Biomedical Engineering Individual Assignment
Gripping system that facilitates continuous additive manufacturing
Mechanical Engineering Design
500666_A21_T1
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For the attention of: Dr Nathaniel Brown, Mr Gavin Cutler

Version number 3

Due date: 11/11/2021

Abstract :

This report aims to discuss the development of a gripping system capable of moving around a rack of multiple levels containing up to 18 3D printers. Once reached, the system is meant to be able to go inside the printers and grip a 3D printed element that could be up to 100 x 100 x 100mm and of any possible shapes. Finally, it places the part somewhere safe. Then repeat the same procedure for any other one. To be able to choose the most adequate system, this report has a product design specification, whose role is to guide and ensure that the concepts are developed to meet the criteria needed. Once the concepts were developed and after going through a concept selection, one design was chosen. The chosen design can move through different levels thanks to a horizontal conveyor belt attached to a vertical belt driven linear actuator. The conveyor belt moves the gripping system horizontally and the belt drive actuators, attached to the conveyor belt, move it vertically. The body of the gripping system is a 6 degrees of freedom robot arm, that not only moves in the x, y, z direction, but can also rotate. The gripping mechanism attached to the arm is a combination of three fingers. Two that hold the object at its sides and one at the top.

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1. Introduction:

During the Covid-19 pandemic, students in the engineering faculty were not able to access the Fablab to use the 3D printing machines. However, the students were able to use a remote access software to print with the 3D printers without entering the lab, but this did not solve the issue as someone has to enter the lab to remove a print to let the next one start. To tackle this issue and create a gripping system that facilitates continuous additive manufacturing, this report will go through a series of concept designs that facilitate continuous printing and choose the most appropriate one.

2. Methodology:

To ensure that the design process is followed correctly, the following stages have been completed:

Product design specification (PDS) = this section will precisely describe what the product must do and sets a series of individual specifications through the metric and value required. The product design specification must be developed at the early stages of the developing process to allow the engineer to produce a final design that obeys those requirements. The PDS should meet the customer needs if they are acceptable target values as well as the actual technological set of constraints.

Concept designs of potential solutions = this section aims to create approximate ideas of the gripping system that facilitates continuous additive manufacturing. It is a rough 3-D modelling of any concept idea relevant to the aim of the report. The figure must be accompanied by a brief description that explains the advantages and disadvantages of said concept and its main kinematic characteristics as well as its role and practicality. In this section, quantity matters more than quality as it helps to address any possible alternative present and lowers the chances of finding a better concept later during the development process of the chosen one.

Concept selection = the concept selection is based on the needs presented in the product design specification. By using the decision matrix that allows us to rate each design against the selected and weighted criteria, the engineer must choose one or more final designs. In this case, the type of matrix used is a binary dominance matrix. This helps us to move from a large set of quantitative designs to a smaller set of qualitative ones. After preparing the selected matrix, rating the concepts, and ranking them, a reflection on the results and processes is required.

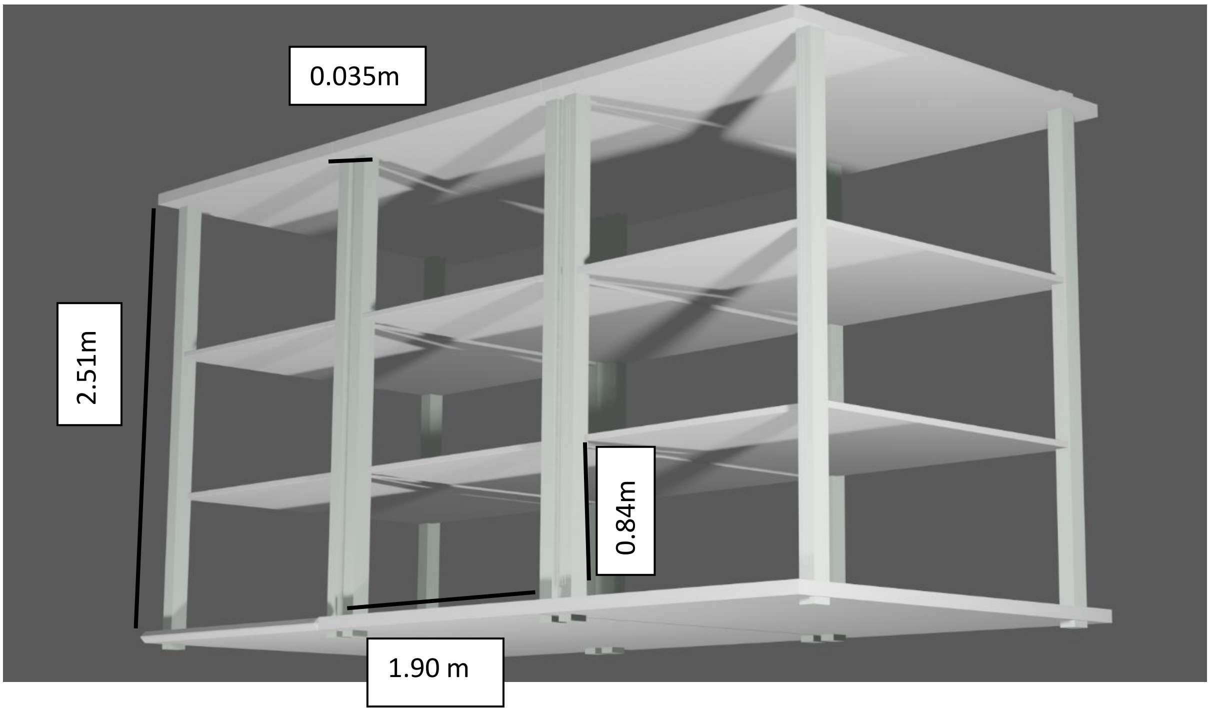


Figure 1.

Figure 1 shows a 3D modelling of the rank where the 18 3D printers are allocated.

3. Product design specification

The table below, called product design specification, is the main reference when it comes to developing the gripping system able to facilitate continuous manufacturing, it defines the design activity. The PDS includes a comprehensive analysis of any constraint the system must adhere to.

Product design specification for a gripping system that facilitates continuous additive manufacturing.	
Customer: Dr Nathaniel J brown. Designer student number: 202007885 Version number: 3. Date: 10/11/2021.	
The product to develop is a system able to pick up 3D printed materials from any of the 18 printers in the 3 levels of the rank in the Fablab. This is to facilitate continuous additive manufacturing as, because of Covid-19, most students were not able to use the printing facility inside the university and remove and collect the prints made. This made students unable to continuously use the 3D printers as a new print does not start until the preceding one has been removed.	
Operation	
Operation and performance	• A system capable of moving between 18 printers fixed in three levels and collecting the printed element (with a maximum size of 100mm * 100mm * 100mm) within the printers and move it somewhere safe. • Must be self-supporting. • May have a fixed point of reference to calibrate it properly as it must move accurately. • Be able to support a weight of 500g. • The robot must wait 15 minutes before removing the material as it must cool down before being removed from the plate. • Print time can be as long as 36 - 46 hours, therefore the system developed will not need to constantly move objects every minute for 24 hours every day. • Power efficiency of 40%. • The arm should be able to operate in the x, y, z-axis. • The system should take no longer than 1 minute to pick the needed objects, move them somewhere safe and start the next order.
Environment	• Working temperature ranges: the 3D printing room, where the machine must operate, needs a constant temperature to ensure that the prints are successful. This temperature ranges from 17°C to 20°C [How to Repair Resin Prints – Leaking and Printer, 2021]. • The machine is supposed to operate in the UK mainland where the ambient temperature in a laboratory ranges from 20°C to 25°C [NCBI, 1995] in the

	summer, this can cause the printers to heat the room up, but it is a negligible difference. • The minimum room temperature the lab can hit during winter is 16°C [HSE – 2021] • The machine can experience low levels of dust. • The system will be stored with the supplier or a warehouse before sale and in the Fablab after. • Maximum machine noise should be lower than 87dB. [HSE: Noise at work, 2021]. • The machine can get damaged throughout its use because of heat, friction and impact damage and therefore needs to be monitored and handled with caution. • A system made with shock absorber material can prevent irreversible damage if the machine hits a surface. • Impact test on the grip needs to be performed before the system is out on the market. • A grasp test must be performed to ensure that the system's gripping hand can pick the object up and release it without damaging it. • A slip resistance test must be performed to check that the 3d printed material does not slip out from the grip. • Software tests, such as regression, unit tests and integration should be performed to ensure that the system's software does not have any anomalies and can move at the velocity required and can easily travel from a point to another.
Health and safety	• The system and manufacturing process must follow the health and safety rules at hse.gov.uk and Hull university health and safety policy statement [Hull university, 2018]. Only authorised and trained staff can use the system. • 1.5mm diameter bevel on exposed sharp edges. • Anyone should stay at least 0.50m of distance from the system when activated to avoid injuries while the system is moving. • Any electrical part should be inspected before releasing it on the market. • The machine should not be used at very high temperatures to avoid overheating.
Weight and size	• The lab is open to a different range of students and members of the staff; therefore, the machine needs to have lifting points in case it needs to be moved. • The end effector must weigh less than 15kg. • Weight must be distributed. • Maximum end effector footprint 200mm x 400mm. • The size of the grip must be able to hold the printed objects firmly. • Must fit on the framework of the printer rack.

	• Must fit in the assigned location and leave space for maintenance.
Time scale	• Designing the robot should not take more than 4 weeks.
Material	• Materials should be ordered from a university of Hull trusted supplier • Materials must not be toxic.
Budget	• The cost of manufacturing or purchasing the mechanical components should not exceed £300. • Electronic components are not included in the budget but are subject to acquisition limitations.
Reliability	• The gripping system should not crush the printed elements or damage them. • The system should be able to smoothly move from one position to the other.
Product life span	• Product operation life span must be able to run continuously. • Shelf life of 10 years. • The product will be on the market for 10 years. • Product parts, during disposal, can be reused or recycled for other applications [WEEE, 2021] or given back with the store take-back policy. • Spare parts will be available 7-10 years after that.
Disposal	• Parts need to be disassembled easily. • Recyclable parts should go to the assigned recycle centre or bin. • Electronic parts should be recycled at the local recycling centre.
Manufacturing facility	• Product pieces must be suitable for in-house manufacturing using the manufacturing capabilities of the engineering department such as the 3D printing lab, laser cutter and the mechanical engineering workplace. • The product will be installed by the manufacturing company. • Electronic items must be collected from active Robotics Ltd.
Maintenance	• Electronic parts should be easily accessible. • Electronic parts and cables should be easily replaceable. • Maintenance of the system should not take more than 1hour. • Screws and joints should meet the BSI guidelines to be easily replaced.

	• Maintenance should be able to be performed using tools belonging to the department of engineering. • System electronics part should be PnP (plug and play).
Language	• The system must operate mainly in English (United Kingdom).
Quality assurance and control	• The producer and manufacturing process offers 6 months of free maintenance. • The system will be examined and adjusted every three years. • The system will receive full control inspection according to local and Hull university quality policies.
Ergonomics	• Product packaging should clearly state how to handle and unload the product. • The system should be straightforward to use.
Customer	• Dr Nathaniel Brown • Mr Gavin Cutler • The engineering department at Hull university • Average height is 175.3 (men) and 161.6 (women) [BBC News, 2021] • The average person can lift less than 130kg [Jared Polowick, 2021]

4. Research material

To be able to develop general ideas and solutions to the problem, research material was used to create a mood board. These images [1 - 5] are meant to be used as inspiration to develop ideas.

Image 1

[AliExpress, 2021]

Image 2

[Amazon, 2021]

Image 3

[Trossen Robotics, 2021]

Image 4

[Industry Plaza, 2021]

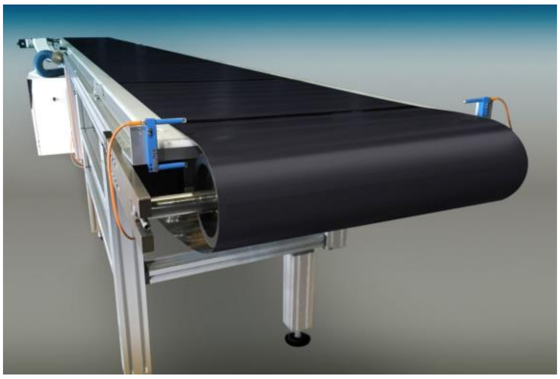


Image 5

[Belt technologies, 2021]

5. Concept Designs of Possible Solutions

This section aim is to develop a series of different ideas that could be able to tackle the problem. The designs have been made using a 3D modelling software called Blender. The annotations aim is to explain the designs kinematic processes and their relevance to the project. Each concept design is followed by an explanation of their kinematic and practicality principles, with a table that contains the advantages and disadvantages of the mechanism and an overall explanation of the design shown.

5.1 Gripping System

The set of concepts in '5.1 gripping systems' have been developed to show ideas and possible solutions to be able to grip the 3D printed material and release it safely.

5.11 Vertical Gear mechanism

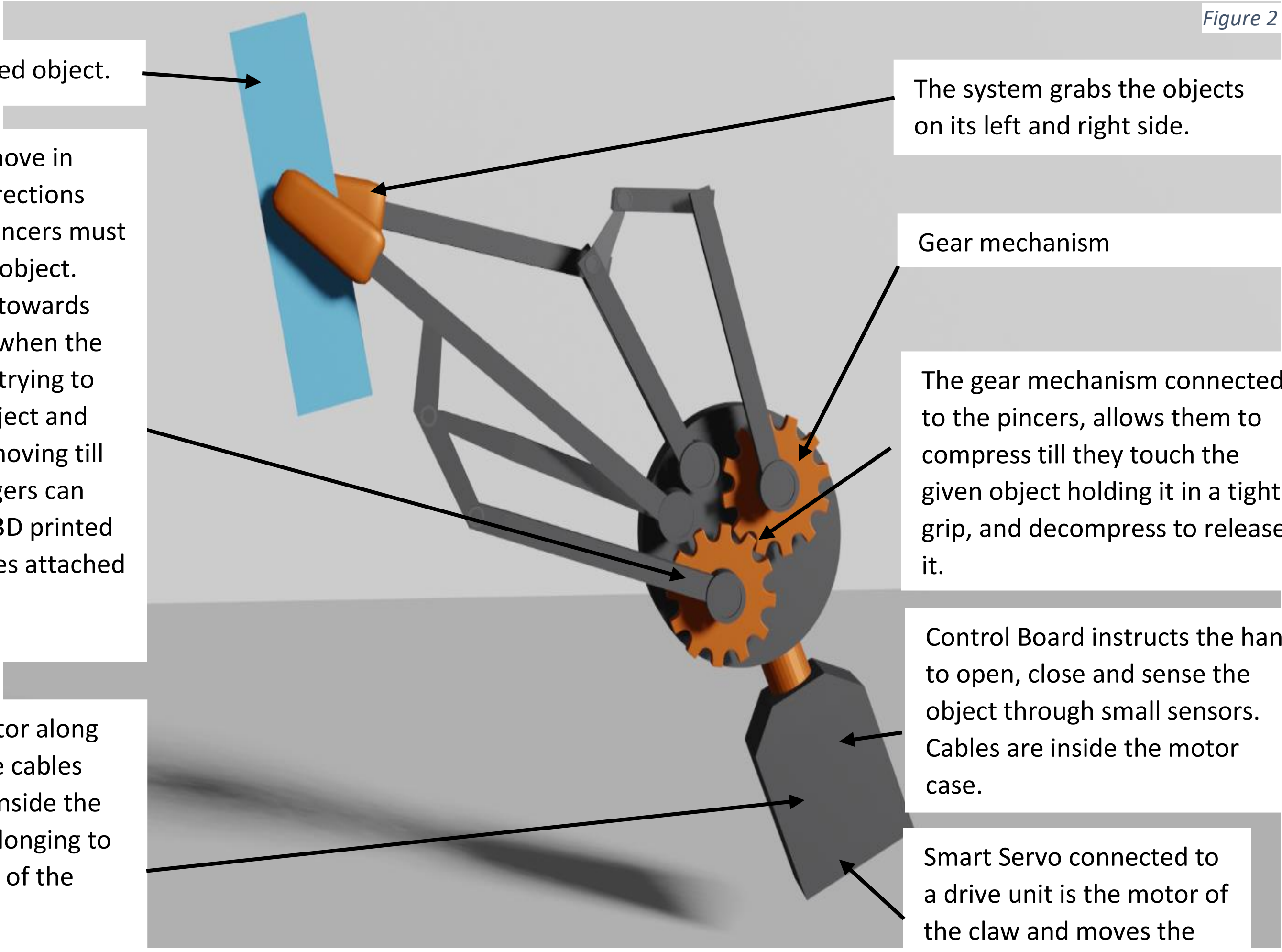


Figure 2

Kinematic and practicality explained:

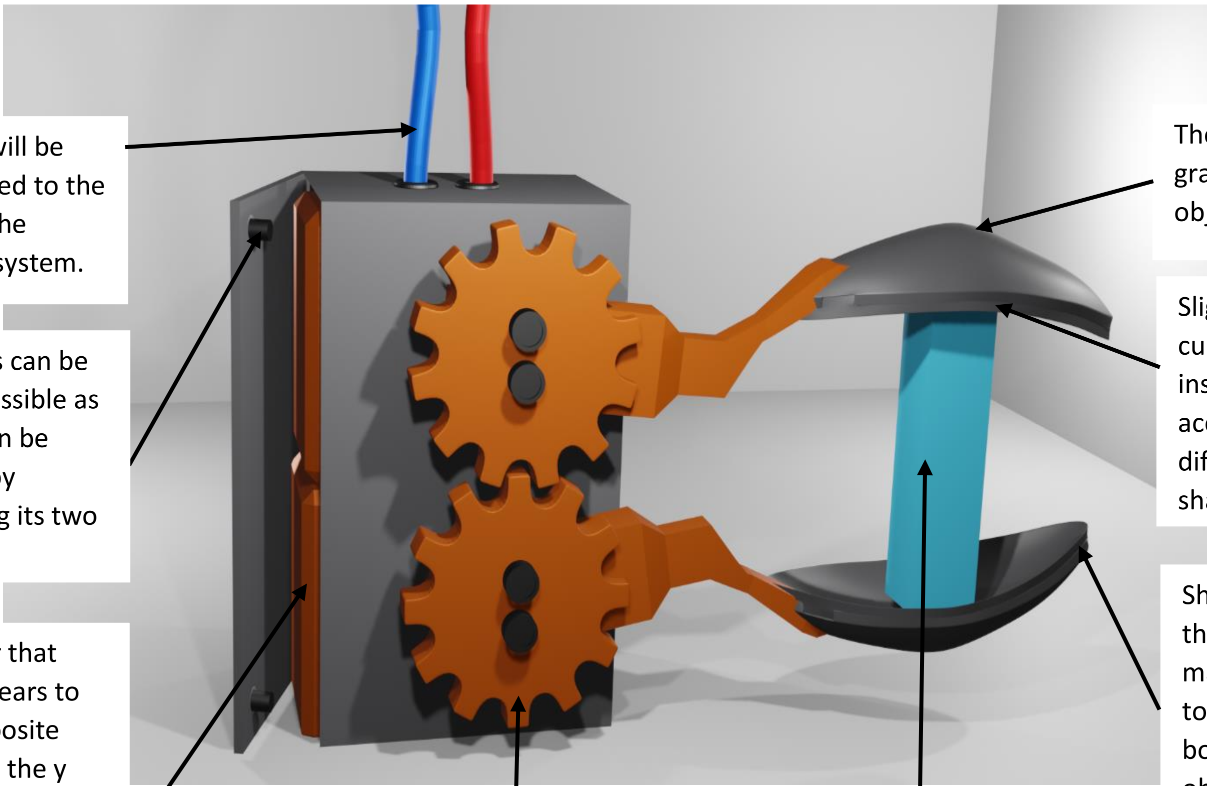
- The grabbing system uses a gear mechanism based on the rotation from the axis of the first gear to the adjacent one, this moves the two fingers slightly left and right and in the y-direction in opposite directions and grabs the element from its sides.
- The gears rotate thanks to a smart servo, this is the motor and drive of the hand.
- This mechanism can grab small objects of the same diameter.
- The claws move in the y axis and have a specific distance from each other. The object must fit within this distance.
- The servo is connected to a control board and its cables get attached to the arm.
- The size of the handle is 0.05 m for the left side and the right one slightly longer with an opening length of 0.10 m, this ensures that at least half the printing material element has been grabbed securely.

