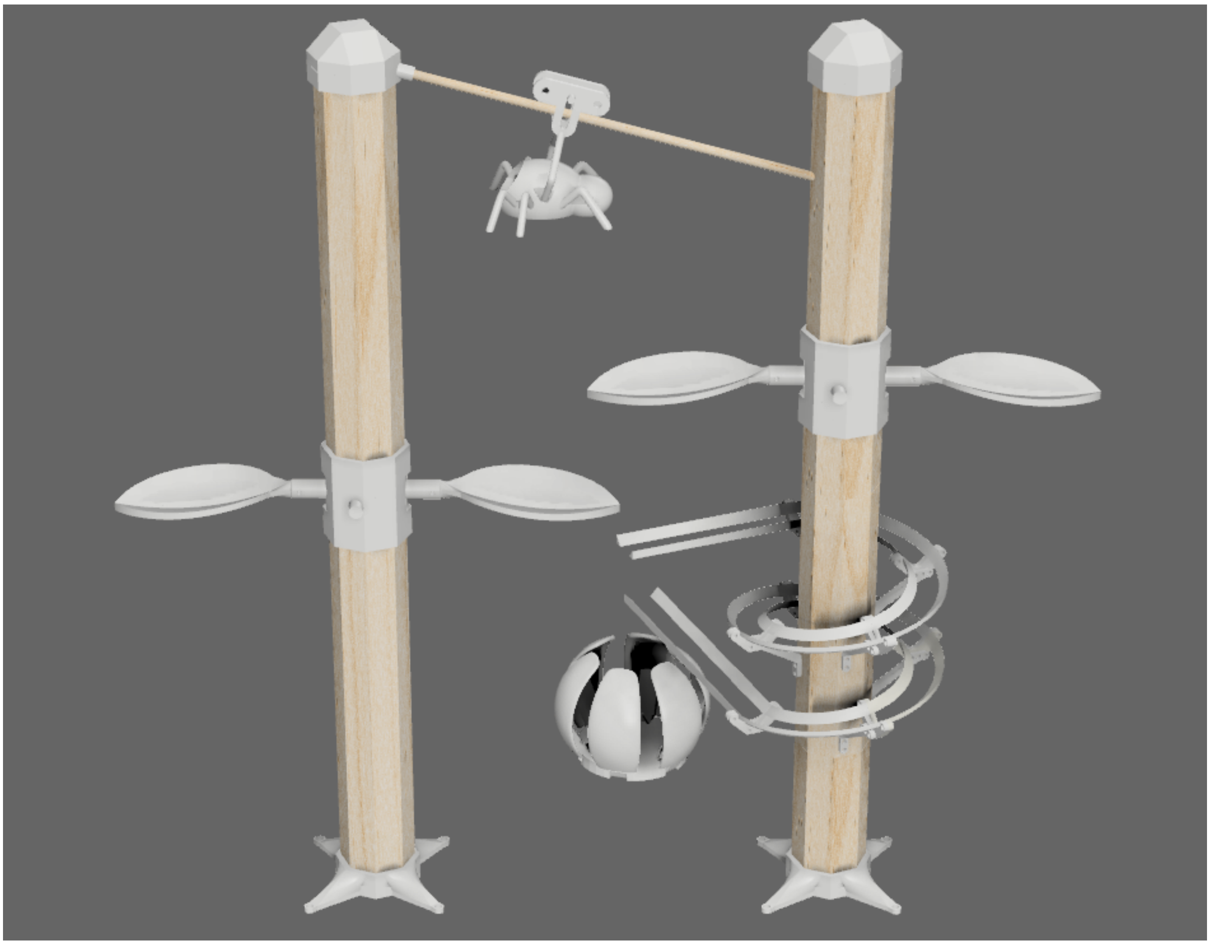
Creative mechanical design, engineering and manufacturing



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26-01-2023

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Concept

In this project we decided to design a marble track. The design had to use mechanical principles; therefore, we chose to make a track with multiple mechanical components. These components are the spider zipline, the leaves, the spiral and the flower. The marble also passes these elements in this order. The marble track is inspired by nature. Since we could use different manufacturing techniques, the organic shapes that are doubly curved and smooth could easily be manufactured. The marble resembles a drop of water, and our marble track will show that water is the driving force of nature. All of the elements are set in motion due to the water.

