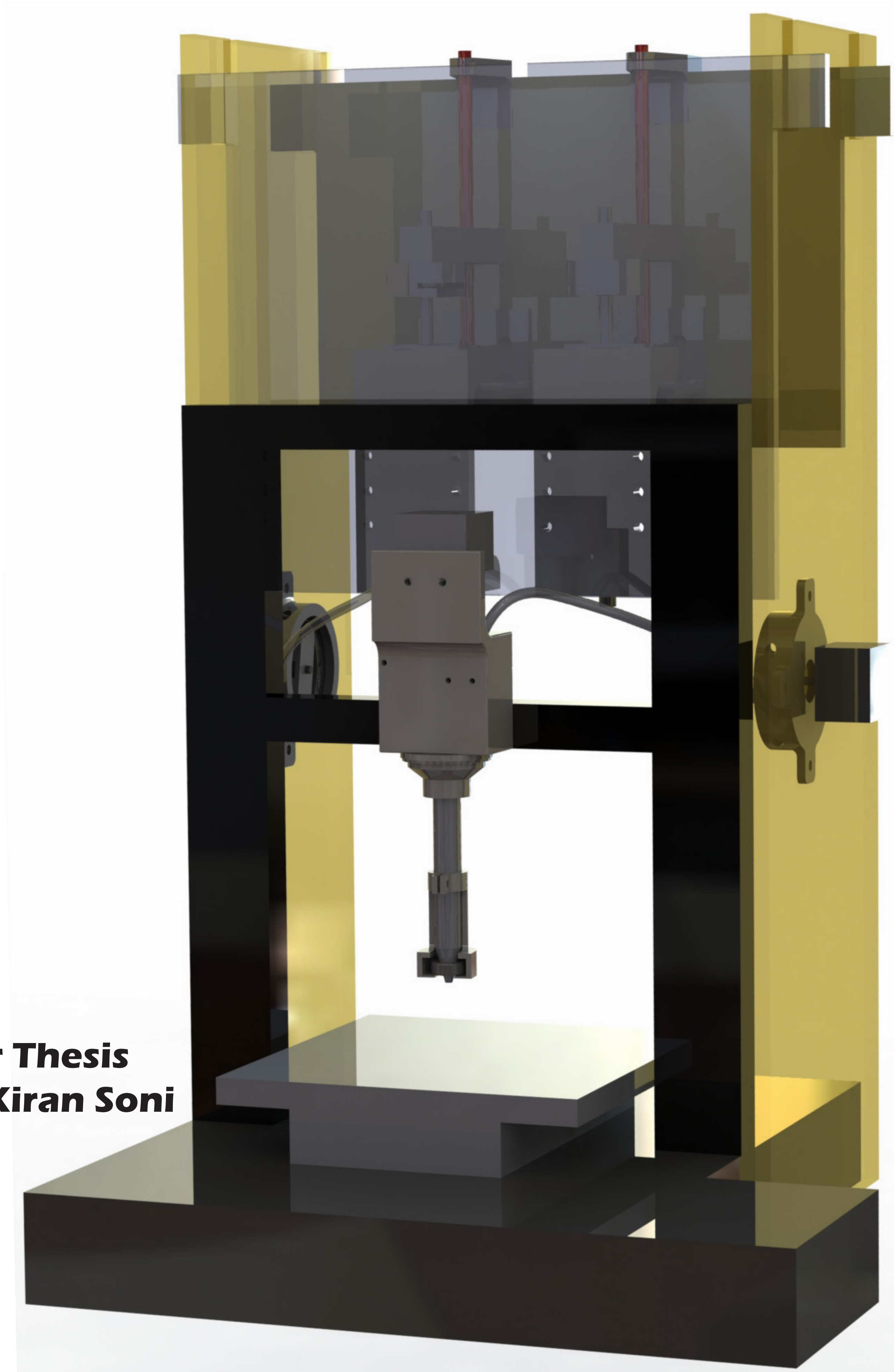
4D PRINTED SOFT MAGNETIC MEMORY MATERIALS: EXPLORATION AND DESIGN



Master Thesis

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Master’s Thesis

4D Printed Soft Magnetic Memory Materials: Exploration and Design

by

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Acknowledgement

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1. Introduction

Magnetic shape memory materials are special types of materials that can change their shape in the presence of a magnetic field, this happens because of how the incorporated magnetic micro or nano particles arrange themselves.