Advantages	**Disadvantages**
- Very high efficiency. - High torque rate. - Gears tend to have a long life, therefore if it does not get damaged, it meets the 10 years requirements. - Constant velocity. - Can lift heavier loads as gears tend to be very strong. - Easy to replace electronics as they are easily accessible. - Can transmit motion at a very low speed.	- Vibrates and makes noises at a relatively high speed. - Hard to manufacture. - Not flexible, the impact can cause damage to the printed elements. - Can grab only small objects. - Cannot grab different sizes. - Requires lubrication. - Dust can damage the gear mechanism. - Hard to grab circular objects. - High maintenance cost. - Difficult to manufacture.

Table 1

5.11 Horizontal Gear mechanism

Figure 3



Cables will be connected to the arm of the chosen system.

The 2 claws grabbing the object.

Electronics can be easily accessible as the box can be accessed by unscrewing its two sides.

Slightly curved on the inside to accommodate different shapes.

Servo motor that guides the gears to move in opposite directions in the y axis. Control board and motor are contained in the same rectangular box under the gears. Cables that come out from the back of the motor are then attached to the main body of the system.

Sharpened at the ends to make it easier to grab the bottom of the object as the print can stay attached to the bottom plate of the

This system uses a gear mechanism that grabs the object from the top and bottom. The two gears move towards each other when the object is meant to be grabbed, the two claws start to get closer too until the object has been grabbed. The mechanism moves in the opposite direction when the print has to be released.

3D printed element.

Kinematic and practicality explained:

- This design uses a gear mechanism system that moves the two claws to hold the object and release it.
- This design differs from Figure 3 in the orientation and shapes of the handle.
- The robot grabs the object on the x-axis.
- The handles are sharpened on the ends and slightly curved inside for a better grip.
- Servo motor and control board are placed together inside a box allocated under the gear mechanism.
- This box can be closed by screwing the two holes at the top left and right of it.
- The size of the handle and opening is 0.11 m to ensure that the system can grab the printed objects efficiently

Advantages	Disadvantages
- Can be used at low speed. - Can grab differently shaped elements. - The driving system and gear mechanism do not get damaged easily. - Easy to replace electronics as they are easily accessible. - At a very low speed, it can still transmit motion. - Simple and easy to manufacture. - Able to carry heavyweights.	- Can be hard to grab bigger objects. - The system can struggle to stay in equilibrium when picking the object, as the weight would not be evenly distributed. - Dust can damage the mechanism. - A high number of noises and vibrations. - 3D printed material can be damaged when released. Needs lubrication. - Has no flexibility. - The maintenance cost is very high.

Table 2

5.11 Gear mechanism with 8 claws

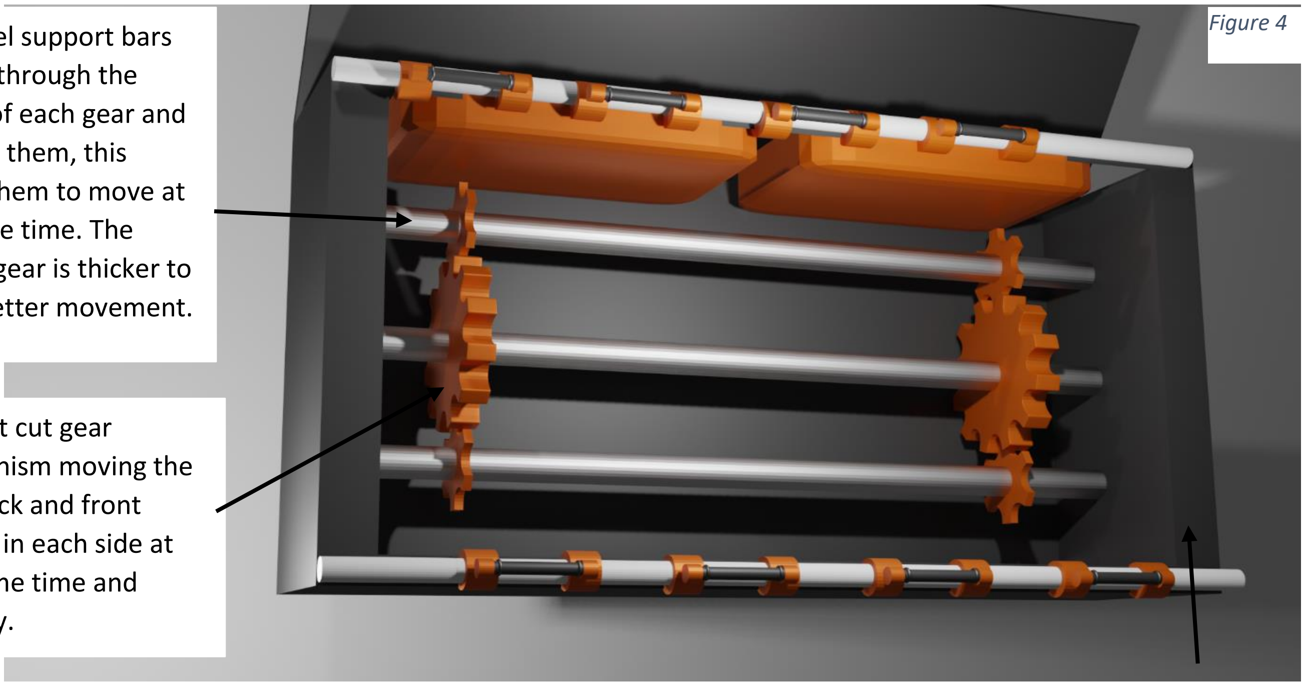


Figure 4

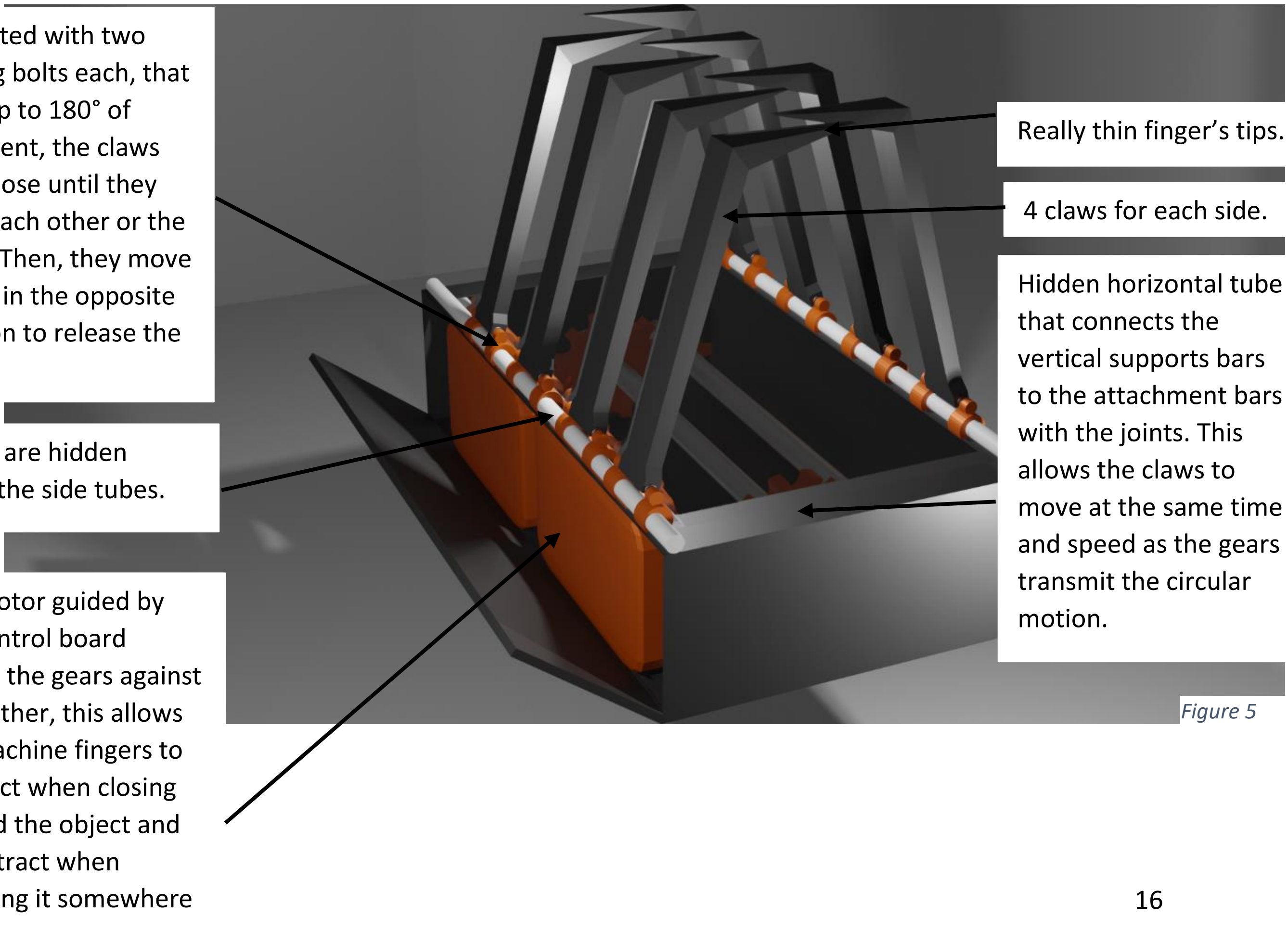


Figure 5

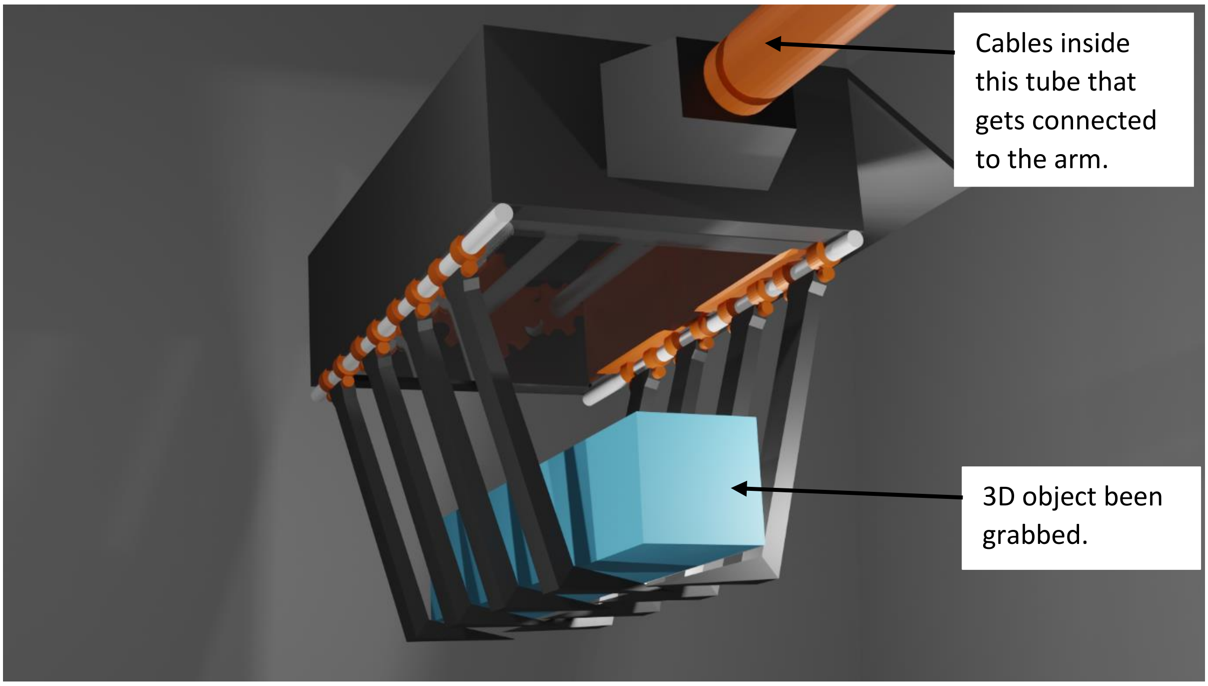

Cables inside this tube that gets connected to the arm.
3D object been grabbed.

Figure 6

Kinematic and practicality explained:

- Motor and control board are at the bottom of the hand.
- Cables are hidden inside the tubes where the claws are fitted.
- The claws move left and right co-ordinately. They move in to grab the object and out to release it with an angle of up to 180°.
- Because of this constant movement, the craws are set to be 0.12 m long with an opening of 0.12 m to ensure that the handle has enough space to oscillate around the printed elements.
- This machine has 8 fingers, 4 on each side to ensure that the object has been grasped properly.
- Two sets of a three-gear system have been used to move both sides at the same time.
- The claw tips grab the object from the top. They cover the object with the claws wide open at its left and right and then close the finger's tips under the object.
- To release the object, they do the same movements in the opposite direction.

Advantages	**Disadvantages**
- More claws mean better grip and better equilibrium as it allows the system to distribute the weight. - Easy to replace electronics as they are accessible at the bottom back of the grip. - At a very low speed, it can still transmit motion. - Large forces can be transmitted between the gears. - High efficiency.	- Gear is not suitable when the shaft is far away. - Noise and vibration as the speeds get higher. - Dust can damage the mechanism. - Requires lubrification. - The impact against the claws can damage the object. - Difficult to manufacture. - The maintenance cost is very high.

Table 3

5.12 Rectangular Shape

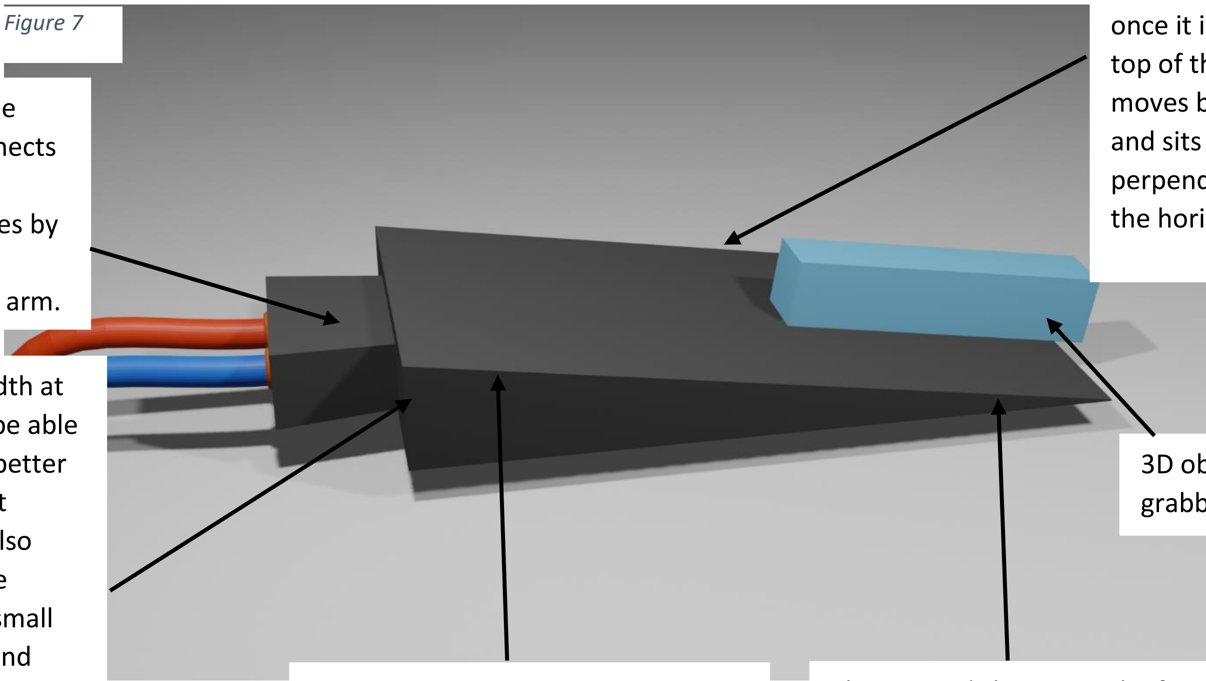


Figure 7

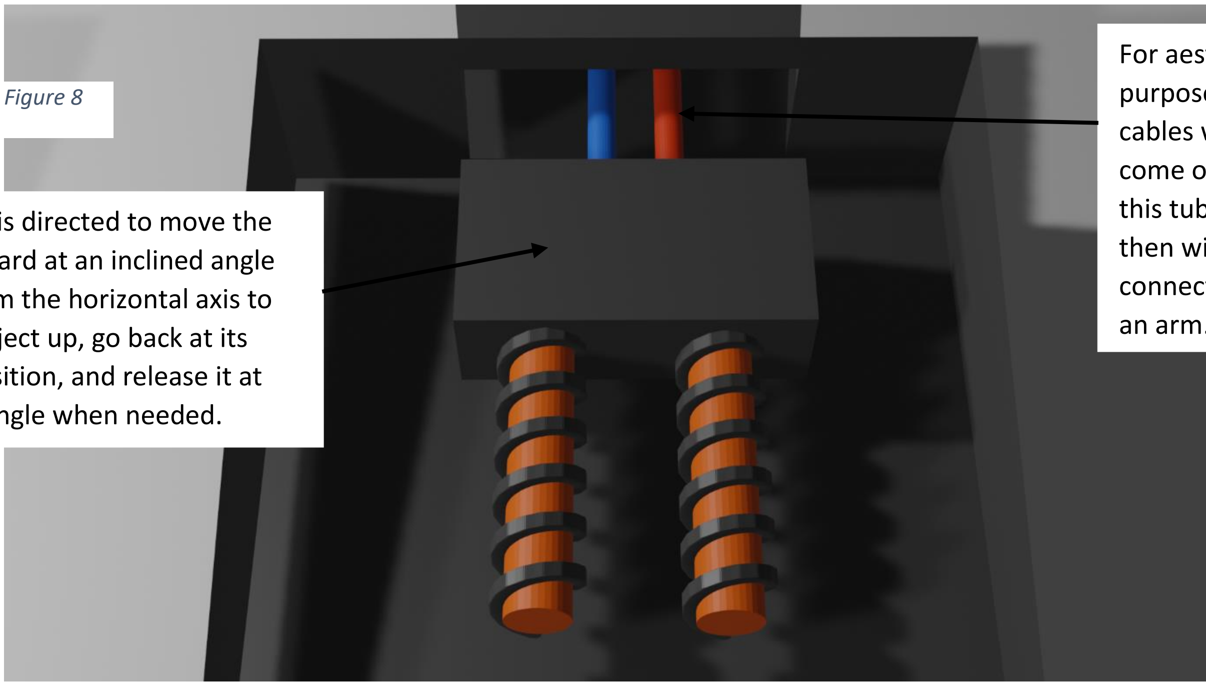

The motor is directed to move the shape forward at an inclined angle of 225° from the horizontal axis to pick the object up, go back at its original position, and release it at the same angle when needed.
For aesthetic purposes, the cables will come out of this tube and then will be connected to an arm.

