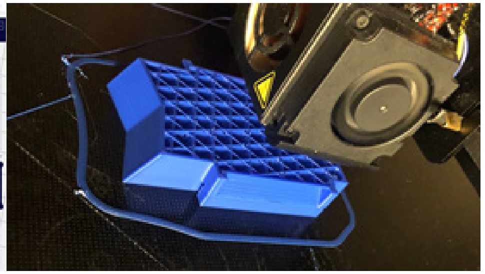


Figure 76

PLA

For the 3D printed designs the material that is used to print with is PLA, or polylactic acid. This common thermoplastic is next to PETG, one of the two most popular and favourable 3D print materials. Advantages of printing with this material is that it is easy to print (able to heat and cool without shrinking), safe to use, reaches a high stiffness (it will maintain its form up until its breaking point), and it is budget friendly. On top of that, the PLA material is a biodegradable and thus durable alternative to traditional plastic: it is a corn-based plastic which will break down over time. For PLA, the print temperature is between 180°C and 230°C. Before printing the assembly for this project, a test was made on two 3D printers that are privately owned. On both printers, 200°C was found to produce the best results.

SUPPORT

Support has played a significant role in the manufacturing of 3D printing designs (Figure 77). The general rule of thumb for when to use support is: 'if an overhang tilts at an angle less than 45 degrees from the vertical, you may be able to print that overhang without using 3D printing support structures (Chakravorty, 2021). Within the software Cura, there are 2 support structures to choose from when applying support; 'Normal' (Figure 78) and 'Tree' (Figure 79). In this project, both support structures are tested with a component that has a complex shape to print. Although both prints turned out nicely, the surface of the actual print turned out cleaner with the 'Normal setting' then with the 'tree' setting. This can be explained when looking at the end or the top layer of both supports. The 'normal' support structure setting has the advantage that it creates a full top layer where the actual print connects upon, whereas the 'tree' support setting only creates an outline. For all the prints in this design, the support interface pattern 'concentric' is chosen to exaggerate this desired effect the most.

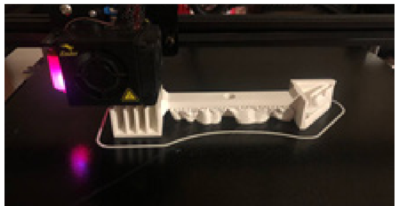


Figure 78

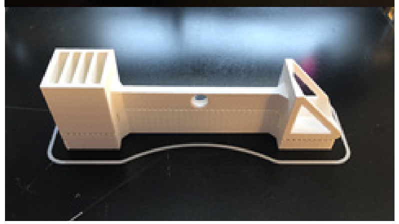


Figure 79

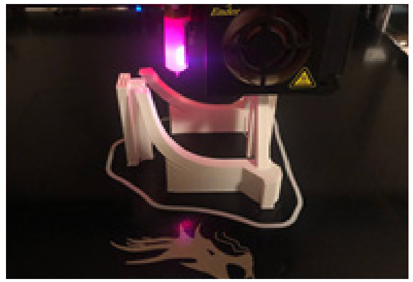


Figure 77

ELECTRONICS

To set the marble machine in motion, a DC motor that is powered by a 9V battery is used. To turn on and off the motor, we use a potentiometer connected to an Arduino Uno as a input method. Through a relay the input signal from the Arduino is translated to the DC motor by closing the second circuit, and therefore allowing the 9V battery to power the motor. The schematic for the connection of the DC motor, the potentiometer, the battery and the relay is shown below (Figure 80).

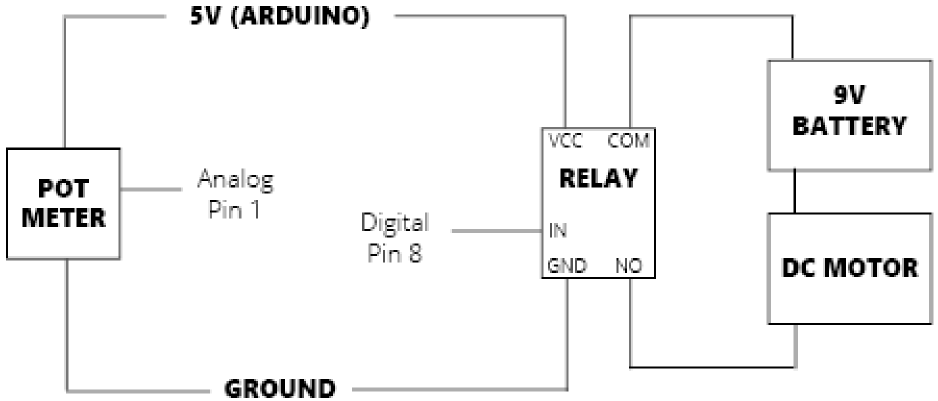


Figure 80: Schematic of the electronics used to activate the motor.