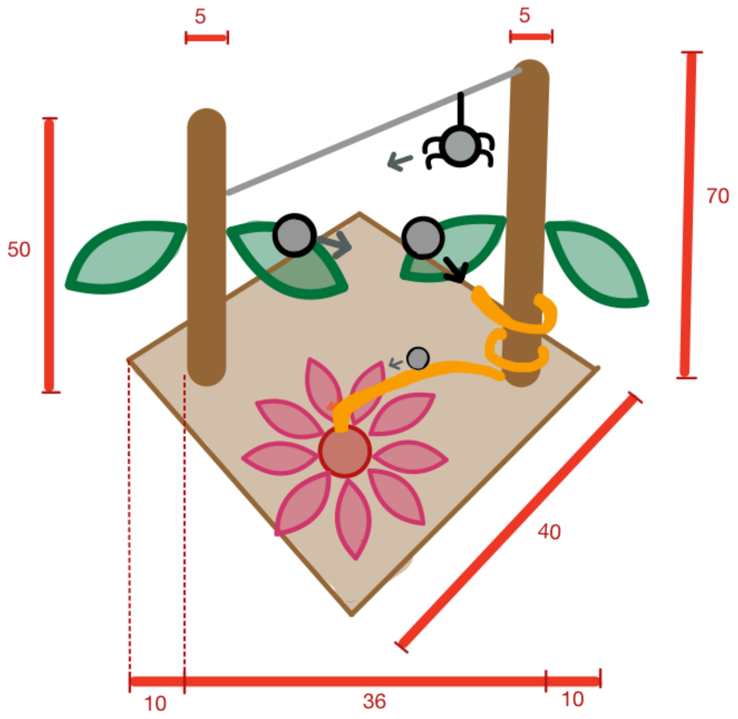

Figure 1

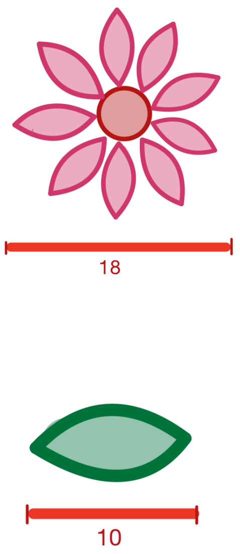

Figure 2

Track

First of all, the marble must be put inside of the spider, which will then start to move along the zipline due to its increased weight. At the end of the zipline the spider will hit the ramp and release the marble, which consequently lands on the first leaf and continues its way down to the second leaf. Following the marble will land on the spiral track and go down. Once the marble reaches the end of the track it will fall into a bowl in the middle of the flower. The bowl will go down and with enough weight the flower will open, and the petals will fall into their place. (Figure 1, 2)