Figure 8

Kinematic and practicality explained:

- The shape tends to be slim and sharp at the front and gets thicker as we reach the back of it. The maximum thickness is 0.02 m.
- This is to ensure that it can go below the object and grip it at an angle of 315° (45 degrees downwards) from the horizontal axis. The shape repeats the movements in the opposite direction to release the object.
- The 3D object sits in equilibrium above the shape while it gets moved.
- Motor and control board are inside the shape and are sealed inside after being placed there.
- Cables come out from a small tube at the end of the shape that gets attached to the arm of the system.
- The shape must be 0.12 m large and long to assure that it can collect any dimensions.
- The shape moves forward and backwards.

Advantages	**Disadvantages**
- Shape is easy to manufacture. - Can be 3D printed. - Hard to damage. - Cheap manufacturing process. - Compact. - Easy to control.	- Not easily accessible motor. - Hard to pick rounded objects and can struggle with other shapes. - If weight is not distributed properly, can easily collapse. - A limited number of movements. - The object can fall off at the sides. - If the shape gets damaged, it will have to be replaced fully.

Table 4

5.12 Circular Shape

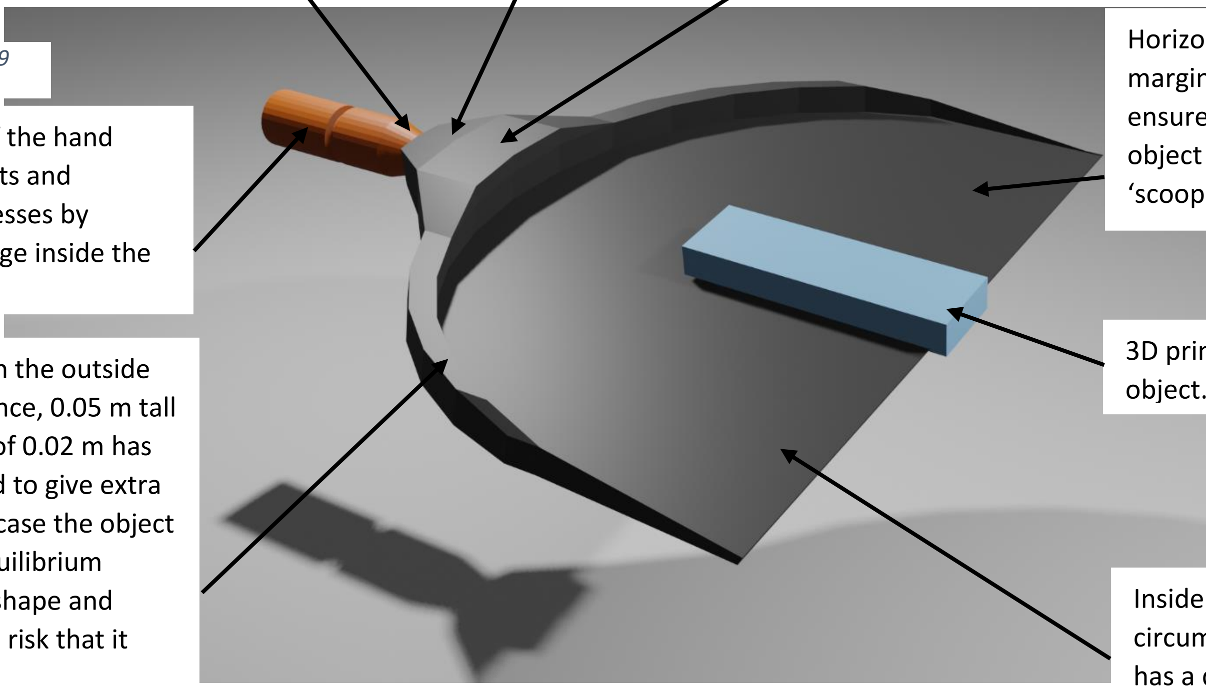


Figure 9

Kinematic and practicality explained:

- The shape differs from Figure 9 as it is a semi circumference.
- The shape picks the object up at an angle of 225° from the horizontal.
- The borders are 0.007 m in width and 0.01 m height to ensure that the object does not slip from the sides.
- The inner length is 0.11 m x 0.11 m.
- The Control board and motor are in the tube attached to the shape.
- The shape tends to scoop the object.
- It maintains the same size and dimensions.
- The shape moves forward and backwards.

Advantages	**Disadvantages**
- Less risk of the object falling out because of the margins. - Motor and cables are safely displaced. - Easy to manufacture. - Cheap cost of manufacturing. - Compact. - Difficult to disassemble and therefore harder to break or damage.	- Electronics parts are hard to access. - Can be hard to scoop bigger objects. - Hard to replace. - The object can move when picked up as it is a fixed size and does not grip the object.

Table 5

5.13 Robotic Hand

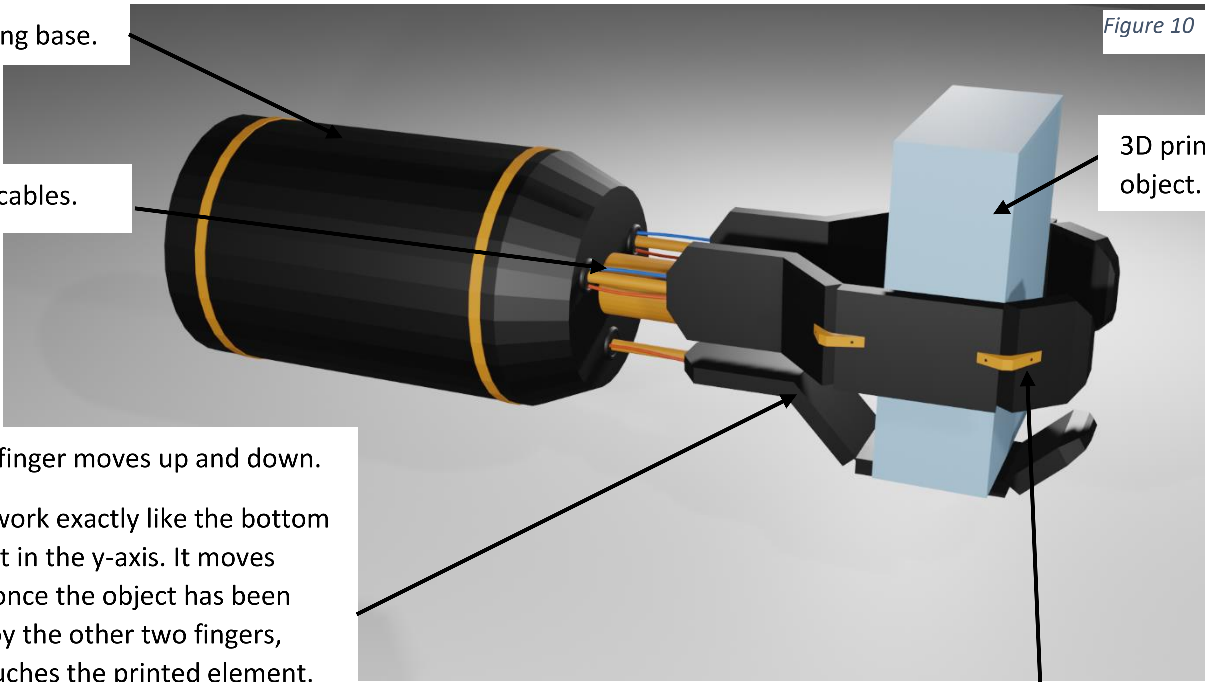


Figure 10

The third finger moves up and down.

Its joints work exactly like the bottom fingers but in the y-axis. It moves upwards once the object has been grabbed by the other two fingers, until it touches the printed element. And moves downwards to release it.

This finger acts as a security craw to make sure that the object does not fall, get damaged or lose equilibrium.

Joints move up to 90° in both directions from the horizontal line.

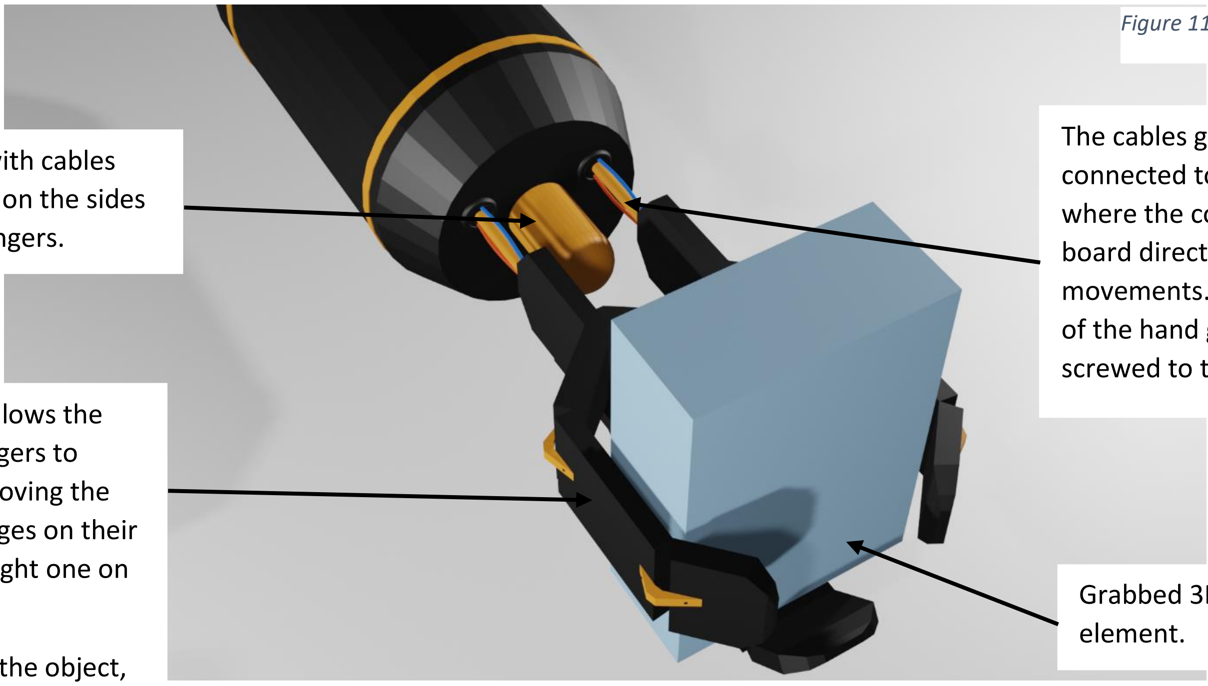

Motor with cables that run on the sides of the fingers.
The cables get connected to the arm, where the control board directs the movements. The base of the hand gets screwed to the arm.
The joint allows the bottom fingers to contract moving the left phalanges on their right and right one on their left.
To release the object, these fingers move in the opposite direction.
Grabbed 3D printed element.

Figure 11

Kinematic and practicality explained:

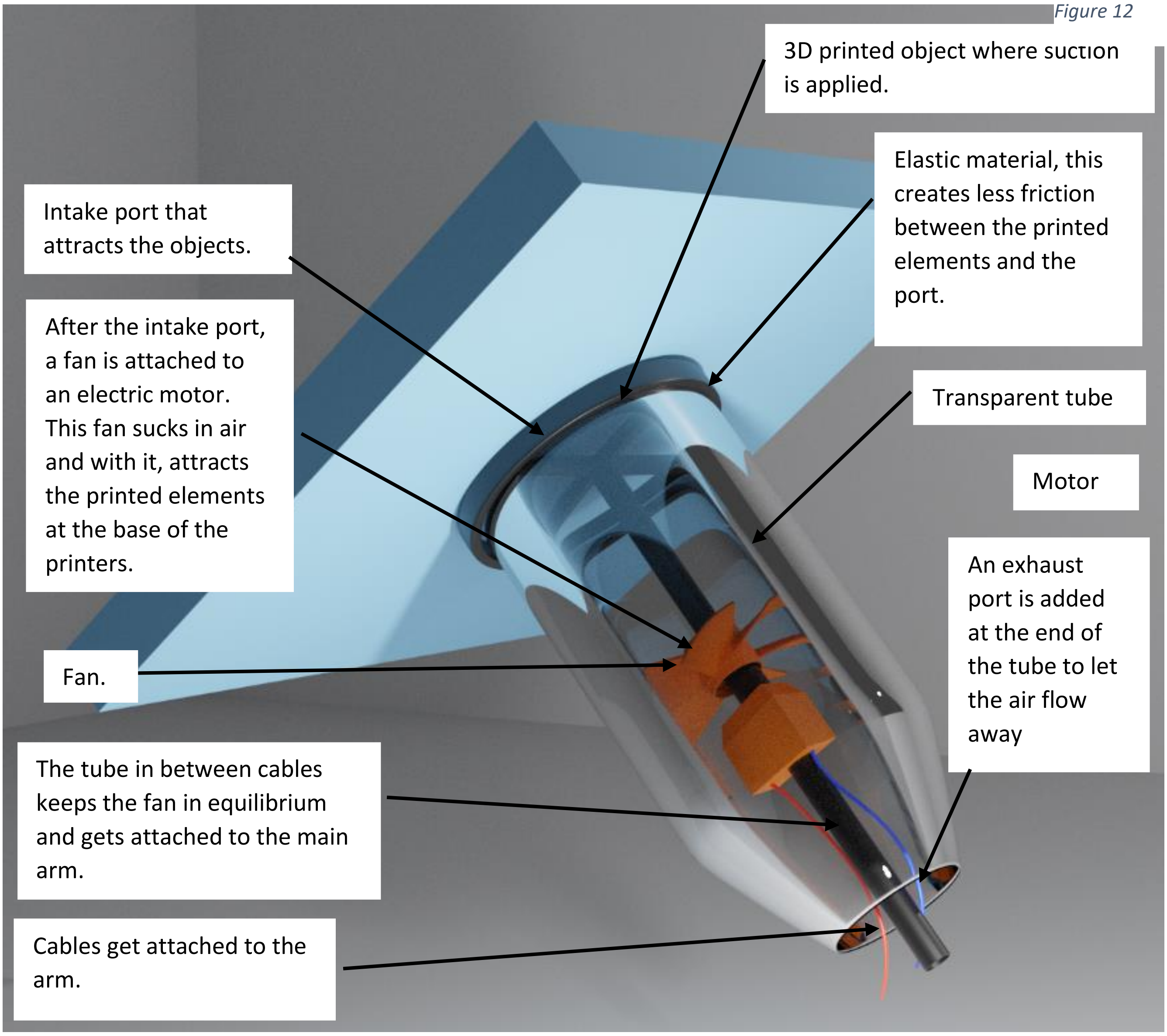
- The robotic hand has screws for joints that allow 45°of movement from the y-axis to an inward motion.
- The cables that connect the motor to the fingers go through the fingers in the centre. The electrical motor, attached to the control board at the base, controls all the fingers simultaneously.
- This hand grabs the object by moving its fingers inwards and releases it by moving them outwards.
- The fingers move inwards till the sensors attached at the distal phalange detects that the object has been grabbed firmly.

Advantages	Disadvantages
- Can firmly grab objects. - No sharp edges therefore avoid damaging the object. - Electronic parts are easily accessible. - It has a very high range of movements - Hard to break. - Can grab any shape and size within the specification limits.	- Can be heavy - The third finger might struggle to get hold of the object as it must reach the bottom of the printed element. - Can be tricky to fix. - Because of the high number of components, it can be expensive.

Table 6

5.14 Suction hand

Figure 12



Kinematic and practicality explained:

- This system differs from the others seen before as it does not grab the object. Instead, the air is squeezed inside the cup and the atmospheric pressure outside, pushes the object inside the cup.
- The suction tube tends to be deformable elastically, this allows the printed object to attach properly.
- The hand works thanks to a rotating motion fan at the bottom and base of the robot.
- Diameter of 0.15 m.
- The mechanism tends to attach to the front side of the object.
- The suction air motion is created at the intake port and the air is released at the exhaust port.

Advantages	**Disadvantages**
- Compact. - Easy to manufacture. - Difficult to break. - Can be upgraded easily. - High power efficiency due to the fan's continuous movement that develops with a small amount of energy, a high suction force. - Does not consume a lot of energy therefore it is environmentally friendly.	- High numbers of electrical components. - Can struggle to keep soft material attached, works best with hard materials - It might attract dust and need lots of maintenance. - Hard to fix. - Can struggle to attract heavy objects and keep them in a hold. - Difficult to control and therefore not reliable. - Small objects can get stuck inside.

Table 7

5.14 Sticky Suction tube

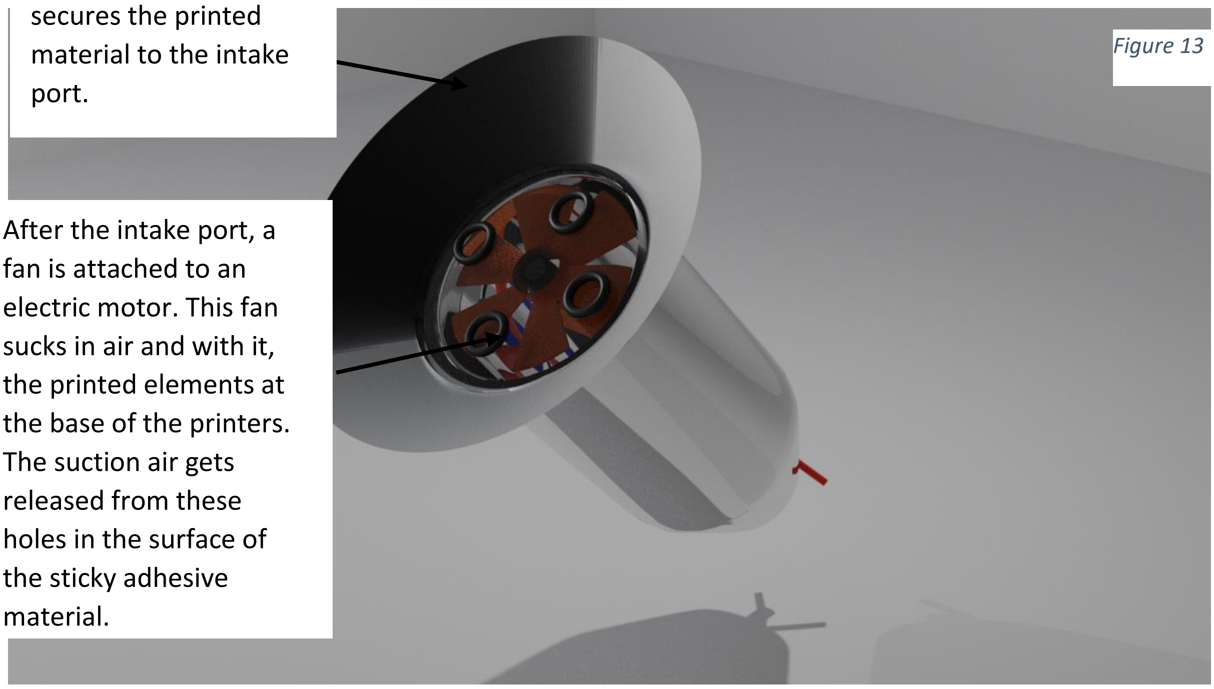
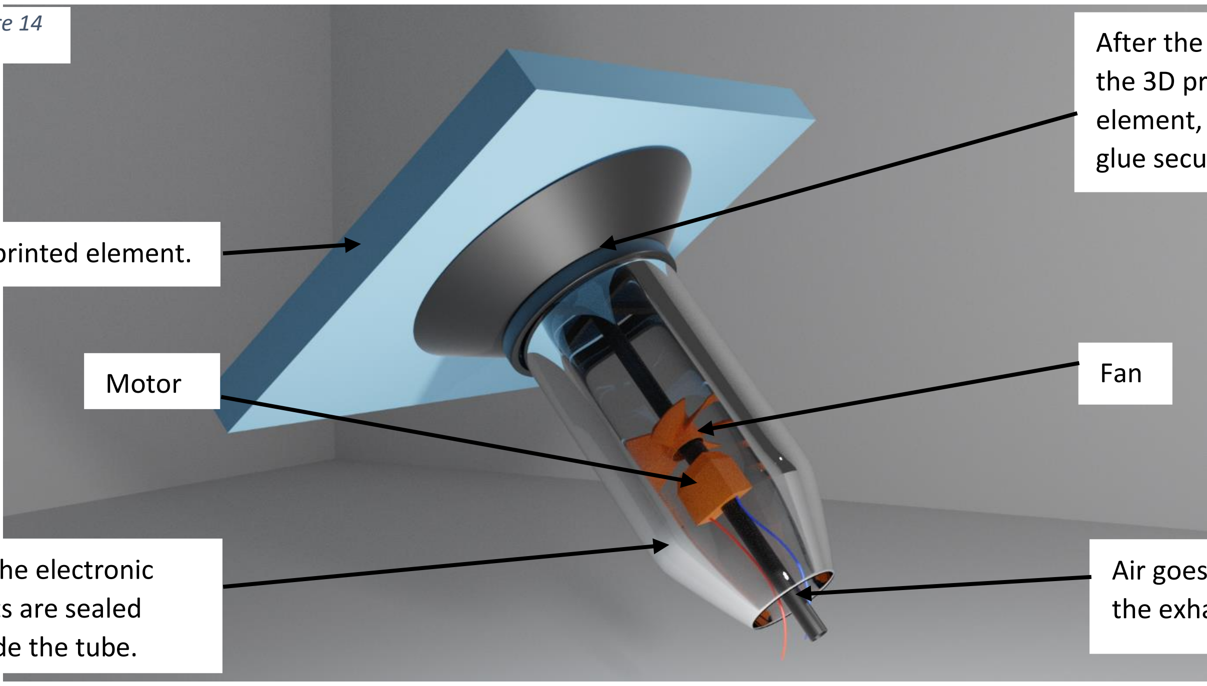