Magnetic shape memory materials have many exciting applications, especially in the fields of robotics and devices that move or change shape. They can be used to create smart devices that can move in a controlled way, like small robots or machines used in medical procedures. These materials are also useful for sensing and responding to changes in their environment.

This project has already seen development at the TU Delft in the Department of Industrial Design Engineering in the form of the 2 graduation projects of Sanne van Vilsteren (Sanne, 2021) and Kevin van der Lans (Kevin, 2022). Both projects focused a lot more on the development of the magnetic ink and researching its different properties and variations to come up with a reliable formulation that could work best as ink to 4D print with. Their projects had used another 4D printing setup (Figure 1) that was based off an Ultimaker S3 3D printer and used piston pressure to facilitate the extrusion. They designed a 4D printing solution which had the extrusion system mounted externally from the printer and the ink would be piped onto the nozzle which was placed on the extrusion system gantry of the 3D printer. They also experimented with having an electromagnet replace the current permanent magnet, placed at the end of the extrusion system, as this would allow for more efficient printing. This general structure of the 4D printer was also replicated in this project.

In this project, the development of the 4D printer setup was overhauled from the previous setup and redesigned to improve upon the various shortcomings of the previous set up. The ink was also experimented with to some extent, testing parameters such as its viscosity and reaction to external magnetic fields. The difference caused by different proportions of the two-part silicone as well as the difference caused by different concentrations of the microparticles on to the viscosity of the ink pastes was

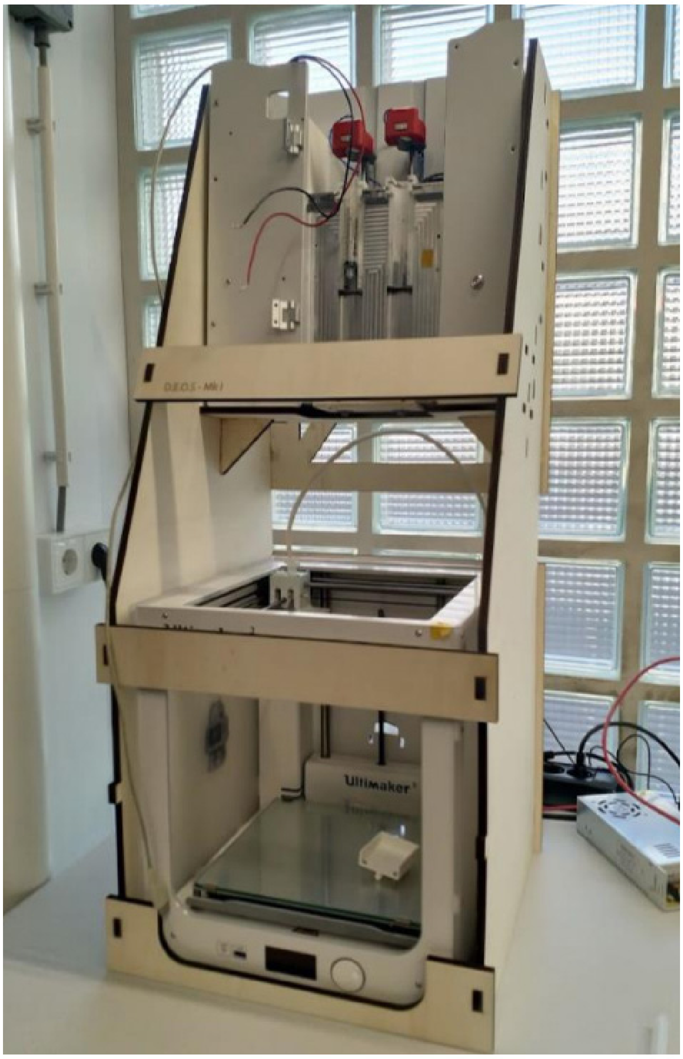


Figure 1. Setup used in the graduation project of Sanne van Vilsteren and Kevin van der Lans (Kevin, 2022)

observed. In addition to this, multiple concepts were ideated, and designed through, to create a set of demonstrators in various fields such as haptics, biomimicry and simple mechanisms to show the various functionalities that can be achieved by this printer. All these demonstrators were designed to make the best use of the shape memory properties and magnet sensitivity of the ink when they have been incorporated in a resin, which cures to a soft material making the titled soft magnetic memory materials.

1.1. Design Challenge

The design challenge faced by this project is relatively straightforward. The idea was to come up with solutions using magnetic soft shape memory materials in any field. These include diverse fields like haptics gaming, everyday objects, actuators, art installations and aesthetic design solutions.