Spider

Zip line

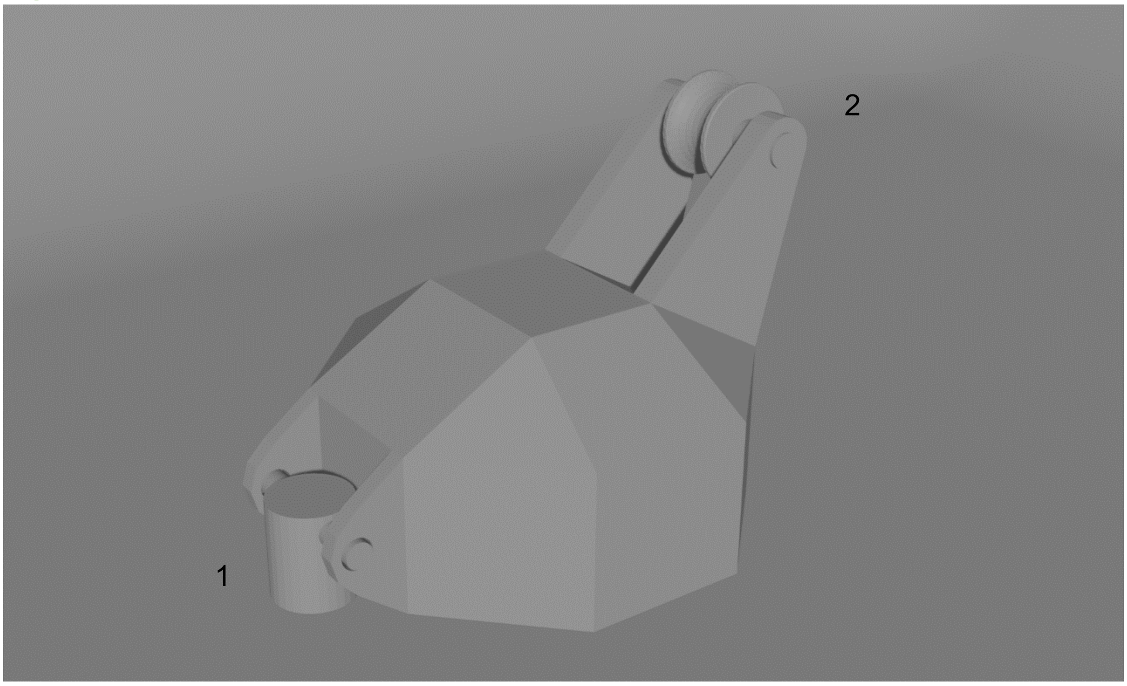

Figure 3

The zip line includes a base where everything is connected, a wooden beam that works as the zipline for the spider, the spider, and a cable with a counterweight. The spider goes down the zip line when a marble is set inside the spider. By putting the marble in the spider, the weight of the marble and the spider increases which will result in an increased force that is larger than the force generated by the counterweight. Therefore, the spider can move down the zipline. Once the marble is released at the end of the track, the force of the counterweight is larger than the spider so the spider will go back up.

Part 1, as seen in Figure 3, is made to avoid stress on the wooden beam. This is done by attaching the beam to a rotary system, which allows the beam to have little movement and reduces internal stresses.

The top part of the spider and the counterweight are attached to either side of the cable. The cable runs over the pulley, to have as little friction as possible. As seen in the picture, the pulley leans over under an angle, this is done to prevent the counterweight from getting stuck on its way down.

To attach the spider to the carrier we used the material property flexibility of plastic, this enabled us to design a clip mechanism to connect the spider to the carrier (Figure 4). This part would be best to print in ABS because of its high stiffness and flexibility.

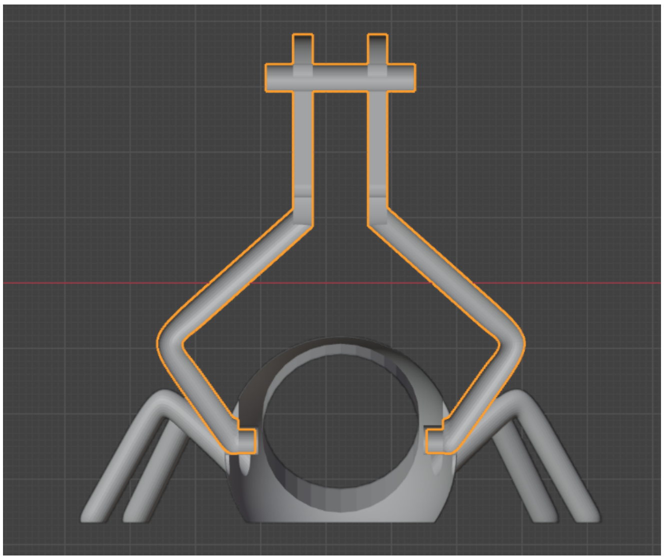

Figure 4

Counterweight calculations:

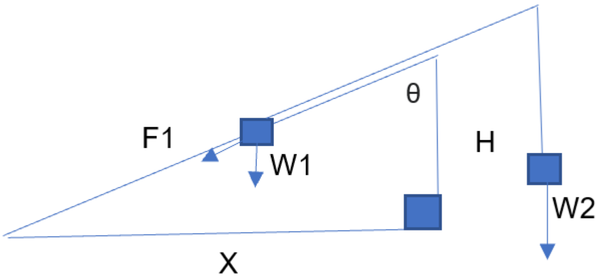

Figure 5

H = 9cm
X = 29cm
M1 = 36g
M1 with Marble = 69g

Θ = tan-1(29/9) = 71 degrees

W1 = M1*9.81

F1 = cos(71)*W1

F1 = cos(71) * 0.036 * 9.81 = 0.115 N

F1 with marble = cos(71) * 0.069 * 9.81 = 0.220 N

To make sure the carrier moves down with a marble and up without, W2 has to be in between 0.115 N and 0.220 N. We decided for 0.150 N because of the energy it needs for tilting at the bottom of the zipline.