Figure 13

Figure 14



Kinematic and practicality explained:

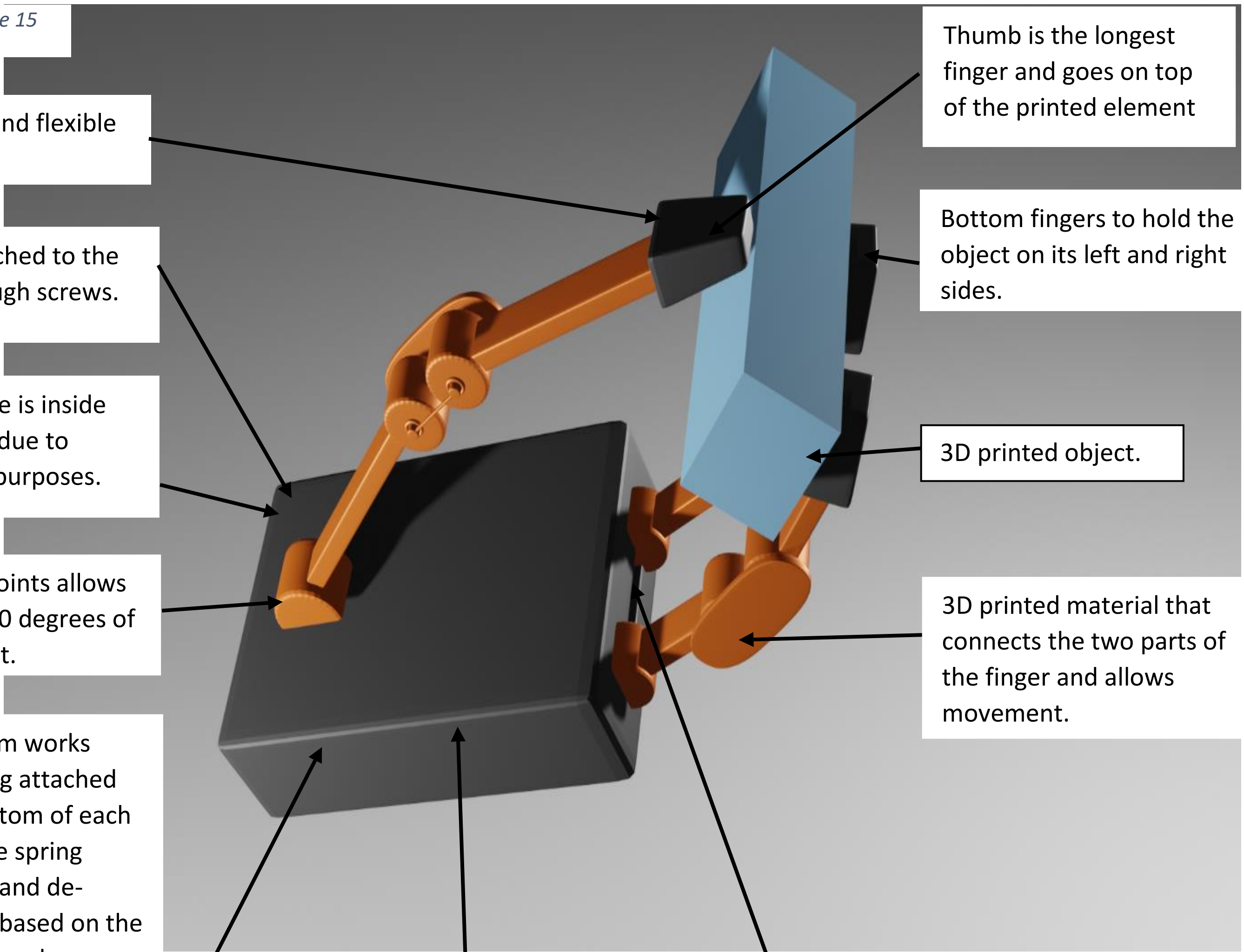
- This circular shape is a sticky suction pad
- The mechanism used is the same one for figure 12 and only differs in shape and material.
- It uses a sticky material that adds extra security when the suction motion grips the printed elements.
- Circumference depth and diameter of 0.11 m.
- A fan is located at the base of the robot.

Advantages	**Disadvantages**
- Keeps object attached to the system. - Easy to manufacture. - Compact. - Difficult to deform. - Power-efficient.	- Can be hard to release it due to the sticky materials. - Electronics are hard to access. - Dust can get attached to the system's material's glue and therefore it needs to be cleaned or replaced often. - Hard to control.

Table 8

5.15 3 fingers Spring system

Figure 15



Kinematic and practicality explained:

- The robotic hand can move the fingers inward to grab the object and outward to release it due to a spring system controlled by a servo motor.
- The system uses hard to deform special-purpose springs.
- The middle and index finger keep the object in equilibrium and grab it from the left and right bottom sides while the thumb adds extra security by securing the top of the element.
- When the spring extends, the system grabs the object and when it goes back to its natural length, the hand releases the object. The middle and index finger are shorter than the thumb as the thumb must extend upwards as well to reach the top of the printed object.
- The two bottom fingers can slide near each other if the material is small. They slide through the rail that is in between them to change the distance in between.
- The index and middle finger are 0.7 m long while the thumb is 0.11 m long.

Advantages	**Disadvantages**
- Good impact absorbing ability. - High durability. - Springs can store and absorb energy. - Screws and electronics pieces can be easily removed and changed. - High tensile strength. - Can be used easily. - Can secure the object without damage due to its rounded corners in the fingers.	- A high number of materials. - Springs lose stability with time. - If broken the system can be hard to repair. - Can be hard to manufacture.

Table 9

5.15 Pegs Spring System

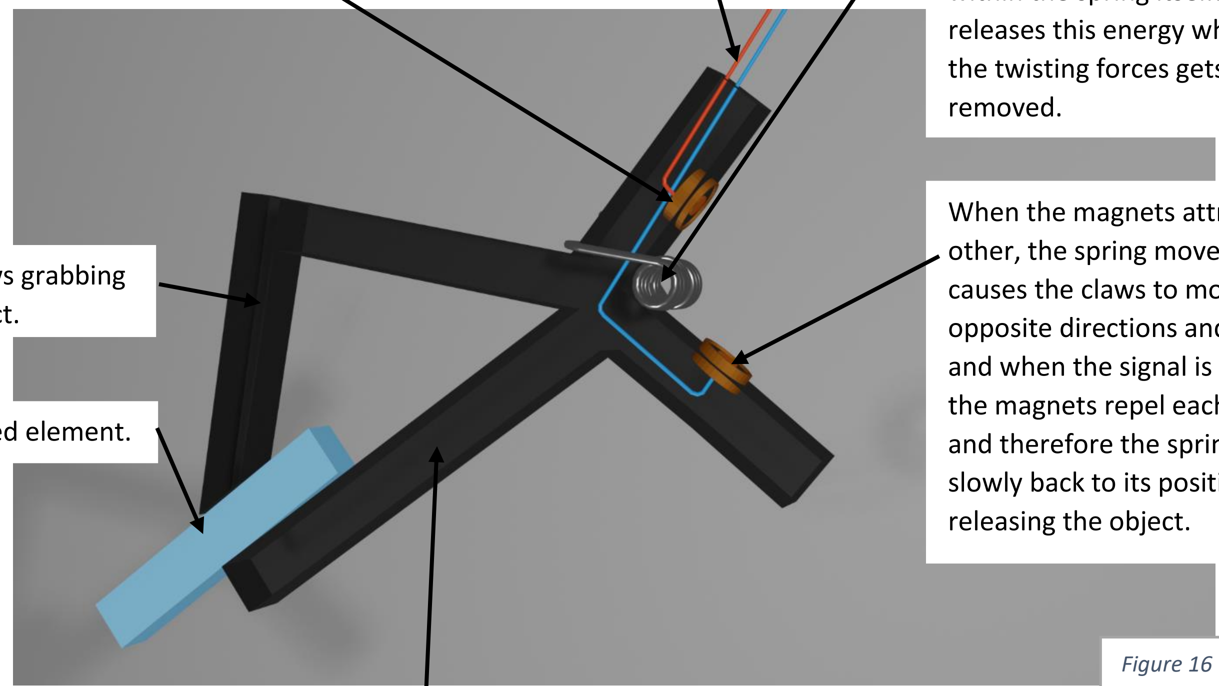
Two strong magnets are placed inside the side tubes and are both connected to the motor that is placed at the start of the arm. The magnets start both with a positive charge, but the motor sends an electronic charge to the right magnet, this causes the magnets to attract each other and move the spring.

The cables connect the magnets to the motor.

When a torsion spring is twisted, it holds the energy within the spring itself. It releases this energy when the twisting forces gets removed.

Two claws grabbing the object.

3D printed element.



When the magnets attract each other, the spring movement causes the claws to move in opposite directions and open and when the signal is gone, the magnets repel each other and therefore the spring goes slowly back to its position releasing the object.

Figure 16

The claws grab the object on its sides, one of them attaches parallel to the object and the other one pinches the object in position and holds the grip.

Kinematic and practicality explained:

- This system uses a torsion spring that is attached to a constant torque motor at the two bottom sides.
- The top two fingers grab the object on the side and have an opening of 0.12 m.
- The shape allows a better and firm grip.
- The system is a few centimetres thick, but it is empty inside. This gives it enough strength and force to be able to hold the object, but it makes it relatively weightless.
- It works by changing the polarity of a magnet. When the magnets have the same polarity, they repel each other and the spring stores the energy released, this causes the claws to release the object. But when the motor changes the charge of a magnet, the spring uses the stored energy to make the claws contract and grab the given object.

Advantages	**Advantages**
- Easy to manufacture - The spring offers smooth movement - Weightless - The system is strong and durable - Easy system and design	- Can struggle to pick the biggest objects - A limited number of movements - Expensive - The force created can damage the objects when they get picked up. - Hard to control force induced. - Magnets can be expensive

Table 10

5.2 Arm System

This sub-section aim is to develop ideas for the body of the system that has been required. This part aims to create a system that can be attached to the gripping mechanism and move it the three-axis based on the needs and requirements of the customer.

5.21 Fixed Stand Telescopic arm

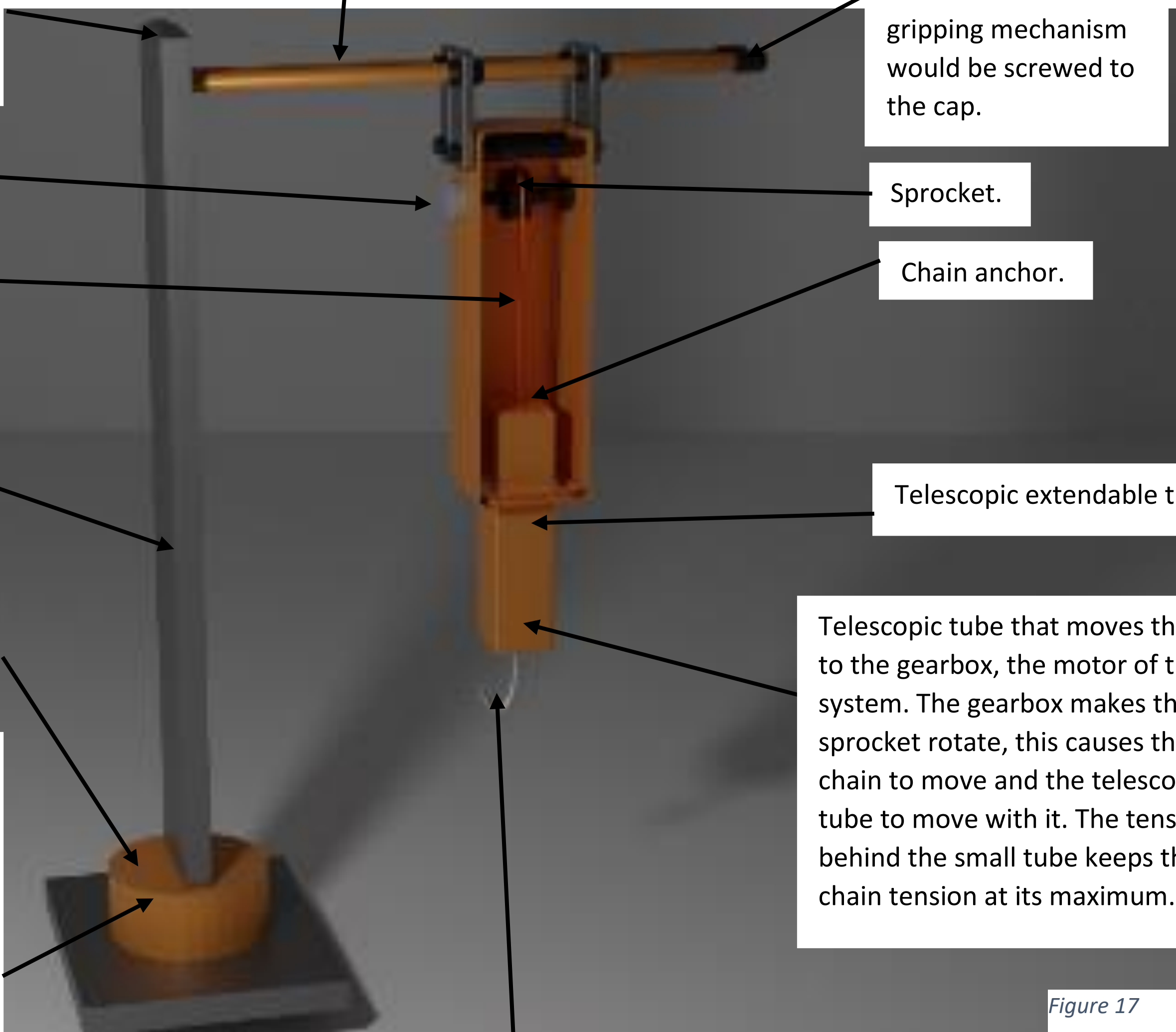


Figure 17

Kinematic and practicality explained:

- A track slider placed in the horizontal direction permits the telescopic tube to move left and right thanks to the help of 4 wheels.
- The telescopic arm uses a chain system connected to a sprocket and gearbox, to move the telescopic part up and down.
- A tensioner keeps the chain in tension and allows the inside tube to move without issues.
- The track slider is electronic and moves the wheels in different directions depending on the location of the object.
- The top of the base has a rotating system and both the motor controlling the rotating system and the track slider are located at the bottom of the fixed part of the robot.
- A large cap is located at the front of the slider to stop the telescopic tube from going of rails and damaging itself.
- Cables are inside the tubes for aesthetic and safety purposes.

Advantages	Disadvantages
- Can reach a wide range of heights. - Can move independently. - Easy to transport. - Lightweight. - Able to rotate. - Moves vertically.	- The 3D printed elements are contained in a printer and therefore the telescopic arm cannot access them as the arm is vertical and not horizontal. - Can struggle to lift heavyweights. - Can move in the y-direction but not z and x. - Electronic parts are hard to access.