LASERCUT BASE PLATE

In order to keep all the 3D printed parts in place, an attachment base is required (Figure 81). Because we chose to use screws to put the assembly in place at the bottom, the choice of getting the material Medium Density Fiberboard or MDF was made (Figure 82). With the use of a laser-cut machine, holes can be cut in this material at precisely the desired positions (Figure 83). Due to the maximum possible piercing length of 6 mm, two plates of MDF are used. The desired holes are present on one of the two pieces of MDF, while the other makes room around these holes in the form of a circle with the intention of using the correct screw length.

To give the base plate a clean finish, a sticker is pasted over the laser-cut MDF (Figure 83). The sticker matches the intended dark color of the design that can be seen in the complete assembly render. Finally, 3D-printed supports are used around the corners.

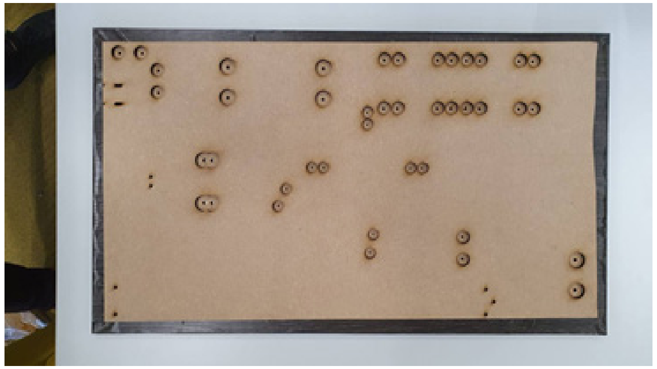


Figure 81

Figure 82

Figure 83

5. FINAL RENDERS

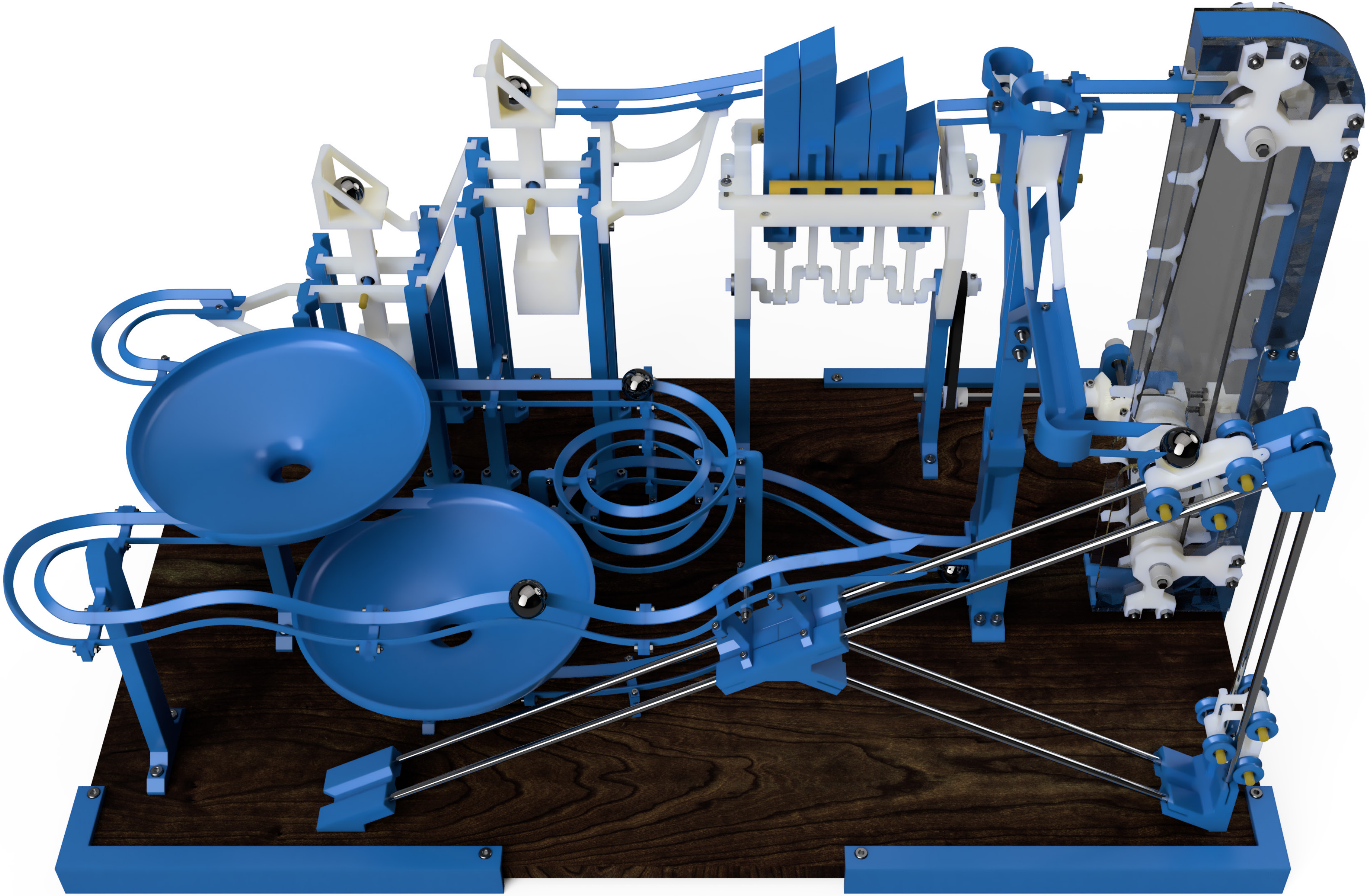


Figure 84