W2 = M2*9.81

M2 = 0.150/9.81*1000 = 15.3 g

Spider rotary mechanism

At the end of the zipline, the marble has to fall out of the spider from the same hole trhough which it entered. To enable this, the back of the spider will tilt backwards to release the marble after it hits the ramp at the end of the zipline. The marble will stay inside the spider if the spider is completely horizontal since there is a slight slope towards the middle of the inside of the spider. As such, the spider needs to be tilted slightly backwards to let the marble roll out. The spider will hit a ramp that is also slightly tilted, ensuring the marble will be able to roll out.

Leaves

The leaves work on the principle of a simple lever mechanism. Two identical leaf models are placed on either end of a beam, and thus act as a counterweight to each other. Due to the difference in distance of the leaves to the hinge, the beam naturally rests at an angle. As soon as the marble comes into contact with one of the leaves, the balance is interrupted, and the leaf angles down, which releases the marble onto the next element. To correctly balance the leaves to allow for this behaviour, calculations were made to find the lengths of the beam at which equilibrium is found, when the mass of the marble is included. If these values were applied, the leaves would theoretically be at rest horizontally if the marble were present. (Figure 6)

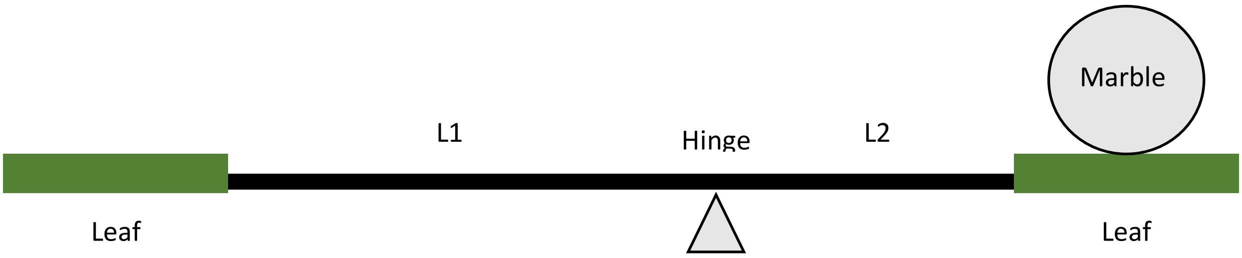

Figure 6

Using the formula for a simple lever mechanism, assuming that the marble is located at the center of the leaf, we can approximate the equilibrium:

$$(m_{leaf} * g) * L1 = (m_{marble} + m_{leaf}) * g * L2$$

Rewriting this gives a length ratio of

$$\frac{L1}{L2} = \frac{m_{marble}}{m_{leaf}} + 1.$$

So, the minimum ratio needed to tilt the leaves with a static marble of mass 32.75 g, given m_{leaf} is 21,13 g, is 2.55. In order to fit two pairs of leaves on a footprint of 40x40cm, we needed to minimize the lengths of the leaf pairs. If the length ratio were any higher, and thus the counterweight-side longer, the marble might not be able to push down the leaf, and it may stick out too much. With a smaller ratio, the counterweight might not have enough leverage to tilt the leaves back as soon as the marble is gone, and the ratio should at the very least be higher than 1 (equilibrium without the marble). With a length ratio of 1.1, we were able to fit two leaf pairs far enough apart to achieve the desired effect, while ensuring that the marble will push the leaf down, and the leaves angle back to their original position afterwards.

The leaves consist of four different components: a piece of the octagonal trunk that holds the lever mechanism, the bar between the two leaves, the two leaves themselves, and a horizontal bar holding the lever bar. The connection between the leaves and the bar is a square insert, limiting rotation around the middle axis of the bar. Additionally, there is a screw insert holding the leaves and the bar preventing the leaves from sliding out. (Figure 7)

Because of how small especially the connection points of the leaves are, we had to manufacture the leaves to be stiff. To achieve that without using an FDM printer and PLA material we made sure that the leaves were printed horizontally. In that way, the layers of the print would be continuous at the base of the small connection point, making it more stable. Otherwise, the layer at the base of the connection point would be easily breakable. (Figure 8)