Table 11

5.12 System with Two Telescopic arms

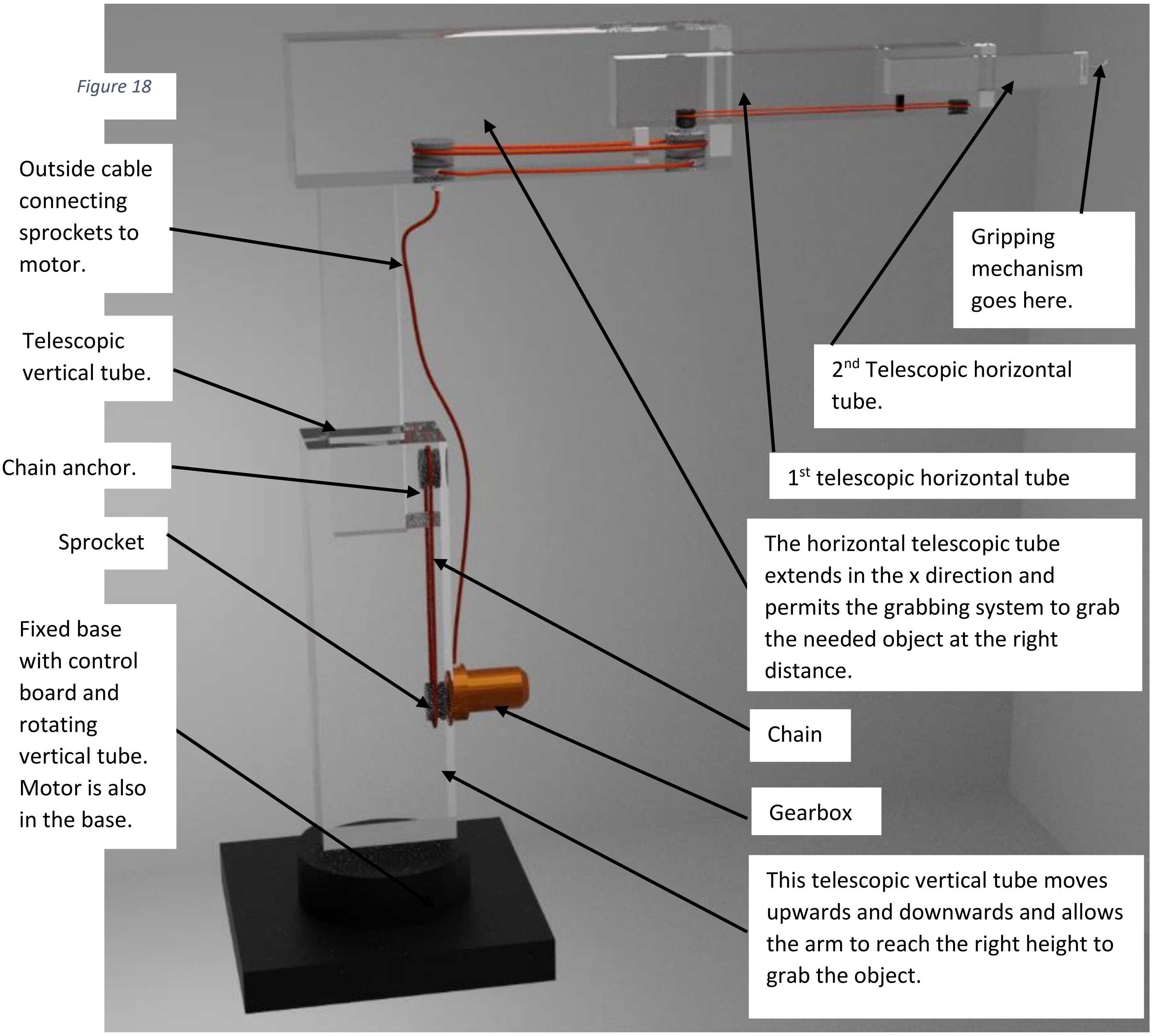


Figure 18

Kinematic and practicality explained:

- A fixed rotating base is attached to a telescopic horizontal and vertical extendable tube.
- The horizontal tube can extend forward and backwards and the vertical one, upwards and downwards. The first facilitates the machine to reach the 3d printed element. The vertical one adjusts the height of the machine, so it reaches the height required to pick the object.
- The telescopic tubes are controlled by an electronic drive unit at the back of the telescopic tube and a motor at the base of the fixed body.
- The mechanism used in the extendable chain can be divided into a few parts: the chain moves thanks to the gearbox, which makes the sprocket rotate. This pushes the telescopic tubes in the direction wanted based on how fast the chain is moving and if is moving clockwise or anticlockwise.
- The rotating base permits the telescopic tube to rotate 360 °.

Advantages	**Disadvantages**
- Can move horizontally and vertically and can rotate. - The mechanical system is cheap and easy to manufacture. - High precision work, the height of the arm and horizontal distance can be adjusted to pick up the object. - Does not produce lots of noise. - Can move fast and be precise. - Machine's speed can be increased or reduced. - Low speed increases torque. - Electrical and mechanical systems tend to be stable in the long term and the machine can work constantly at the same rate very fast. -	- Cannot take heavy loads. - Could break easily as it has two sets of telescopic arms. - Gearboxes tend to have very low efficiency. - The electrical system can be very heavy and expensive.

Table 12

5.22 Suction arm

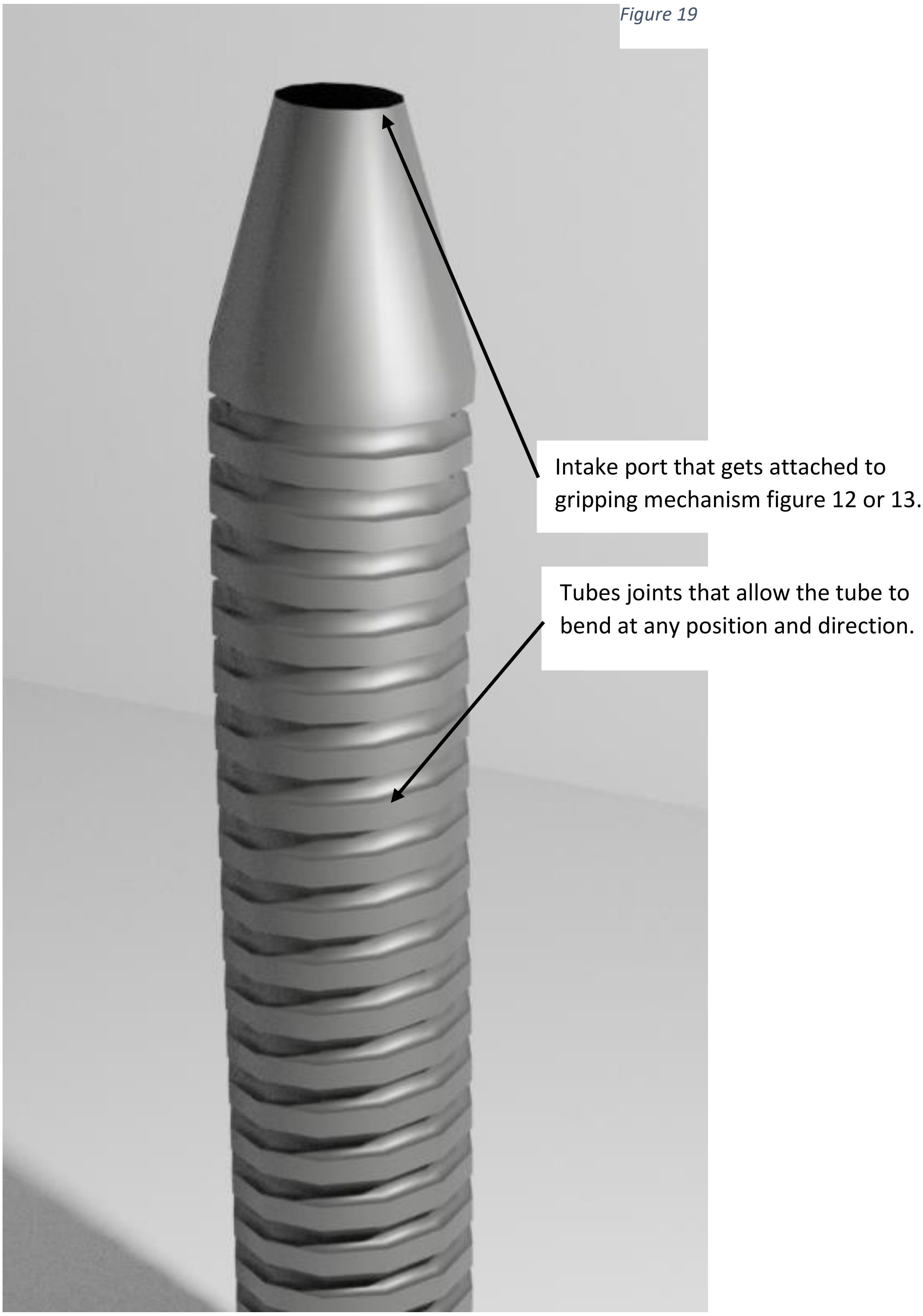


Figure 19

Kinematic and practicality explained:

- Elastic material extendable tube.
- The tube can move in any direction and bend at any joint.
- Figures 12 and 13 suction hands are meant to be attached to this design with a fan motor at the fixed gripping mechanism.
- The lines in the tube act as joints that permit the tube to bent in any direction based on needs.

Advantages	Disadvantages
- The tube is easy and cheap to manufacture. - The system is hard to break. - Does not get influenced by temperature. - Can attract heavyweights. - Low-cost materials. - Hard to break and safe system. - Can be quite resistant to electrical systems.	- Can damage the objects when released or attracted to the tube because of impact. - Can be loud and noisy. - Very hard to control. - Can heat up easily and burn out after being used a lot and continuously. - High power consumption.

Table 13

5.23 Hydraulic pump

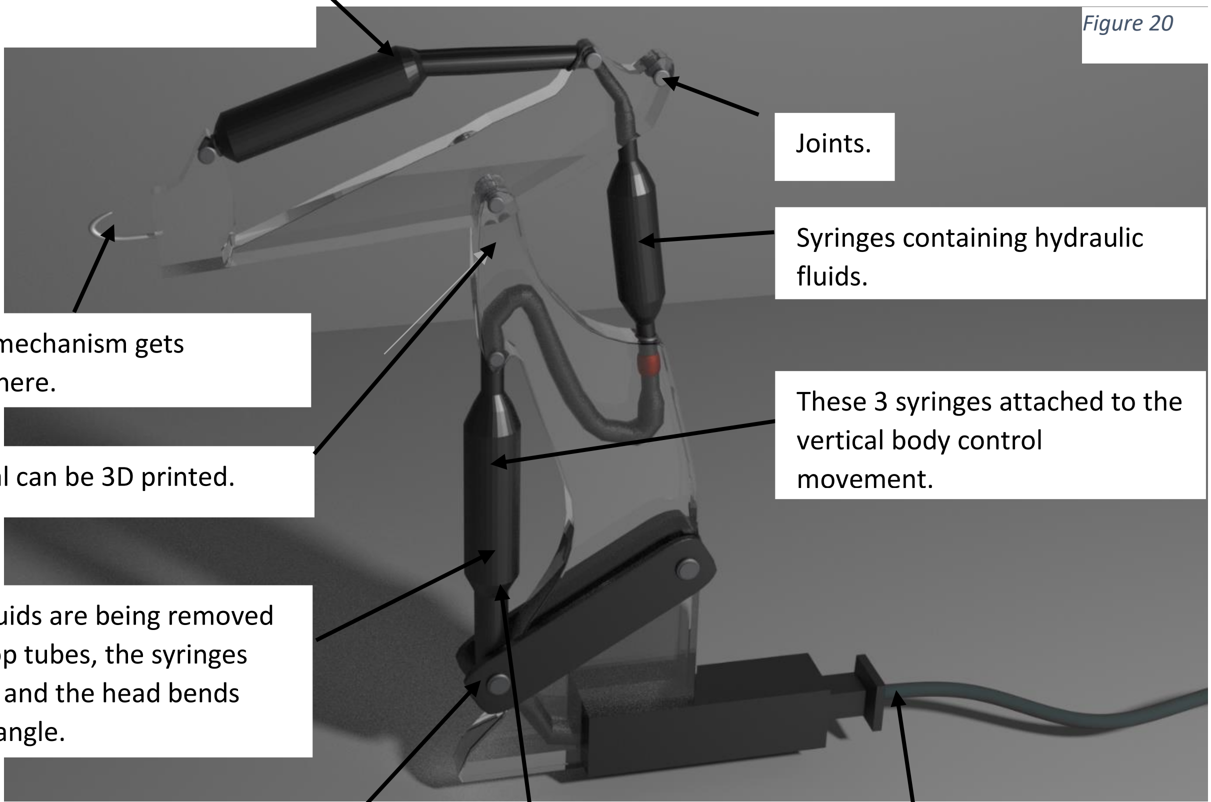


Figure 20

Kinematic and practicality:

- The robotic arm is controlled by syringes filled with hydraulic fluid.
- When the syringes are filled with fluids, the system is at its stationary position shown in Figure 20 and when they are getting emptied and the fluid is moving across the robot, the machine head and body, bend.
- The generator is located at the bottom of the machine and driven by an electrical motor.
- Three syringes allow the system to move freely. The top syringe permits the arm to grab the object.
- The bottom syringes permit the object to bend 70 degrees and let the machine pick the object.
- The body of the machine can be made of metal and screws that allow the syringes to direct the movement and act as joints.

Advantages	**Disadvantages**
- Pump speed is easy to control. - Does not only move in the y and x-axis but the arm moves at an angle too. - Increasing speed does not change the force, therefore the force given can be constant. - Can deliver constant torque. - The system is simple and safe. - Can handle heavyweights. - Use fewer mechanical parts, compared to the other systems therefore this one is the cheapest. - Easy to spot leakages, therefore it’s easy to know when it needs maintenance.	- The liquid used can leak. - Cannot rotate. - If a leak occurs, the system can be messy. - If a leak occurs, there is the risk of a fire hazard. - Hydraulic fluids tend to be corrosive.

Table 14

5.24 Linear actuator

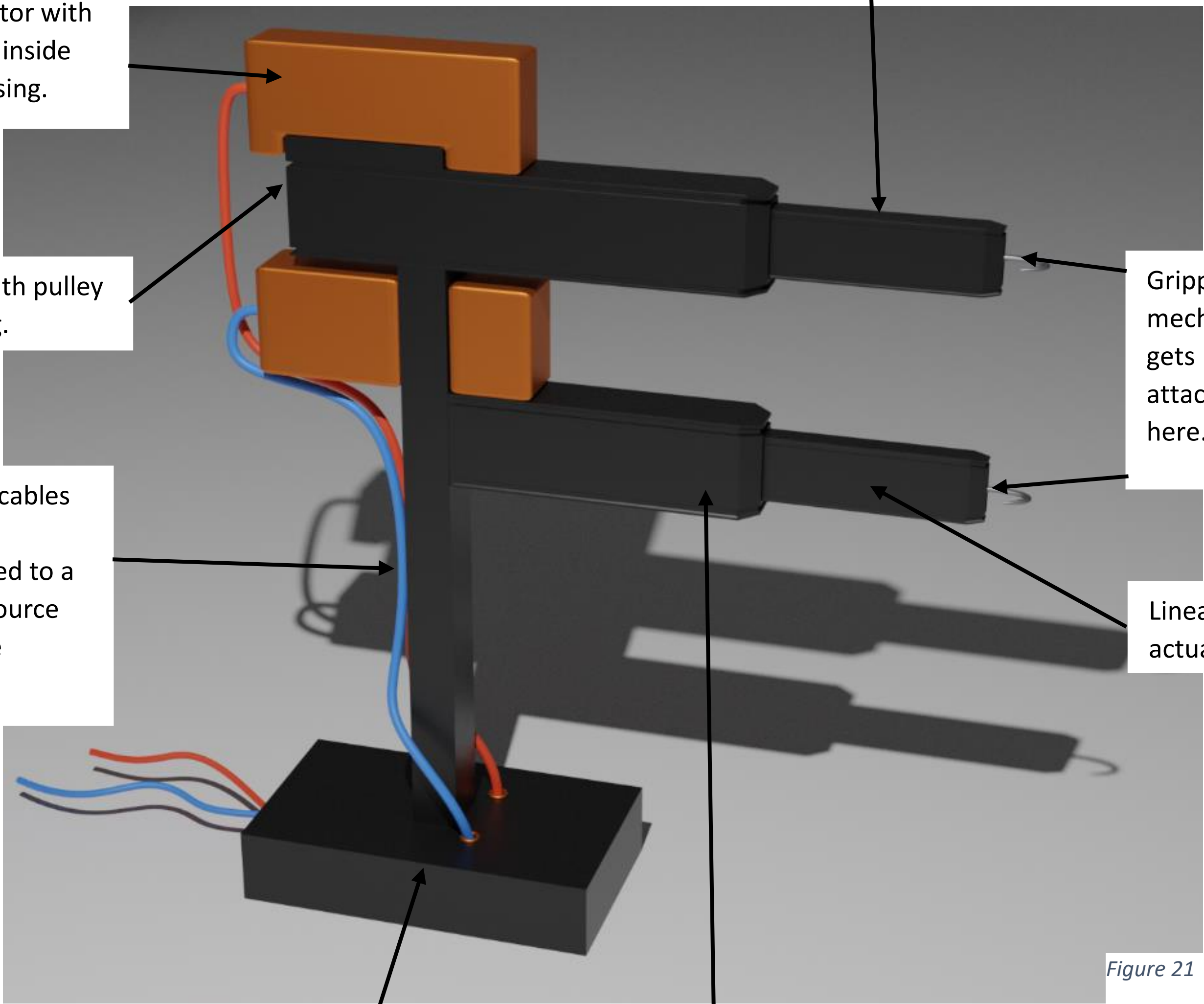


Figure 21

Kinematic and practicality explained:

- Two horizontal linear actuators are located at the top of a fixed body.
- The actuators move out when the DC motor is powered and in when the polarity is reversed.
- The linear actuators motors are located at the top of the fixed tube and attached with cables outside the tube itself.
- The actuators act as an arm and move forward and backwards, this allows the grabbing mechanism to grab the object and release it.
- The actuators move at the same time, the two arms move horizontally and grab objects from two different printing machines simultaneously.
- Every piece of electronics is contained inside the tube.
- The control board that moves the machine is allocated at the base of the fixed body.
- It has two motors that move at the same speed and start the gear's circular motion. The lead screw connected to the gear transforms this motion to linear.

Advantages	**Disadvantages**
- Force and speed can be controlled. - Can work at high speed and be precise. - It is reliable. - Can easily carry a high number of weights. - Can pick up two objects at the same time saving time. - Can move horizontally. - Simple to design. - Does not consume much power.	- Can be expensive as it has two linear actuators. - One of the most expensive out of the arms shown. - Cannot rotate. - Cannot move upwards or downwards. - Having cables outside can be a health hazard. - Fixed height.

Table 15

5.25 DOF

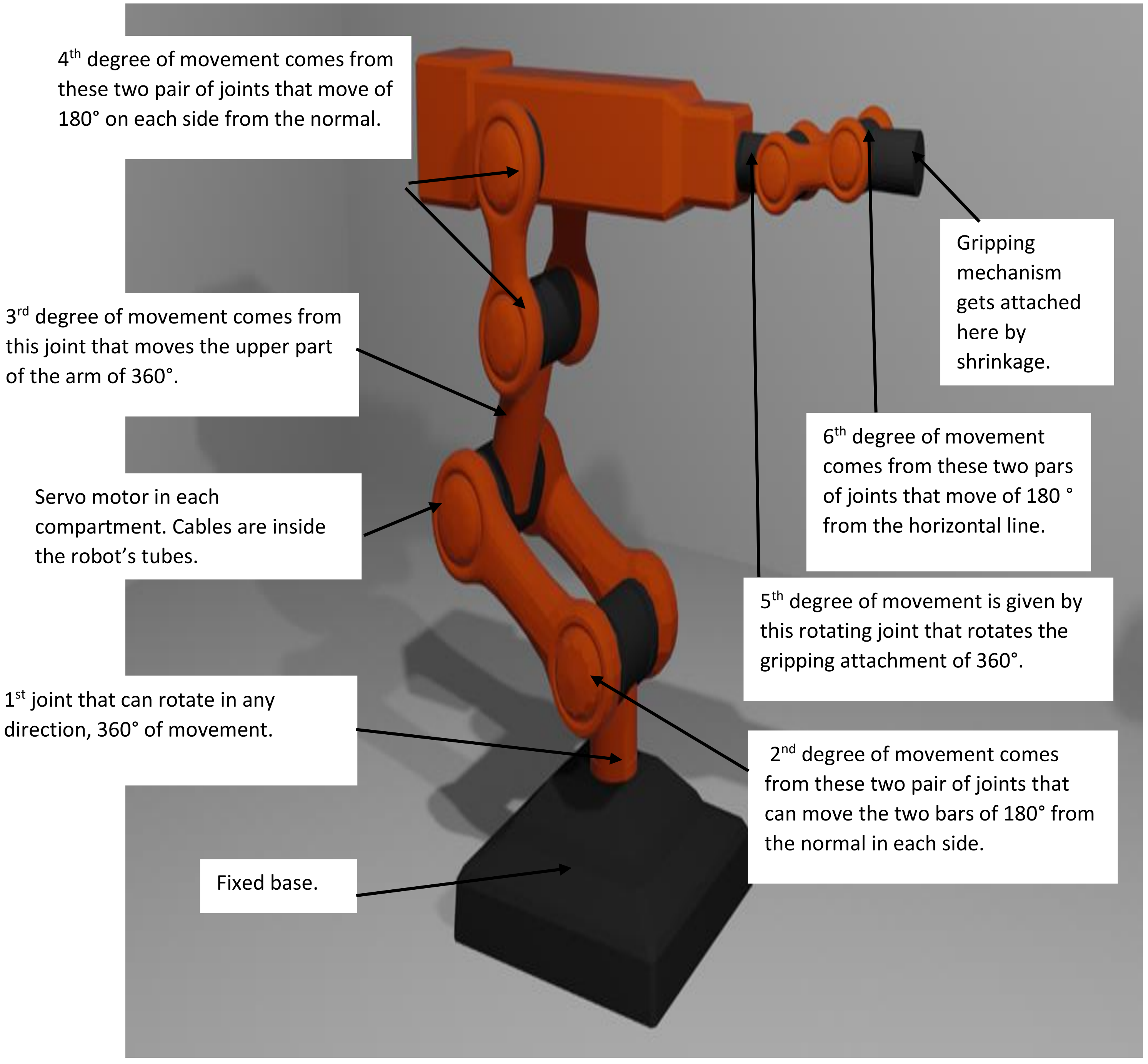


Figure 22

Kinematic and practicality explained:

- This system has 6 degrees of freedom.
- The system requires around 6 servo motors.
- Joints 1, 3 and 5 can rotate 360 degrees.
- Joints 2,4,6 can move 180 degrees in each direction.
- When the system has to grab an object from the stationary position shown in figure 22, joint 2 inclines of 90° clockwise and joint 4 of 45°clockwise. Joint 6, inclines of a few degrees to let the gripping system capture the 3D printed element.
- The gripping system is attached to the arm by shrinkage.
- The system curves when an object has to be picked and has three servo motors that control the movements.
- The motors are all located near the joints while the control board is at the bottom base.
- Joint 1 and 2 move left and right at an angle of 135°.
- The bottom joint, joint 3, can only rotate.