The core of the project revolves around utilizing magnetic memory materials in a manner that effectively showcases their unique capabilities. However, a significant consideration is the constraint imposed by the 4D printer's capabilities, which would limit the production of prototypes using these materials. Therefore, it's essential to design products that are compatible with the 4D printing setup to ensure successful fabrication.

1.2. Problem Definition

The project has two main objectives. Firstly, it aims to create a functional setup capable of 4D printing a two-part epoxy that can be magnetized selectively to achieve the desired shape morphing effects. Previous attempts, such as Kevin van der Lans' graduation project, faced challenges in material extrusion and magnetization, resulting in an incomplete working system. To overcome these issues, the system will be redesigned to reduce flow resistance.
The second part of the project focuses on developing a product service system that utilizes these magnetic shape morphing materials. The goal is to explore various applications and demonstrate the potential and ease of incorporating these materials into everyday products. Since this technology is still in its early stages, the emphasis will be on haptics-based applications, which involve tactile sensations such as texture, touch, and movement. While Kevin van der Lans previously developed a concept in this area in 2022, a fresh approach will be taken to create a functional application that combines both domains.

1.3. Approach (methodology)

This section describes the methodology employed in the project for developing the printer and demonstrating its capabilities through various concepts. It also addresses the different approaches required for printer development and material aspects to achieve their respective goals.

1.3.1. Printer Development:

The project utilized a modified Ender 3 V2 printer for manufacturing complex geometries using a two-part silicone incorporated with magnetic materials. The previous project setup was replicated, with the addition of a piston extrusion system. Changes included using larger pistons within a completely enclosed holder and a mixing nozzle with a larger diameter and reduced flow resistance. The mixing nozzle was dynamically powered by an external motor, improving material mixing control and flow. The system was tested, iterated upon, and further improved by implementing a peristaltic pump in conjunction with the piston extrusion for more controlled and dependable material flow.

1.3.2. Demonstrator Development:

The project aimed to develop various demonstrators that accurately depicted the range of applications achievable with magnetic memory materials. Multiple rounds of ideation were conducted, drawing inspiration from previous graduation projects. Exploration across different domains was undertaken to ideate potential solutions and compare them to determine the best applications achievable using soft magnetic memory materials. Literature review and individual ideation sessions contributed to the development of multiple ideas, which were combined and refined to create a set of potential demonstrators. These ideas and concepts were then compared against a list of requirements to identify the most suitable demonstrators.

By following this methodology, the project aimed to advance the printer's capabilities and effectively demonstrate its potential through a range of concept demonstrators. The iterative approach to printer development and the thoughtful ideation and refinement process for demonstrator development ensured the project's objectives were met.

2. Literature Review

Shape memory materials (SMMs) are a unique class of materials that possess the ability to “remember” their original shape and recover it after being deformed. This unique property is due to the presence of a reversible phase transformation that occurs in these materials when they are subjected to external stimuli such as temperature, stress, or magnetic fields.

The discovery of SMMs dates back to the 1960s, and since then, they have attracted significant interest from researchers across various fields such as material science, engineering, physics, and chemistry, among others. SMMs find widespread applications in various fields such as biomedical engineering, aerospace, automotive, and robotics, among others, owing to their unique shape memory behavior and other favorable properties such as high strength, corrosion resistance, and biocompatibility.

This literature survey aims to create a review on the various possible applications for shape memory materials, the domains of its applications, the various actuations possible by various geometries, and the impact of different printing parameters to better define the optimum working parameters for a magnetic shape memory material creation setup.