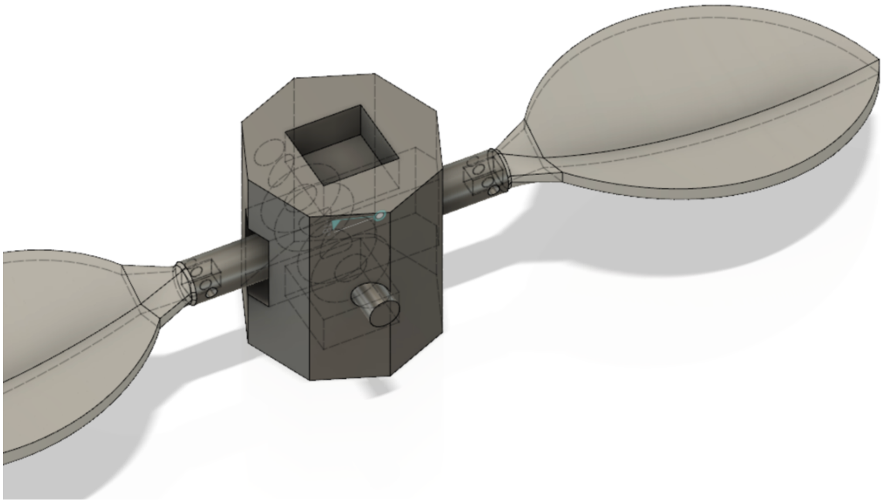

Figure 7

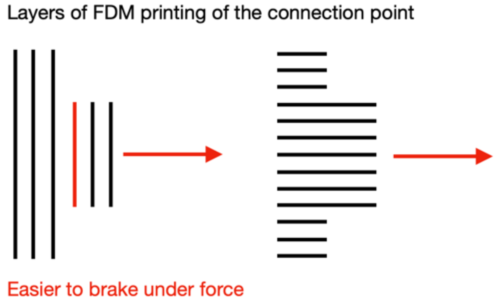

Figure 8

Spiral

The spiral consists of two corkscrewed tracks, circling around one of the wooden trunks. The tracks are placed 12.5 mm apart, ensuring a marble with radius 20 mm will fit snugly in-between. (Figure 9) The tracks are supported by a diagonal beam after every track section (90 degrees). The tracks are connected to each other by two M3 screws, placed in parallel, restriction rotational movement in 1 axis and limiting translational movement in 2 axes, with a bolt restricting the third axis (along the screws). (Figure 10)

By making the spiral consist of two tracks we reduced the amount of friction between the marble and the track. This way the curvature of the marble and the surface of the track always match, which made the tolerances for the tracks larger.

The quarter-circle parts are each printed 6 times, creating a spiral of 540 degrees. The diagonal support beams are attached to the wooden trunk with two nails. Since the track is attached at every 90 degrees, movement is limited in both x and y axes. The marble imposes a torque around the point where the diagonal beams are attached to the wood. Since the rotational movement around the outward axis is limited by two parallel nails, and the entire track is limited in this way (and thus in 2 rotational axes), the track should be able to support the marble without bending downwards to the point that it fails to contain the marble.

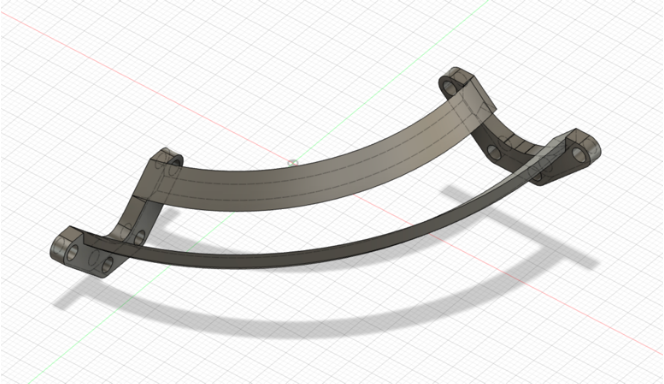

Figure 9

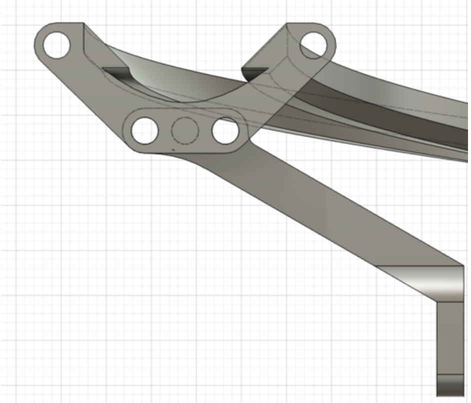

Figure 10

Flower

The flower consists of three main components. The bowl, the base and the petals (Figure 11).