Advantages	**Disadvantages**
- Can rotate - Has 6 degrees of freedom. - Can move upwards, downwards, left, and right and at an angle. - Can reach any angle - As it is a long arm, it can reach any volume. - Every joint can rotate and move in the three axes. - Accurate movements. - Efficient and fast. - Can do hard operations. - Can easily adapt to changes. - Highly versatile. - Can provide the best-coordinated motion as it moves in multiple axes. - Tireless coordination. - The external body is cheap.	- Can be hard to control. - May need constant monitoring. - Can be hard to program. - The high number of motors. - Can consume a high amount of power.

Table 16

4.0 Rank Movement System

This sub-section targets how the arm attached to the gripper moves within the different levels of the rank both in the x and y - axis.

4.1 Belt driven linear actuators

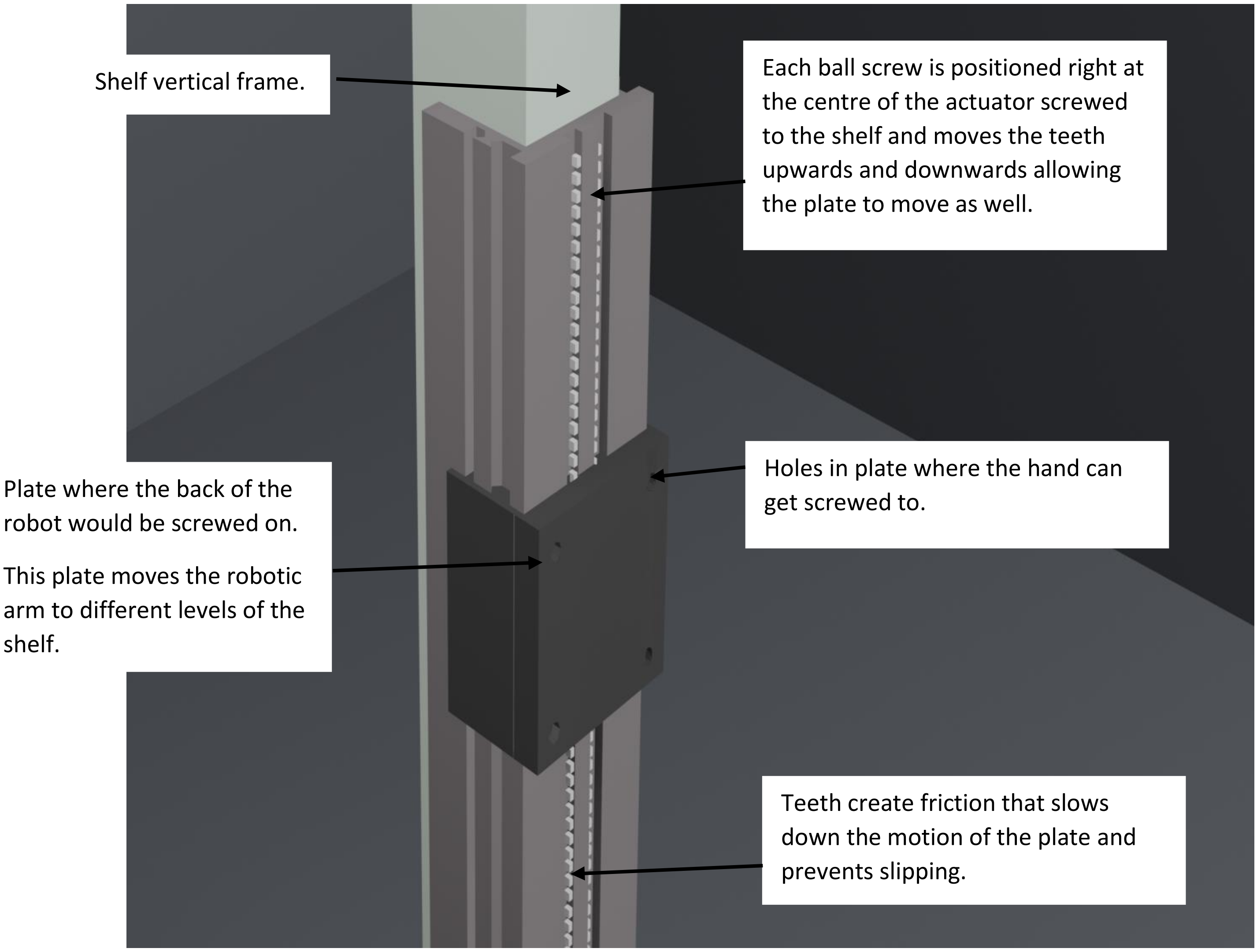


Figure 23

Kinematic and practicality explained:

- The belt-driven linear actuators are attached on the vertical sides of the rank, moving the system up and down. They work exactly like the linear actuators arm, by converting circular motion to linear motion.
- At the bottom of each vertical frame, a motor and gear would be attached so that the ball screw can push the plate up and down based on needs.
- The robot can reach the printers near the vertical frame of the rank based on their positions.
- It includes a plate with four wheels that slide up the shaft.
- The belt includes teeth that slide against the plate transferring torque.
- The belt is started with a stepper motor connected to a controller.
- The arm’s base, right side, is going to get connected to the plate with screws.
- The linear actuators belts are going to have to be mounted on all three vertical sides of the rank frame. The robotic hand with the plate will have to be moved manually to each one of them depending on the position of the 3D printed element. The grabbing mechanism will have to position the objects on a table at the side of the rack, to be able to pick the next 3d printed object up.

Advantages	**Disadvantages**
- Move the robotic system upwards and downwards the rank. - Teeth prevent sleeping of the object attached to the belt. - Can travel long lengths. - Can reach very high-speed saving time. - Can accelerate easily. - Highly efficient and reliable.	- Does not move horizontally. - May need lubrification - Is not self-sufficient. - Can be very expensive. - Speed decreases with time because of the tension within the belt. - Needs lots of maintenance. - The belt needs to be thicker to take a high load. - The belt can stretch out. - Travel accuracy with time diminishes. - Can struggle to carry a vertical load. - Needs periodic maintenance.

Table 17

4.2 Conveyable belt

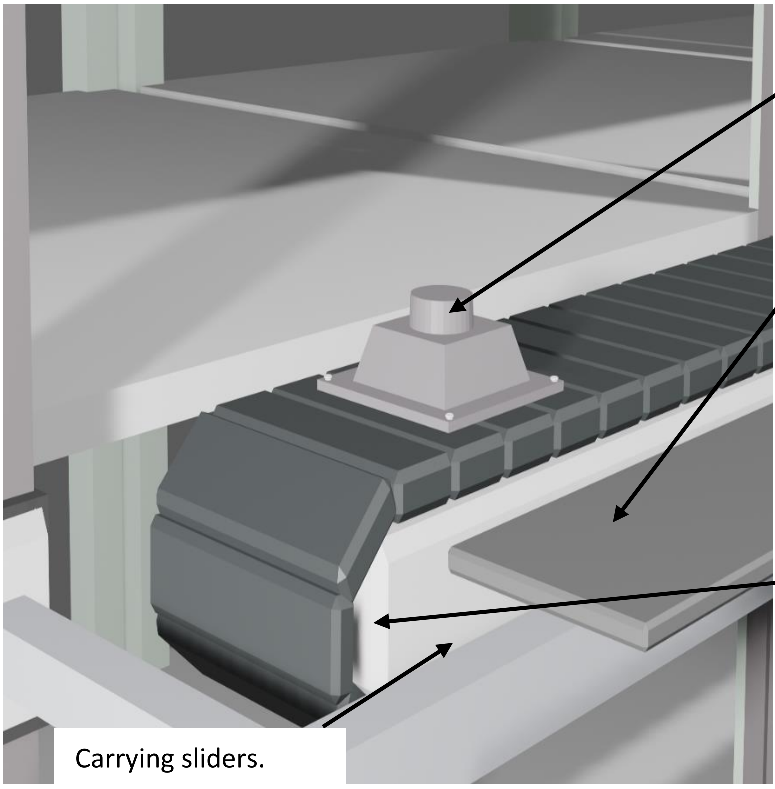


Figure 24

4 plates are attaching the conveyor belt to each vertical frame section of the linear actuator. These plates move at the same time, direction, and speed. This distributes the weight of the belt between the frames of the shelf.

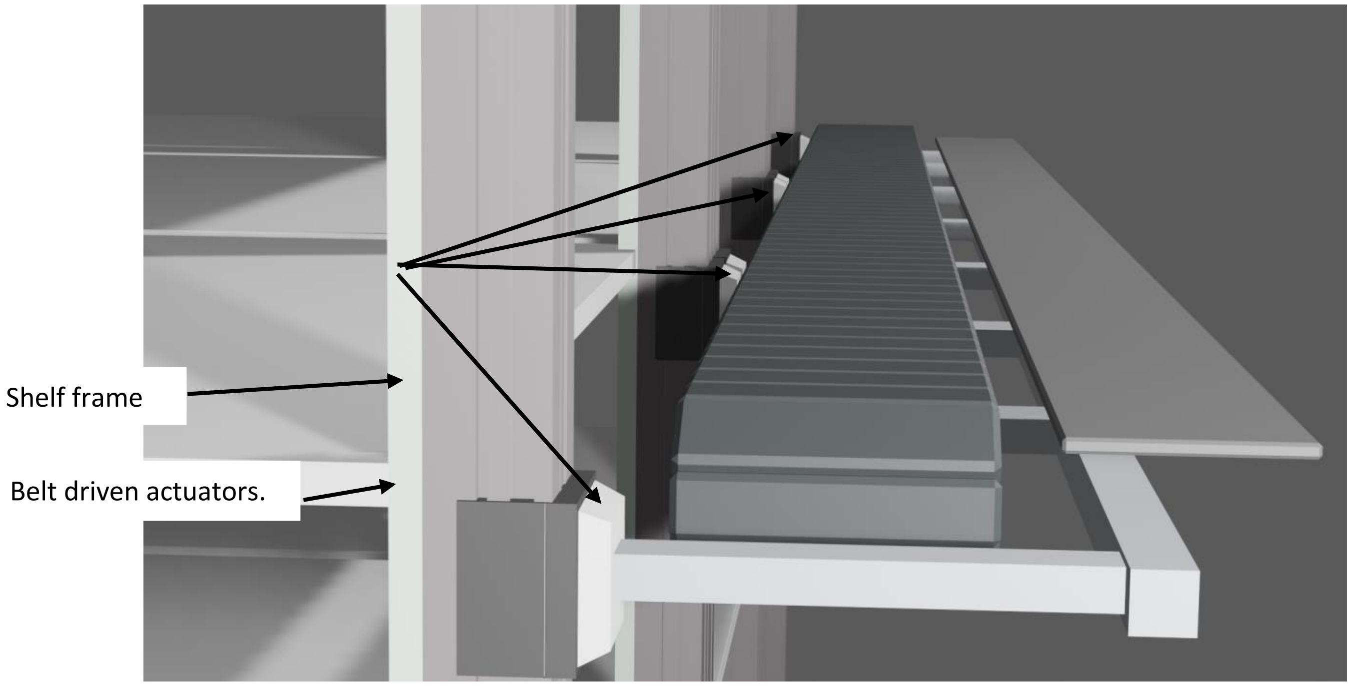


Figure 25

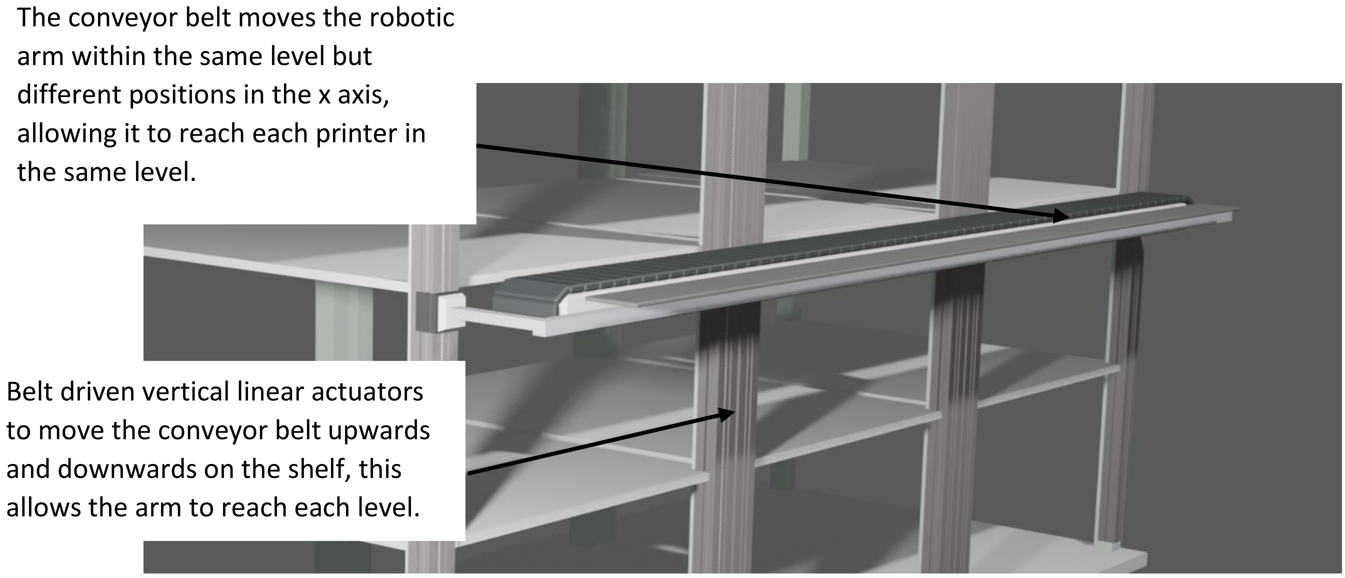


Figure 26

Kinematic and practicality explained:

- A horizontal conveyor belt moves the grabbing mechanism left and right and permits it to reach the needed print in the horizontal axes.
- The conveyor belt is attached to a linear actuator vertical mechanism that moves the conveyor belt upwards and downwards in case the grabbing mechanism needs to grab something from different levels.
- The body of the linear actuators are screwed on the rank and the rank is attached to the wall. This gives the conveyor belt extra support and permits the linear actuators to carry heavyweights.
- The weight of the conveyor belt is equally divided across the different vertical frames of the shelf thanks to horizontal supports attached to the linear actuator's plates.
- The rectangular shape near the belt was made to facilitate where the robot has to leave the 3D material before picking the next one..

Advantages	**Disadvantages**
- Can move the object left and right and up and down. - Permits system to reach any height and position. - The cheapest way to move a high number of objects over a long distance. - The conveyor belt won't ruin or drop the 3d printed objects because of the stability it has if the object gets dropped on the belt. - The belt can move left and right easily based on the object to grab. - The speed of the belt can be controlled.	- Belts tend to be difficult to clean. - Sticky materials can get stuck and damage the belt. - Has a high level of noise. - Can be costly to fix if it breaks down. - May need lubrication in the long term.