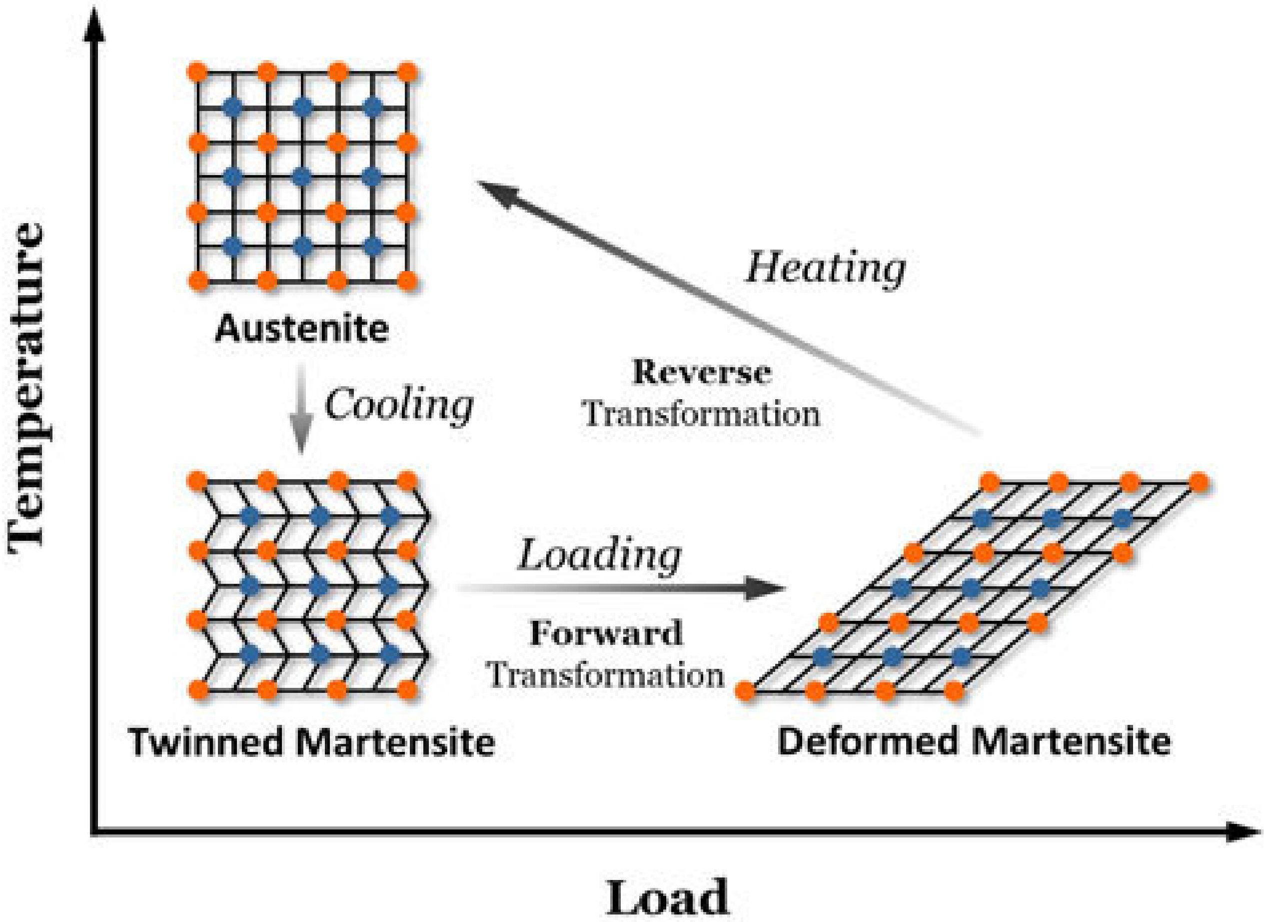


Figure 2. Transformation between phases observed in shape memory alloys subjected to stress and temperature changes (Chu et al., 2012)

2.1. Types of shape memory materials

2.1.1. Shape Memory Alloys

Shape memory alloys have been one of the earliest found materials that display a shape memory effect (Huang et al., 2010). These are metallic materials that are able to deform when subjected to external stimuli like temperature, electricity, magnetism. This actuation to external stimuli is facilitated by a phase change in the grains of an alloy (see Figure 2), the material changes phase between twinned martensite and austenite. The most popular of them has been NiTinol (Funakubo & Kennedy, 1987) created in the Naval Ordnance Laboratories, USA, at the same time there are other Cu-based and Fe-based materials that have been developed.

SMAs are generally made to be thermo-responsive/electro-responsive, but there are some that are created with magneto-responsive natures(Karaca et al., 2009).

The shape memory effect of SMAs arises from their ability to undergo a reversible phase transformation between austenite and martensite phases. The transformation occurs due to a temperature-induced change in crystal structure, and it can be triggered by either heating or cooling the material. This phase transformation leads to a significant change in the material's mechanical properties, such as its stiffness, strength, and ductility (Constanza & Tata, 2020).