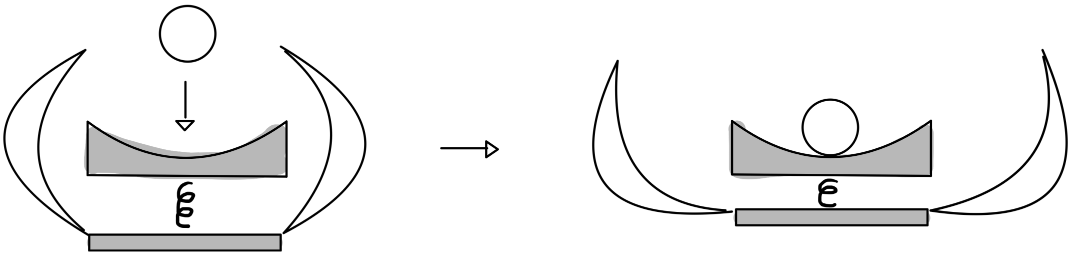

Figure 11

The bowl is curved such that the marbles will not roll out of it. Once the marbles fall into the bowl, the bowl will have an increased weight which will compress the spring underneath it. There is a wire running from the bowl through a loop on the base and through the petals. By compressing the spring the tension on the wire will lower and the petals will be able to fall down. The movement of the flower is limited to vertical movement. To constrain this movement the bowl is surrounded with 3 linear bearings. On the outside of the bowl there are holes in which the bearings fit. Elastic bands around the bowl make sure that the bearings stay in place, for this to work the bearing and the bowl have a small inset in which the band falls.

The petals of the flower are attached to the base with an elastic fit. This is done to prevent too much stress on the plastic.

The petals are curved to reduce the material that is needed while increasing the durability of the part. For the petals fall down easily, a thicker part is made right below the middle of the petal to have the center of gravity not directly above the hinges but towards the outside of the flower. This means that the petals want to fall outwards and will not collapse inwards. The shape is very rounded to have the bowl and the inside almost completely covered when the flower is closed.

To find out what strength of the spring was needed we had to find out the amount of force was being pressed onto the spring. This was calculated with in mind that the flower should be fully opened when 3 marbles had fallen into the flower. We calculated this with multiple springs, the following calculations show the spring that was most suited.

Spring:

229 grams made 1.3 cm displacement of the spring. So the spring constant is:

$0.299 * 9.81 / 1.3 = 1.7$ N/cm

We need 0.6 cm displacement for the leaves to be fully opened.

Bowl + bearings weight: $Wb = 20.12 + 18 = 38$ grams

Marble weight: $Wm = 32.75$ grams

Hooke’s law:

$F = -k * \Delta X$

$\Delta X = F/-k$

$Fbowl = Wb * 9.81$

$Fbowl = 38 * 9.81 = 372.78$ N

The displacement of the spring:

$\Delta X = Wb * 9.81 / 1.7$

$\Delta X = 0.038 * 9.81 / 1.7 = 0.219$ cm

$\Delta Xd = 3 * 0.032.75 *9.81/1.7 = 0.57$ cm

This means that with the strength of this spring the flower can be opened when three marbles fall into the bowl. The spring has a high spring rate and a high initial deflection.

Exact Constraints

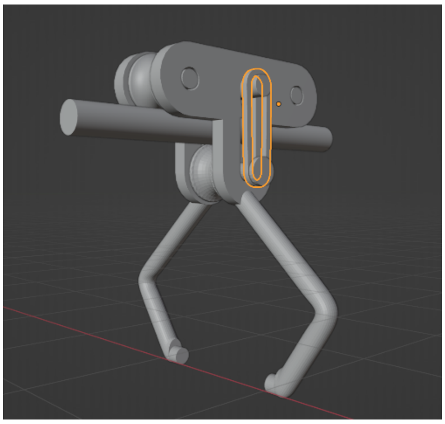
Figure 12

To make sure the carrier of the spider is only able to move in one linear dimension we used a constraint that consists of two concave bearings and a nesting force. This results in the carrier being constrained against rotation and movement perpendicular to the zipline. The carrier will still be able to rotate around the axis parallel to the zipline but this won't be the case due to the gravitational force. To make sure the movement perpendicular to the zipline on the horizontal axis was also constrained, we used concave bearings. For the nesting force, our original plan was to have a rubber band that pulls a third bearing towards the rod (Figure 12).