Table 18

4.3 Rack and pinion

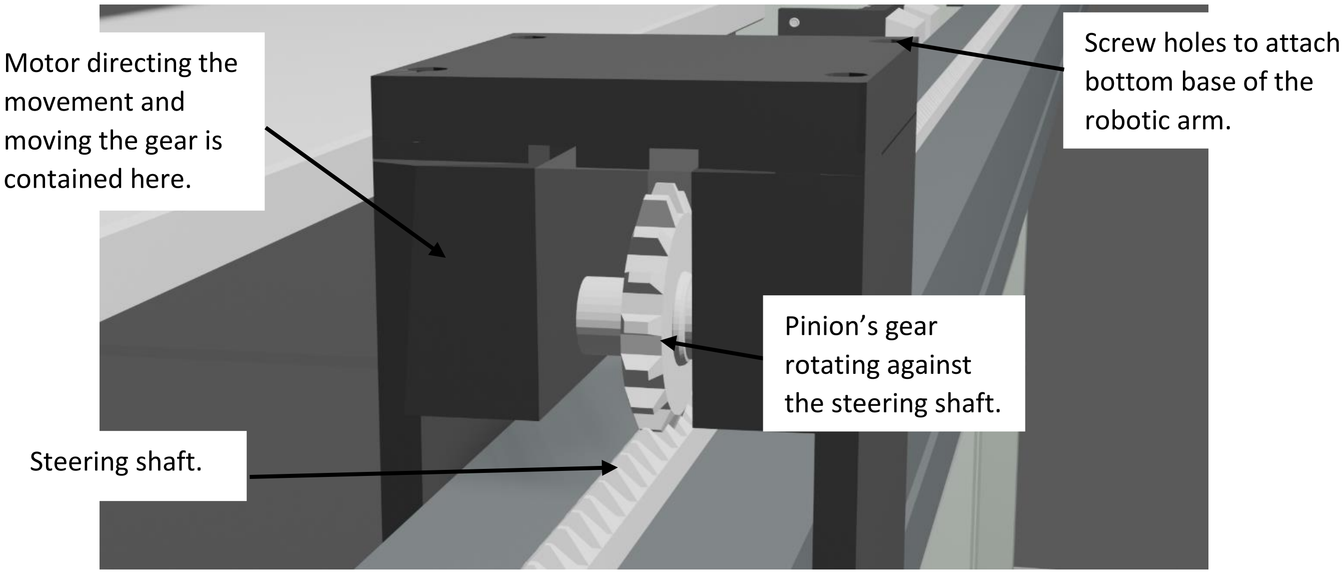


Figure 27

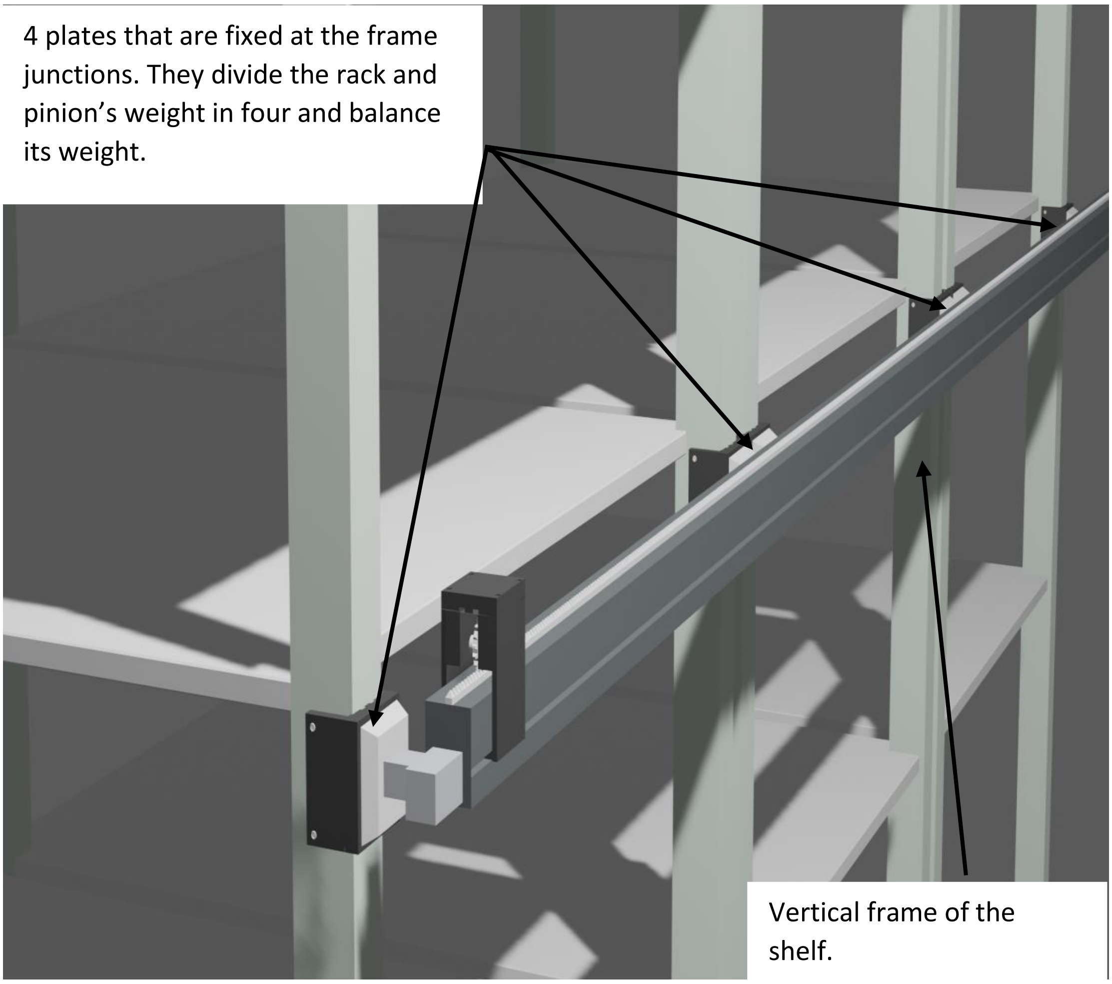

4 plates that are fixed at the frame junctions. They divide the rack and pinion’s weight in four and balance its weight.
Vertical frame of the shelf.

Figure 28

Kinematic and practicality explained:

- Rack and pinion is a linear actuator that moves a circular gear against a linear gear, and this converts circular motion to linear motion.
- The system cannot be built vertically because of its mechanism, which can't support the arm vertically, therefore the system must only exist horizontally.
- The pinion's gear moves against a steering shaft transforming circular motion to linear motion.
- The motor directing these movements is found inside the plate connected to the pinion's gear.
- The bottom of the robotic arm's base will be screwed to the plate and permit the robotic arm to move in between printers and reach the selected one.
- It is mounted similarly to figure 25. The plates are attached to the 4 vertical frames of the robot.
- The arm must go back to the bottom of the rack each time to leave the objects on a table at the side of the rack.

Advantages	**Disadvantages**
- Least expensive - More compact. - Easy to design and produce. - Robust. - Easy to control. - The system can move horizontally	- Malfunctioning gear can cause - Limited accuracy. - Needs constant lubrification to translate smoothly - Not as power efficient as other systems. - The system cannot move vertically. - High noise. - Slower than other systems. - A lot of the power produced is lost as friction. - May need to be replaced often because of the constant friction within the mechanism

Table 19

6. Concept selection

This section was created to choose a final concept through binary matrix dominance. To be able to objectively choose a design, the binary dominance matrix allows us to define the weighting of each criterion and rank them by importance.

Concept selection for the gripping mechanism

This sub-section identifies, by using a dominance binary matrix, which gripping mechanism would be more appropriate for the final embodiment design.

Here is a list of the objectives the final design must adhere to:

- Cost: The system should not exceed the limit of £300 with the other mechanical components attached.
- Operation and performance: The system can grip the 3d printed elements. It can grip different shapes and release them safely. It can grip them without damaging them. The system can pick up to 50g and object sizes up to 100x100x100mm.
- Compatibility: Can be used with a different range of arms and bases.
- Easy to manufacture: The system can be manufactured within the university facilities detailed in the specification. It can be produced easily and safely.
- Maintenance: The parts are easy to access. Electronic parts are easy to remove and change when needed. The components are easy to repair.
- Environment: The system is acceptable for the specified safety requirements.

Objective	a	b	c	d	e	f	Total	R
a Operation and performance	/	1	1	1	1	1	5	1
b Cost	0	/	1	1	1	1	4	2
c Compatibility	0	0	/	1	1	1	3	3
d Easy to manufacturer	0	0	0	/	0	1	1	5
e Maintenance	0	0	0	1	/	1	2	4
f Environment	0	0	0	0	0	/	o	6

Table 20

Objective	Ranks	Weight
Operation and performance	1	0.33
Cost	2	0.27
Compatibility	3	0.20
Maintenance	4	0.13
Easy to manufacture	5	0.07
Environment	6	0.00

Table 21

From this weighting table, we can see that operation and performance have the highest weighting, this ensures that the system does the role assigned.

The second most important part is the cost of the mechanism: if the gripping system chosen and attached to the other mechanical components exceeds the budget assigned, the design cannot be manufactured. Compatibility has a score in the same range as operation and performance as to be able to manufacture the gripping system, it must be compatible with a least one of the arm and rank movement systems. Maintenance and ease of manufacture are relevant but do not influence massively the outcome wanted. The environment is relevant but holds the last position on the weighing scale.

Design name	Design n°
Vertical gear mechanism	1
Horizontal gear mechanism	2
Gear mechanism with 8 claws	3
Rectangular shape	4
Circular shape	5
Robotic hand	6
Suction hand	7
Sticky suction hand	8
3 fingers spring system	9
Pegs spring system	10

Table 22

In the x-axis of Table 23, we can see the weighting of the objectives (W) and the concept designs corresponded numbers as illustrated in Table 22. In the y axis, the list of objectives based on the ranking is shown.

Objective	W	1	2	3	4	5	6	7	8	9	10
Operation and performance	**0.33**	**30%**	**60%**	**75%**	**50%**	**65%**	**60%**	**30%**	**40%**	**75%**	**50%**
Cost	**0.27**	**40%**	**60%**	**30%**	**75%**	**70%**	**75%**	**75%**	**75%**	**70%**	**75%**
Compatibility	**0.20**	**80%**	**80%**	**80%**	**75%**	**75%**	**75%**	**10%**	**10%**	**75%**	**70%**
Maintenance	**0.13**	**40%**	**60%**	**40%**	**30%**	**30%**	**70%**	**20%**	**20%**	**70%**	**70%**
Easy to manufacture	**0.07**	**40%**	**60%**	**50%**	**65%**	**65%**	**65%**	**75%**	**60%**	**75%**	**80%**
environment	**0.00**	**40%**	**40%**	**40%**	**40%**	**40%**	**100%**	**30%**	**30%**	**100%**	**100%**
total		**45%**	**40%**	**58%**	**60%**	**64%**	**69%**	**37%**	**42%**	**73%**	**65%**

Table 23

Discussion of results

The blueprint of design 1 has many segments that if broken, can be hard to replace. Because the brackets must be built as a whole, they can be hard to manufacture and pricy to replace. It also has a gear system that may need constant lubrication. It cannot easily grab a multitude of sizes and may struggle to grab oval shapes or shapes without a defined edge.

The gear can make a high amount of noise, which may be unpleasant for some people. It is, however, compatible with a high number of arms that can safely grab and release the printed object. Design 2 overall performance is quite similar to design 1, except that it has simply shaped claws, making it easier and cheaper to manufacture, as well as easier to replace compared to design 1. Because of the high number of claws, design 3 will be inclined to be the most expensive and is comparatively more difficult to replace. The score for design and operation, for concept 3, is one of the highest on the table, as it can safely grab the object with a tight grip and extra support, as the weight is balanced between many claws.

Designs 4 and 5 are simple, and this is shown in their cost. However, due to the shape, if they lose balance, they can easily drop and permanently damage the 3D printed machines. As electronic parts are sealed inside, they can be hard to fix and locate. Between the two, design 4 is the lightest but because design 5 has a margin, it has better operation and performance. With time, the heat generated from the motor can permanently damage the shapes and can be a possible fire hazard.

Design 6 is also simple to build. Nonetheless, because it uses 3 claws grabbing the object on different sides, the grip is overall, better. The only flaw with design 6 is that it can be hard to manufacture as the cables stay inside the fingers at its borders. It must grip the object from the bottom as well, and it can easily fail if the object is resisting or the bottom surface of the print is thin, giving it a lower performance score.

Design 7, because of the suction mechanism, will make a lot of noises and is not compatible with most arms. As it uses a suction mechanism, it may drop or break some printed elements or will not be able to grab some others because of their shape or weight. The electronic parts, both in designs 7 and 8, are inside the tube and consequently making it hard to reach during maintenance. Design 8, due to having glue on the intake port, is even more difficult to clean and fix.

Design 9 has an all in all high score, as the principal mechanism is similar to design 6, apart from the fact that, instead of grabbing the bottom of the object, it grabs from the top. As it does not make noises and it is easy to replace and clean, and because it uses a spring mechanism, both the maintenance and environment are extremely high in percentages. Therefore, design 9 has been chosen compared to the different concepts.

Design 10 is straightforward and ticks most requirements excluding its performance, as the shape and structure can damage the 3D printed objects and can struggle to pick up a variety of shapes.

Concept selection for arm mechanism

This sub-section discusses the designs for the arm mechanism that is meant to be the body of the system and must carry the weight of the gripping mechanism and the 3D printed object. It uses the same weighting criteria used for the gripping mechanism.

List of objectives:

- Cost: The system should not exceed the limit of £300 with the other mechanical components attached.
- Operation and performance: The system can rotate, move in the y, z, x-direction and be able to carry weight.
- Compatibility: Can be used with the selected gripping mechanism and for the role assigned.
- Easy to manufacture: The system can be manufactured within the university facilities specified in the specification. It can be produced easily and safely.
- Maintenance: parts are easy to access. Electronic parts are easy to remove and change when needed. The components are easy to repair.
- Environment: the system is adequate for the specified safety requirements.

Design name	Design n°
Fixed stand Telescopic arm	11
System with two telescopic arms	12
Suction arm	13
Hydraulic pump	14
Linear actuator	15
DOF	16

Table 24

In the x-axis of Table 25, we can see the weighting of the objectives (W) and the concept designs corresponded numbers as illustrated in Table 24. In the y axis, the list of objectives based on the ranking is shown.

Objective	Weight	11	12	13	14	15	16
a Operation and performance	0.33	50%	65%	30%	65%	40%	75%
b Cost	0.27	50%	40%	70%	75%	50%	80%
c Compatibility	0.20	80%	50%	0%	50%	70%	75%
d Maintenance	0.13	60%	40%	40%	45%	50%	50%
e Easy to manufacture	0.07	90%	70%	90%	70%	65%	50%
f Environment	0.00	80%	75%	60%	40%	70%	80%
Total		60%	52%	40%	62%	52%	71%

Table 25

Discussion of results:

In design 11, the telescopic arm can move only in the vertical direction even though it can rotate. It also struggles to hold the heaviest objects as the weight is not properly balanced. The mechanism slider and chains can produce a limited but negligible number of noises. It is, however, easy to manufacture and easy to design. Design 12 struggles with the same issues but can move in the y-direction as well, therefore the performance score is higher. However, as it uses two telescopic arms, maintenance can be tricker and the overall height is even less balanced when the telescopic vertical arm starts to expand. By using two telescopic arms, it makes lightly more noise compared to design 11, and therefore the environment score is lower.

Design 13 is cheap to produce as it is only a suction tube but cannot be used with the chosen grip and it is hard to control. It makes a higher amount of noise and therefore the environment score is low along with the maintenance score as electronics are not easily accessible and parts cannot be changed easily. Design 14 cannot rotate, and this influences his performance skills, it also cannot expand much in any other direction and is not that compatible with the gripping spring mechanism. However, it is easy to manufacture. The liquids can be toxic and damage irreversibly the machine or the 3D prints if leaked and this gives it low maintenance and environmental score.

Linear actuators tend to be very expensive, and the system can only move in the y axis, therefore design 15 tends to have these low scores for cost and operation. However, it is compatible with the gripping system. Using two linear actuators makes it harder to fix. On the other hand, the electrical parts are easily accessible. It is not easy to manufacture.

DOF robots can move in nearly every direction and are easy to design but tricky to control, therefore, design 16 has a performance score of 75%. The arm mechanism system is compatible with the gripping system, but it can need more maintenance considering how many parts it has. Because of the higher number of parts, it is harder to manufacture as well. The DOF robot has obtained the highest percentage and therefore will be carried on in the final design.

Concept selection for Rank Movement System.

This last subsection for the concept selection uses the binary dominance matrix to find a system able to move between different levels and in the horizontal frame while holding the weight of the 3D printed elements and the arm attached to the gripping system.

List of objectives:

- Cost: The system should not exceed the limit of £300 with the other mechanical components attached.
- Operation and performance: The base mechanism must be able to move the robotic hand within the shield fast both in the y and x-direction.

- Compatibility: Can be used with the chosen arm and hand.
- Easy to manufacture: The system can be manufactured within the university facilities specified in the specification. It can be produced easily and safely.
- Maintenance: parts are easy to access. Electronic parts are easy to remove and change when needed. The components are easy to repair.
- Environment: the system is adequate for the specified safety requirements.

Design name	**Design n°**
Belt driven linear actuators	17
Conveyable belt	18
Rack and pinion	19

Table 26

In the x-axis of Table 27, we can see the weighting of the objectives (W) and the concept designs corresponded numbers as illustrated in Table 26. In the y axis, the list of objectives based on the ranking is shown.

Objective	**Weight**	**17**	**18**	**19**
a Operation and performance	**0.33**	**35%**	**95%**	**35%**
b Cost	**0.27**	**70%**	**40%**	**75%**
c Compatibility	**0.20**	**100%**	**100%**	**100%**
d Maintenance	**0.13**	**75%**	**60%**	**75%**
e Easy to manufacture	**0.07**	**70%**	**60%**	**80%**
f environment	**0.00**	**70%**	**40%**	**70%**
total		**65%**	**74%**	**67%**

Table 27

Discussion of results:

Design 17 and 19 are easier to manufacture and cheaper than design 18 as they do not use a combination of mechanisms. However, both designs, unlike design 18, can only move in the x-direction and cannot move the robotic arm on different levels, therefore they both have low-performance scores. Design 19 is the cheapest and easiest design to manufacture, however, design 18 can easily hold the weights of both robotic system and 3d printed machine and has an attached compartment to hold the objects, its weight is also more distributed. Design 18 is also the loudest system and therefore has the lowest percentage in the environment.

Design 18, with a percentage score of 74%, has the highest score and therefore it will be assembled with the other pieces.