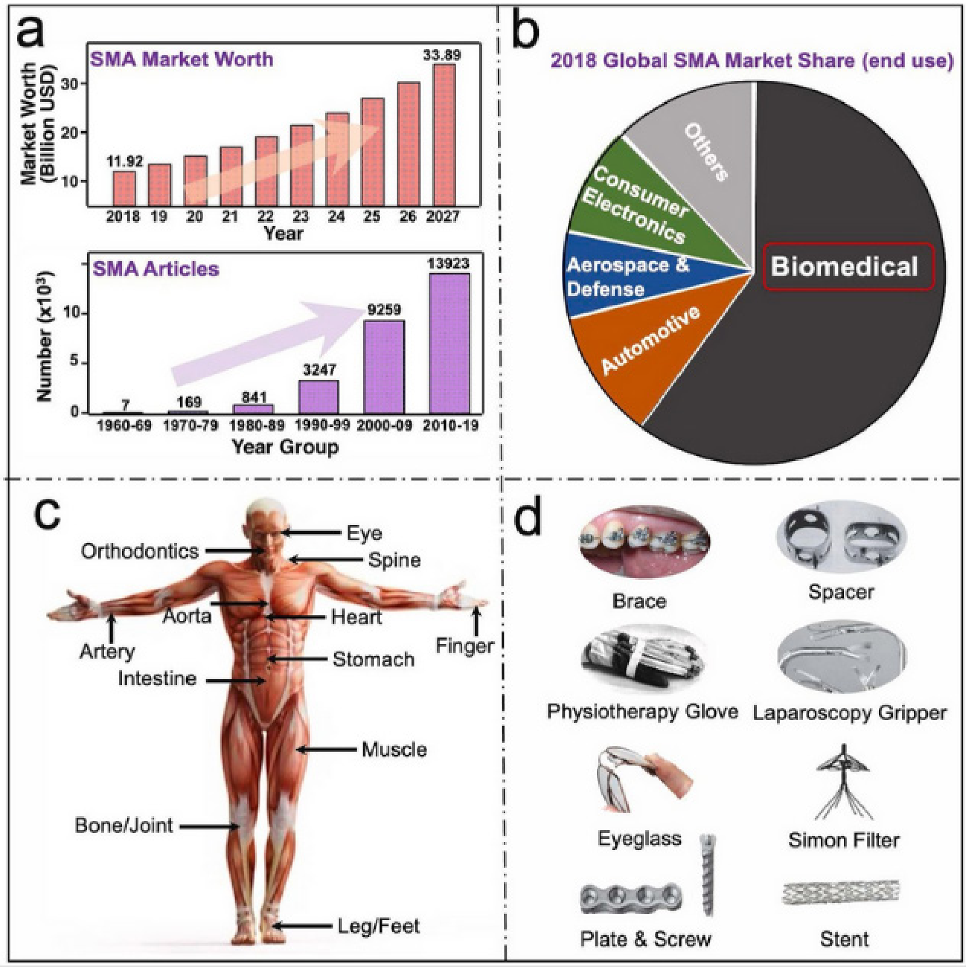


Figure 3. The market and applications of shape memory alloys (SMAs) in the biomedical area. (a) SMA global market forecast from 2018 to 2027, and numbers of SMA research articles from 1960 to 2019. (b) 2018 global SMA market share according to the application. (c) SMA biomedical applications in the human body. (d) Examples of SMA-based biomedical devices (Wang et al., 2021)

2.1.2. Shape Memory Polymers

Shape Memory Polymers are polymeric materials that are able to change their shape when subjected to various stimuli. Pure polymers as well as polymer solutions or colloids can be created with various additives to achieve the desired result (Mather et al., 2009). The most common stimuli for SMPs include temperature, electricity, magnetism, humidity and light. (Khalid et al., 2022) There are many polymer bases that are commonly used to create SMPs like Polyurethane, PDMS, PLA, and silicones. The additives used are also able to impart sensitivity to various stimuli or change the nature of the polymers to react to stimuli, such as, using CNTs to impart electrosensitivity, ferromagnetic particles to impart magneto-sensitivity and various chemical additives to impart photo-sensitivity and chemo-sensitivity. Shape memory polymers have found use in various applications, including minimally invasive surgery, where they can be used to insert medical devices in a compact, temporary shape through a small incision. However, the challenge with using shape memory polymers in biological environments is the need for an energy source to activate the shape transition. Current concepts involve the use of highly