However, this resulted in a lot of friction and therefore wasn't possible. We solved this by only having the two bearings at the top and using the normal force from the zipline on the carrier as the nesting force.

The bowl inside of the flower is limited to a vertical motion and no rotation. We achieved this by attaching three vertical rods between the bowl and the base. To let the bowl lower smoothly and with little friction we attached 3 vertical bearing to the bowl. The bearings move vertically along the three rods that have been sanded to make it even smoother. The 3 rods make sure that the bowl isn't able to move horizontally and also unable to rotate along all axis. We connected the bearings to the bowl by putting them in a slid that was a little too large and then tightening them down using rubber bands. This ensures that the bearings can align themselves to the rods.

Materials

To minimize the use of unnecessary material we have made the 3D designs such that they had as few overhangs larger than 50 degrees as possible, so no or little support material was needed. Also in the spiral material was saved due to having only two tracks on the spiral and not having to print half a tube.

One of the requirements of the design was given in the form of a limitation; The total volume of 3D-printed parts should not exceed 1 dm^3. As such, only the parts that had complex, (doubly-)curved surfaces were decided to be produced using FDM methods. In these methods there are usually tight tolerances you have to account for. To make up for these we used elastic fits. We used these for example to connect the petals to the base of the flower. The main benefit of this is that the tolerance becomes larger and there is less stress on the material.

The 'trunks' of the trees, as well as the base of the installation, were crafted out of pine wood and MDF respectively. The trunks are the major load-bearing parts of the installation, and thus required sufficient strength to bear the loads the other parts and the marble would impose. However, since the overall weight of the parts that the beams should support is low, due to the use of PLA, the Strength σ_f is not much of a limiting factor. (See: Mechanical Calculations)

Due to the nature of the project, it being a single production with minimal time available, any material that was low-cost, solid, and easily shaped was viable. The decision fell on Pine Wood, as it is readily available, relatively cheap, and easy to shape using conventional machining methods. Additionally, it fit aesthetically with the natural theme the project was based on.

Manufacturing

Since only 1 installation was crafted, the batch size for individual parts was low (<10). Therefore, it was economically viable to use Rapid Prototyping techniques. For the wooden beams, conventional machining methods were sufficient, given that they consisted of simple, geometric forms. The beams were able to be cut by hand using a linear saw machine. All other, more complex parts were 3D printed using Fused Deposition Modelling 3D printers, such as the Ultimaker, Snapmaker F350 and Snapmaker original. Most of the 3D parts had to be sanded afterwards. This process added an extra step to the manufacturing. Especially the zipline needed to be sanded to have as little friction as possible. To make the manufacturing less time consuming, some parts, such as the pulleys, were made to be universal; they could all be printed at once and then be used in multiple elements.

Weights of the 3D-printed parts:

Leaves + Hinge Part = 70.40 g x 2

Top Part = 16.5 g

Flower Basket = 20.12 g

Spider body = 25.5 g

Spider Mechanism = 12.5 g

Flower base = 37.5 g

Flower Petal = 8.42 g x 6

Tracks (Total) = 42.37 g

Base Part = 17 g x 2

Mechanical Calculations

To help with selecting the material for the wooden trunks, some calculations were done to find the minimum Strength necessary. For a beam, the stress from tensile load is given by: (Young & Budynas, 2002)

$$\sigma = \frac{F}{A}$$

Given a cross-section A of 1369 mm^2 for an octagonal beam with radius 22 mm, and a load of up to 0.33654 kg * 9.81 = 3.3 N (the weight of all load-imposing parts combined, plus the marble and 1 wooden beam), any material with a failure stress of over 2412 Pa would have sufficed.

Since the wooden trunks are shaped like beams, and bear tensile loads, buckling had to be taken into account. Fortunately, the low loads and relative width of the beam pose no threat of any buckling to occur. The critical force at which buckling occurs is given by: (MechaniCalc, n.d.)

$$F_{crit} = \frac{\pi^2 * E * I}{(K * L)^2}$$

The moment of inertia I for an inscribed octagon is 0.6381 r^4, which gives $I = 1.49*10^{-7}$ m^4 for a radius r = 22 mm. The Young's Modulus E for (pine) wood is 10.1 GPa (https://matweb.com). Since one end of the column is fixed, and the other end is free to move laterally, the effective length factor K is 2.0. So, for an octagonal column with Length L = 2100 mm, which is the longest column in use, the critical force at which buckling could occur is

$$F_{crit} = \frac{\pi^2 * 10.1 * 10^9\ Pa * 1.49 * 10^{-7}\ m^4}{(2.0 * 2100 *\ 10^{-3}\ m)^2} = 842\ N,$$

Which amounts to approximately 86 kg of force that the beam can withstand before buckling.