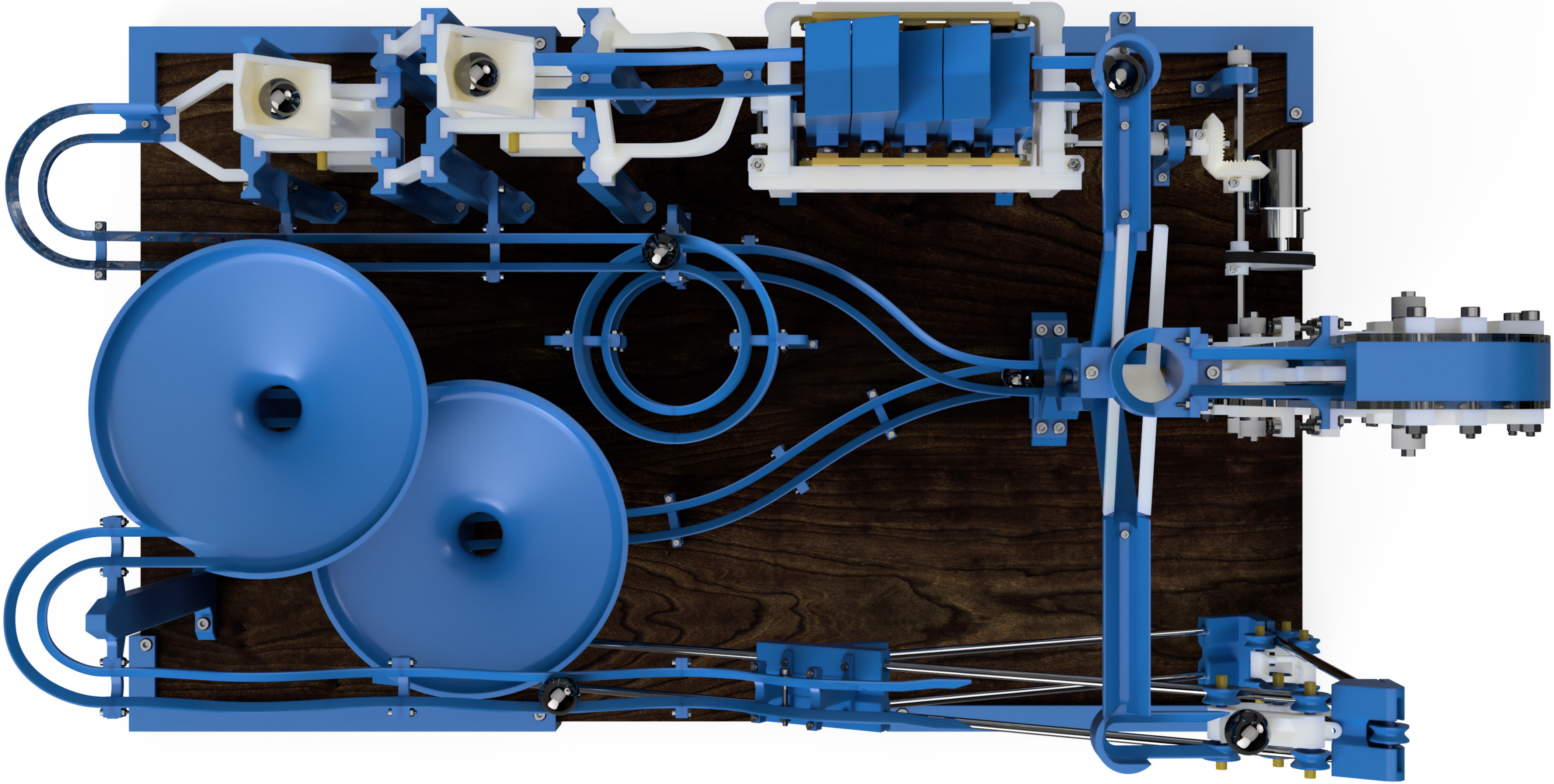


Figure 85

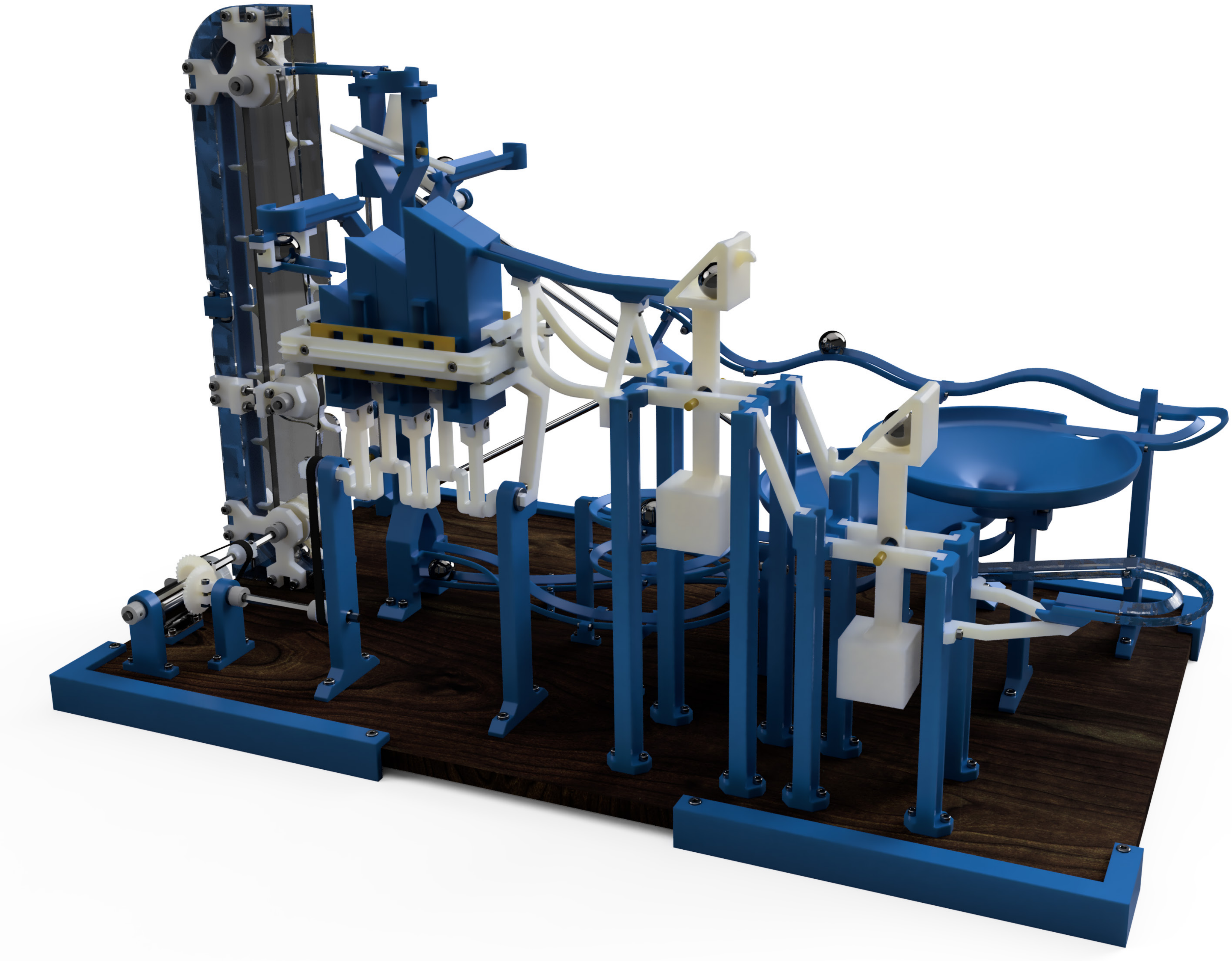


Figure 85

6. WORK STRATEGY

TOOLS WE USED

The tool we used the most to make the design come to life was the CAD package Autodesk Fusion 360. This software was used chosen mainly due to it having cloud-based collaboration and that Petr has years of experience with it. By having experience in the group, the full scope of what could be done in the software was already established, allowing us to start off by having a realistic design choice.