7. Final Concept

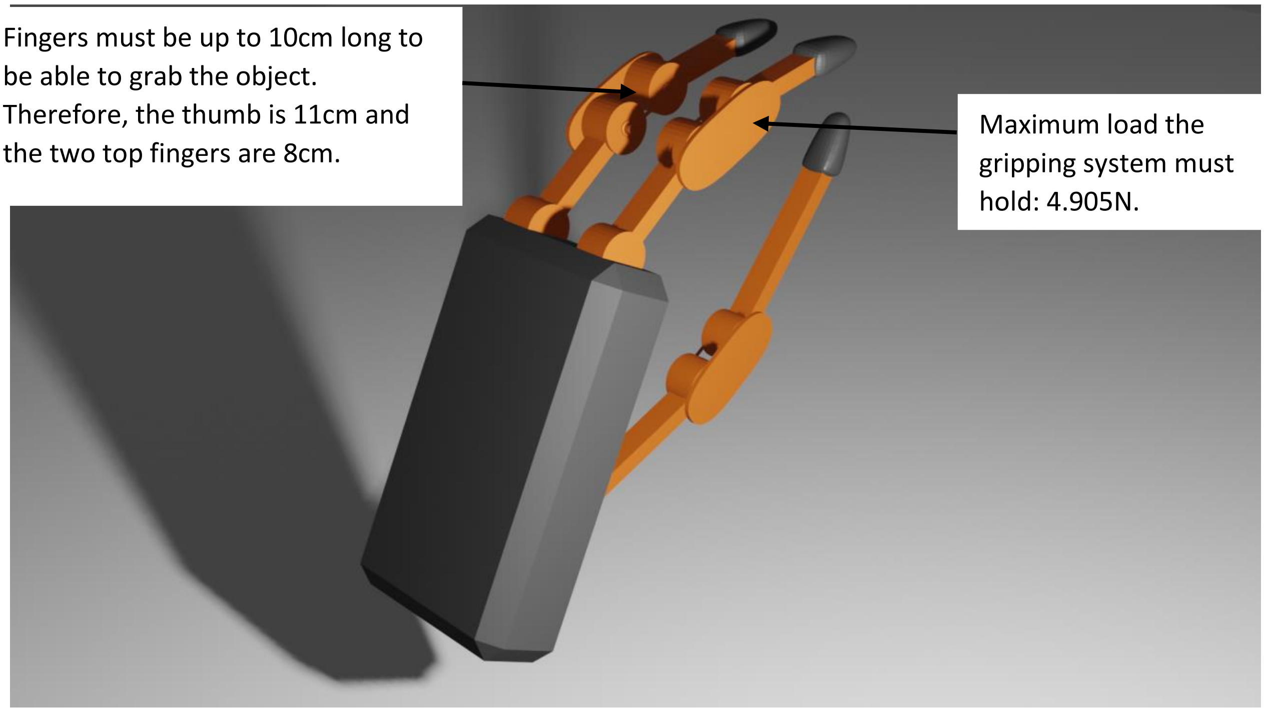


Figure 29

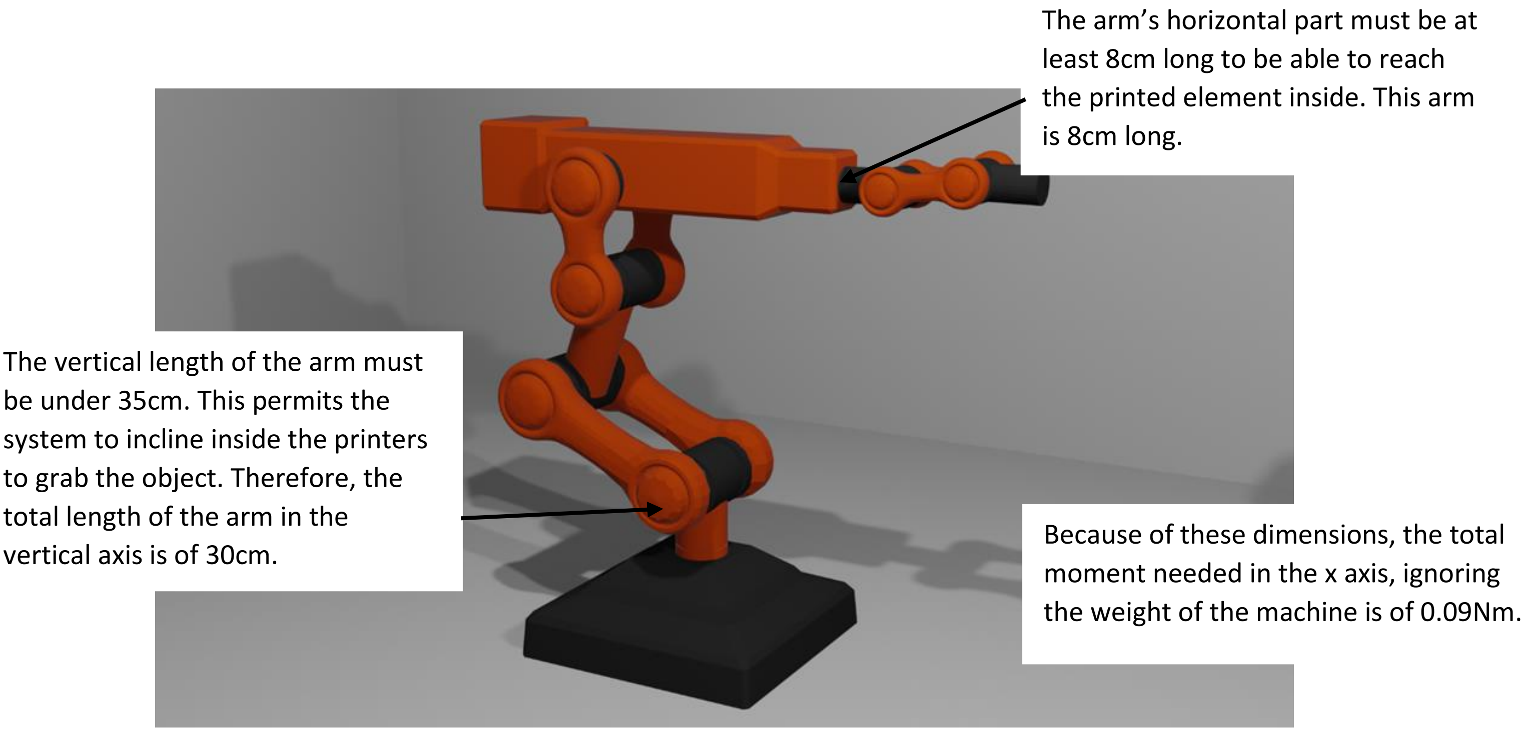


Figure 30

The annotations show us that the system needs to be able to produce a force of up to 4.9N and need a torque of 0.095Nm to be able to rotate its body while holding the object.

Because the system must grab at least 1 object per minute and move it somewhere safe before grabbing the next one, we can deduce that in the worst-case scenario, the distance it must travel is 12 meters. It should at least have a velocity of 0.2 m/s.

And therefore, have at least acceleration of 0.003 m/s². The chosen motors must satisfy these requirements to let the system function properly.

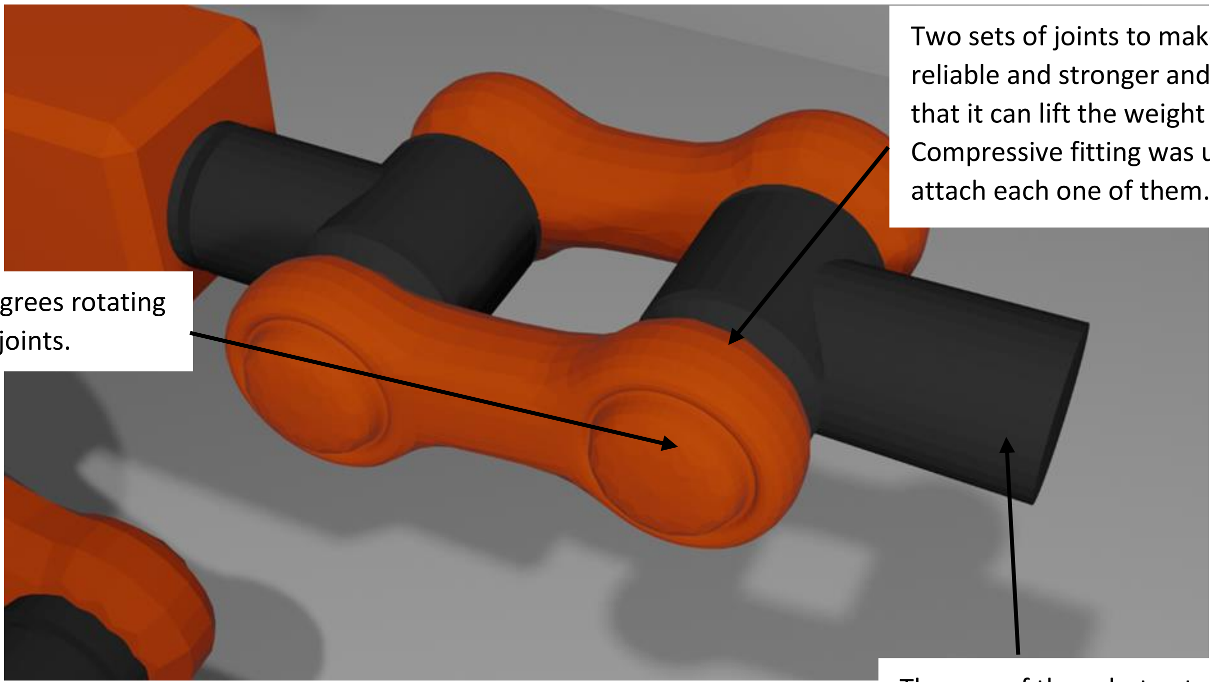


Figure 31

Figure 32

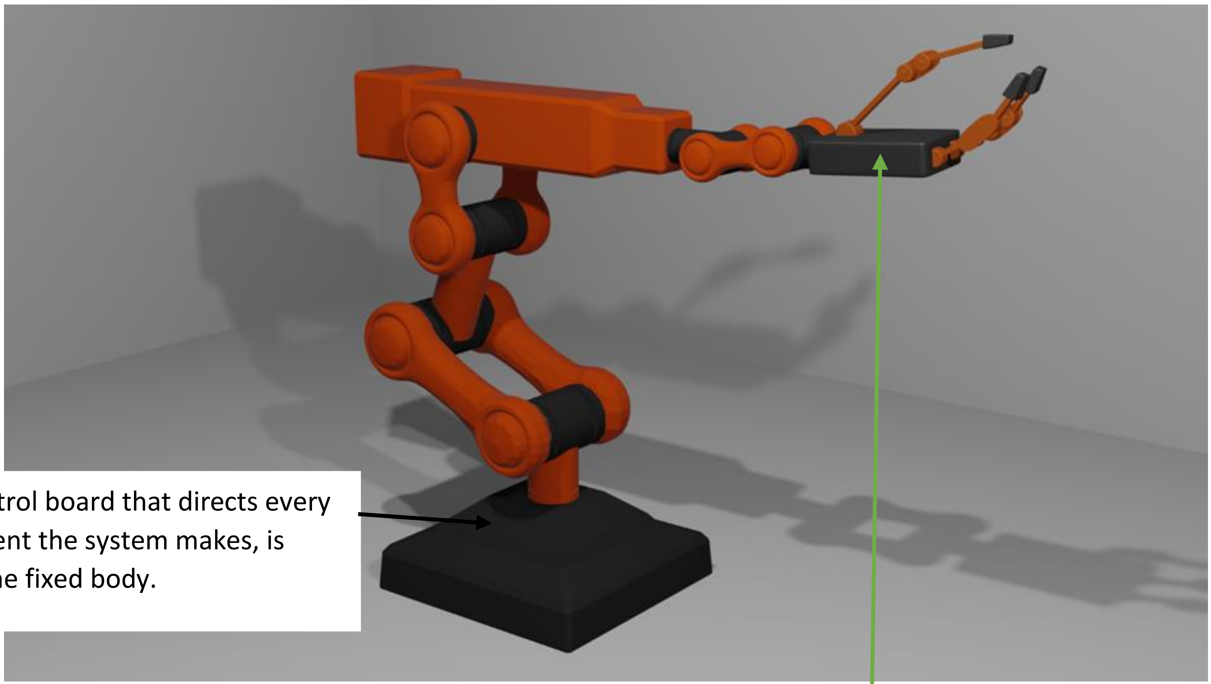


Figure 33

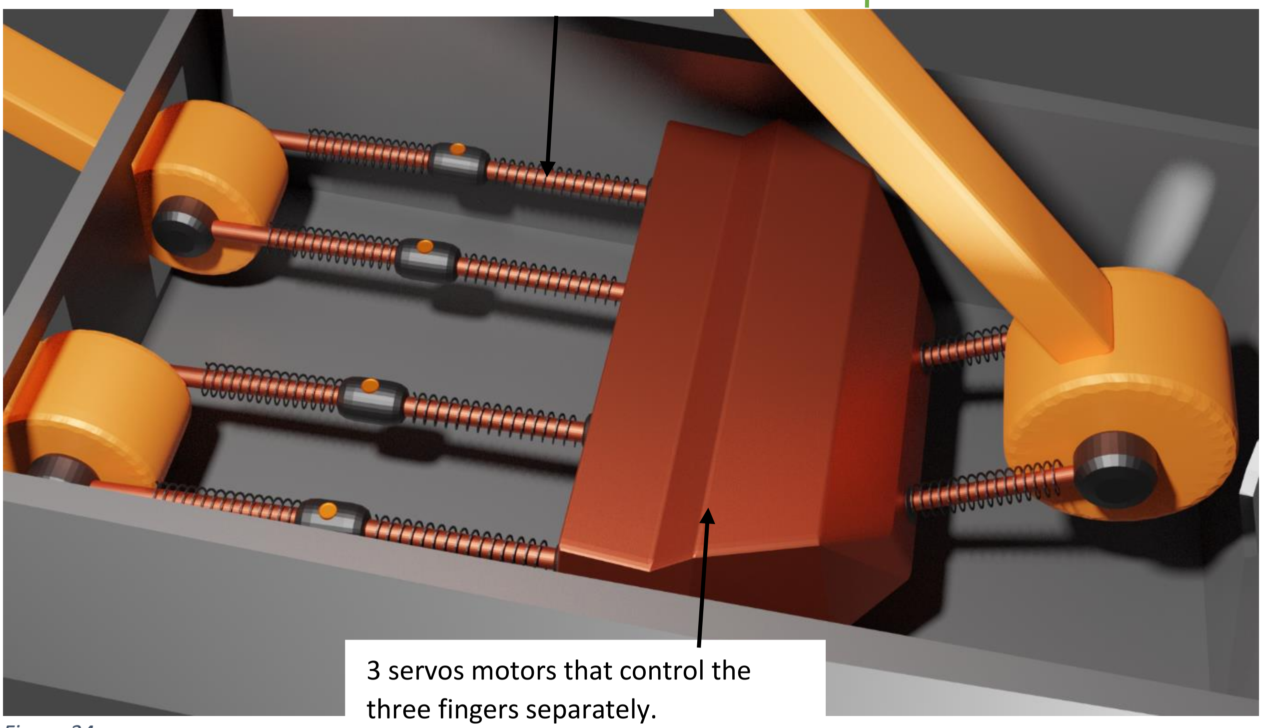


Figure 34

The 3 servos motors are each attached to a gear mechanism that moves the spring filaments allowing each finger to move separately. The control board that directs each movement is found at the base of the robotic arm.

This image shows how the system with the conveyor belt and the linear actuators works. This system must be attached and screwed to the vertical frames of the rank.

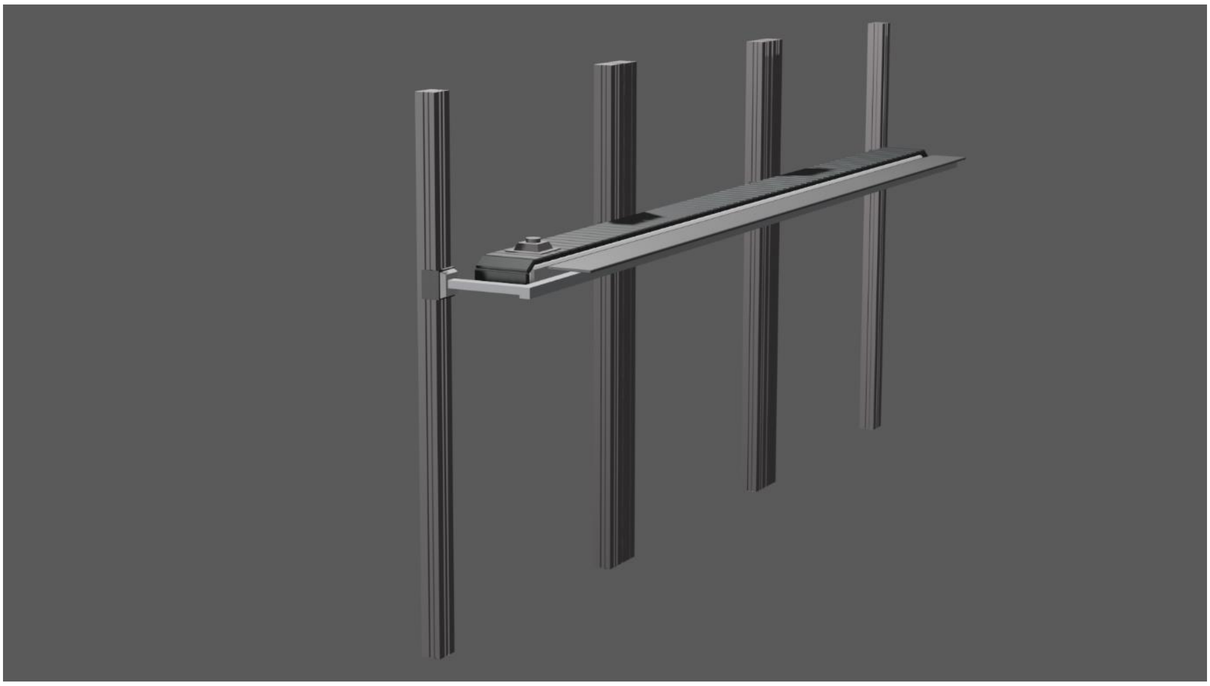


Figure 35

The arm base gets attached and screwed on here. Once attached, the top of the plate, as it is also attached to the conveyor belt, acts as battery for the robotic arm.

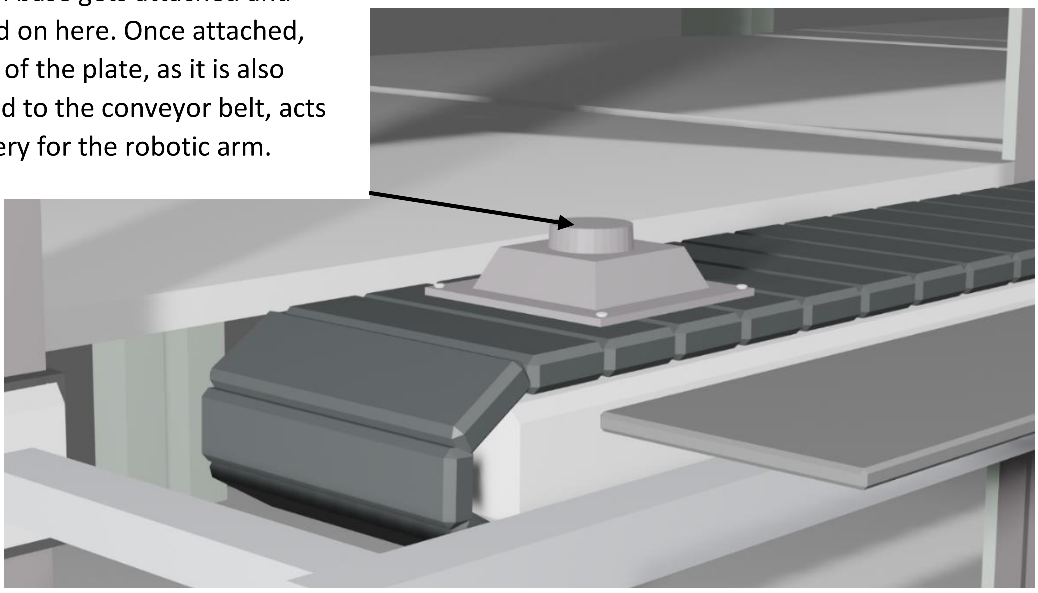


Figure 36

The final concept assembled:

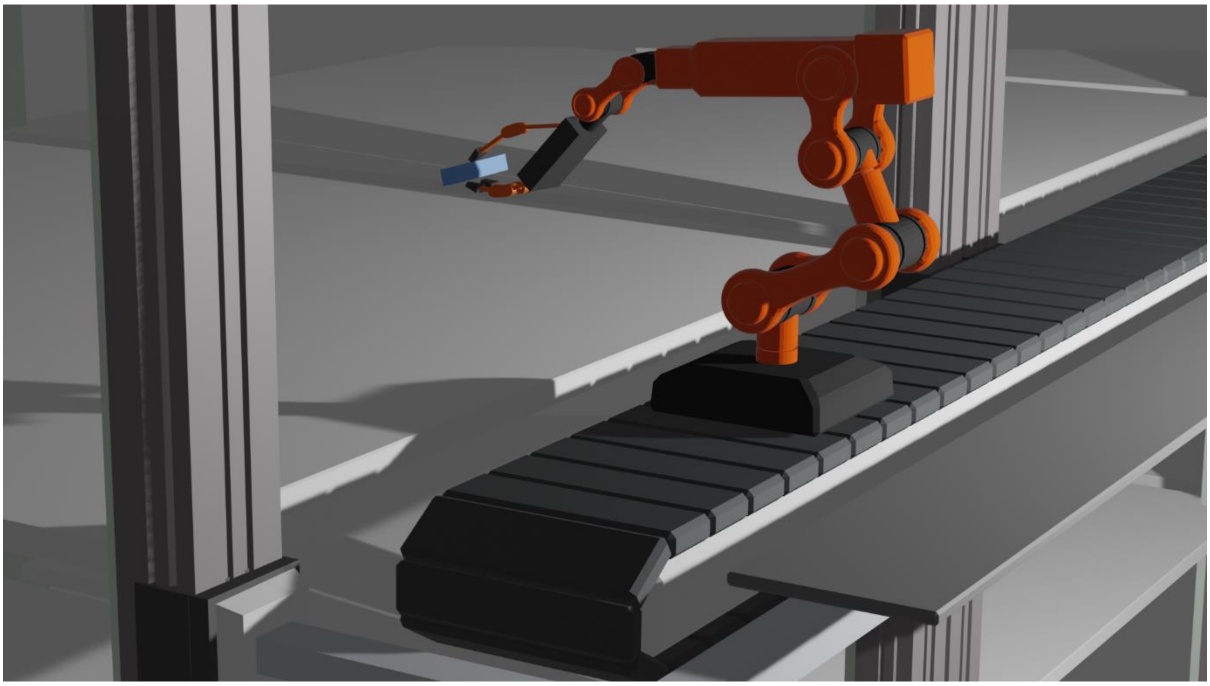


Figure 37

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