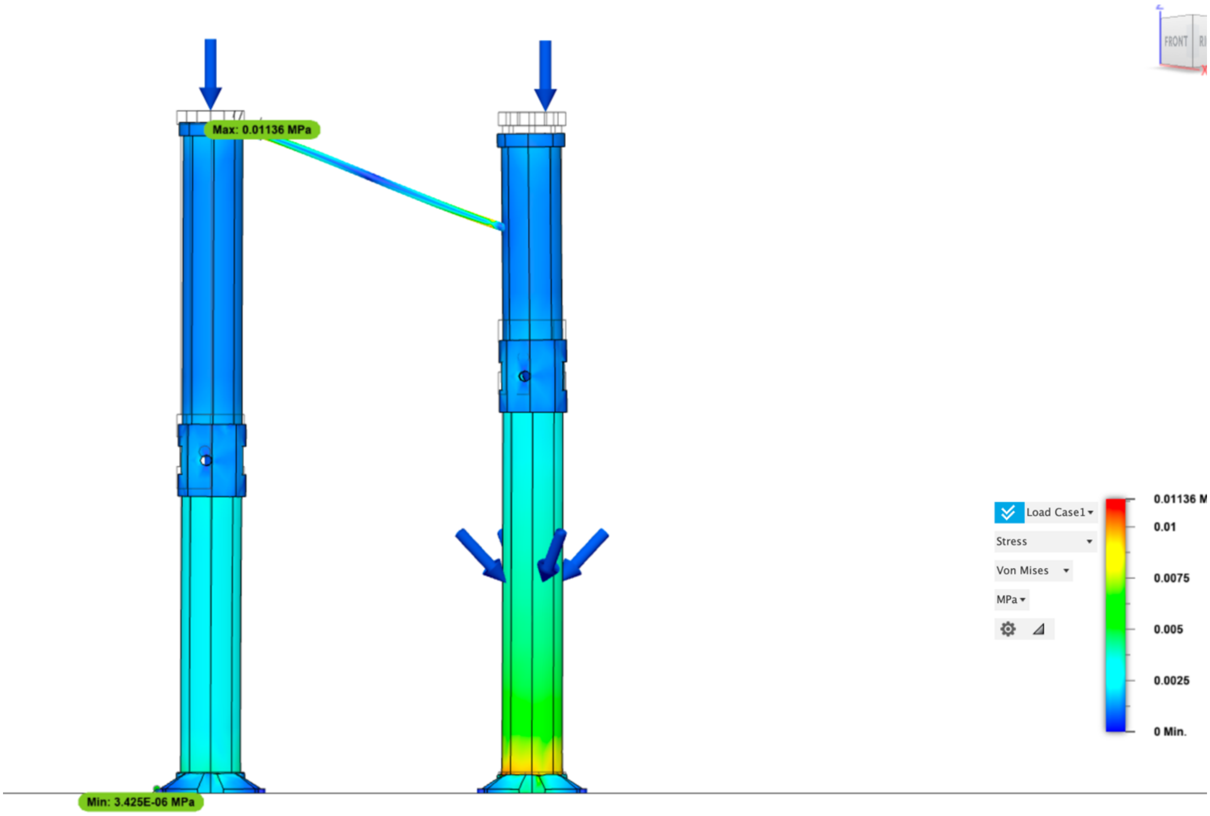

Figure 13

Using a simplified model for the two beams, a Finite Element Analysis on Static Stress was performed in CAD-modeling software Autodesk Fusion 360 to confirm the assumptions made when selecting the materials. The results can be seen in Figure 13. The highest stresses are found on the bottom two wooden beams and the diagonal wooden rod, but these are low enough not to be of any concern. The Pine wood used is more than capable of withstanding these loads. There is very minimal predicted deformation, several orders of magnitude smaller than the size of the parts. The deformation in the visual is scaled by 2.5%. The results indicate that the machine should be able to withstand the static stresses it endures.

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