THE INITIAL IDEA

In the first meeting, it was decided that we should all come up with ideas, taking inspiration from already existing systems as well as coming up with our own. We discussed the requirements, and what is exactly expected from us. As the project had to be a kinetic chain machine, the group brainstormed with the prepared ideas on what the project could be. From there the first idea of a musical marble machine was introduced. The idea was that there would be varied mechanical components that each produce a different sound, which altogether creates a simple melody. The homework for the second meeting was then to create and draw 10 different mechanics that in the next meeting only 6 were decided.

However, during the next meeting that idea was quickly scrapped as creating musical components that are sonically pleasing from scratch wasn't feasible in the scope of this course. We kept the original idea, and the mechanical components, but eliminated the musical element.

HOW THE ROLES WERE SPLIT

Our priority was to ensure everyone gets to learn how to work in CAD. The harder and more complicated components were given to Petr as he was significantly more experienced than the rest of the group, and the easier components were given to the others. This allowed there to be a certain degree of equity within the group, where the more advanced member could aid the beginners without doing the work for them.

When the design was at a stage where tests needed to be done with certain components with regards to 3D printing, Petr and Susan took charge of that as they had their own 3D printers. This also led to them printing most of the components in their own printers for the final product. The pieces that were too detailed for the print whilst still being functional were printed at the printers in university. By spreading the printing task between 3 printers, the final product was able to effectively be developed. Furthermore, we minimized the use of 3D printers at university for multiple reasons. It was more convenient to print ourselves as we could keep a close eye on the printing process, select our own filaments and make last minute changes. Furthermore, there is the benefit of slicing the files ourselves and being able to modify the settings to suit our needs.

7. COST ANALYSIS

ITEM	STORE	PRICE (EURO'S)
10mm bearing 4/10pc	https://www.123-3d.nl/123-3D-Kogellager-623ZZ-10-stuks-i1436-t15106.html	12
20mm steel ball x10	https://www.conrad.cz/p/modelcraft-ocelova-koule-20-mm-220865	12
WD40	brought from Czech Republic	0
3mm steel rods 1m	https://www.kutil.cz/zelezarstvi/hutni-material/nerezovy/tyc-kruhova-nerez-1-4301/	0.8
5mm steel rods 2x1m	https://www.kutil.cz/zelezarstvi/hutni-material/nerezovy/tyc-kruhova-nerez-1-4301/	2.5
Filament PM - Pearl bl	https://shop.filament-pm.com/pla-pearl-blue-1-75-mm-1-kg/p154	16
GT2 belt 240mm	https://www.amazon.nl/gesloten-tandriem-afhankelijk-groot	8.5
Electronic components	Tinytronics	5.5
2mm bolts	https://jaakvanwijck.nl/webshop/CK-M2	11.14
2mm nuts	https://jaakvanwijck.nl/webshop/moer-m2-gegalvaniseerd	6.27
Wood print foil	https://www.praxis.nl/verf-laminaat-decoratie/woondecoratie/wanddecoratie/stickers/transform-zelfklevende-decoratiefolie-wood-zwart-45x200cm/5632572	6.49
Other shipping costs		5
	TOTAL	**80,51**

9. REFERENCES

Anon. Belt length calculator. Omni Calculator. Retrieved from https://www.omnicalculator.com/physics/belt-length

Chakravorty, D. (2021, November 5). 3D Printing Supports – The Ultimate Guide. All3DP. Retrieved from https://all3dp.com/1/3d-printing-support-structures/

CNC Modeller. (2019, April 26). How to create a GT2 timing pulley in Fusion 360 - Cad Tutorial. YouTube. Retrieved from https://youtu.be/qV_C6Xu-WKY

Keskin, Ü. (2021, August 11). Bevel Gear. The GrabCAD Community Library. Retrieved from https://grabcad.com/library/bevel-gear-164
Żuławińska, J. (2019, September 10).

Yeany, B. High road low road track race, potential-kinetic energy racks/Homemade science with Bruce Yeany. (2014, June 13). YouTube. Retrieved from https://www.youtube.com/watch?v=_GJujClGY-JQ