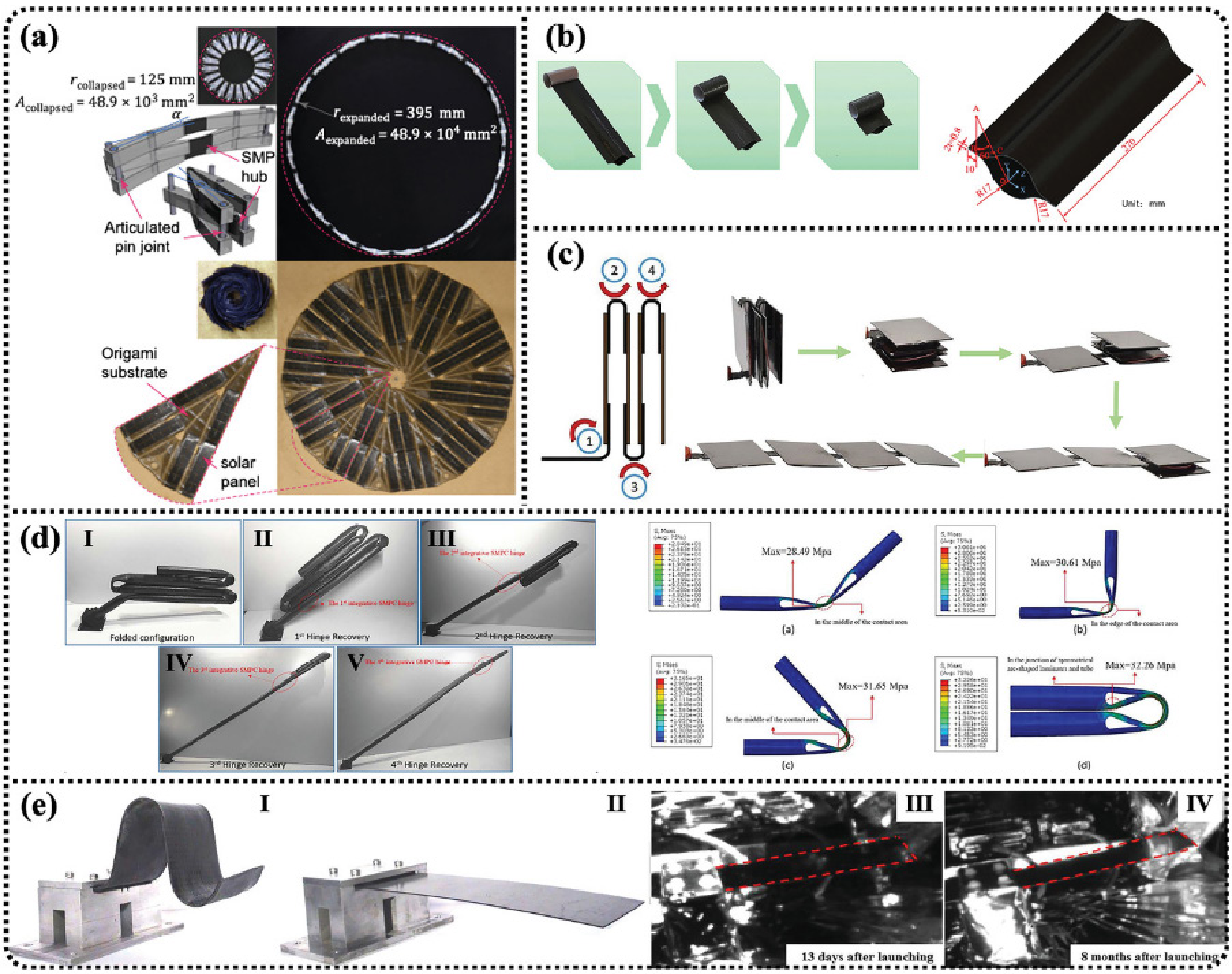


Figure 4. a) A fabricated specimen of scissor mechanisms and of origami substrate in both collapsed and expanded configurations, showing tentimes change in area. b) Model and dimension of the lenticular collapsible composite tube.c) Deployable solar panel array for a satellite with step recovery under near infrared (NIR) irradiation.d) Multiple-shape recovery behavior of the self-deployable structure and von Mises stress distribution bent with different angles. e) The configuration of Mission SMS-I (Yuliang et al., 2021)

dielectric susceptible components like carbon nanotubes or liquid crystalline phases to induce a shape transition by the application of electric or magnetic energy. The lack of biocompatibility and the need for direct contact with electrodes restricts the use of these systems in biological environments (Schmidt, 2006).

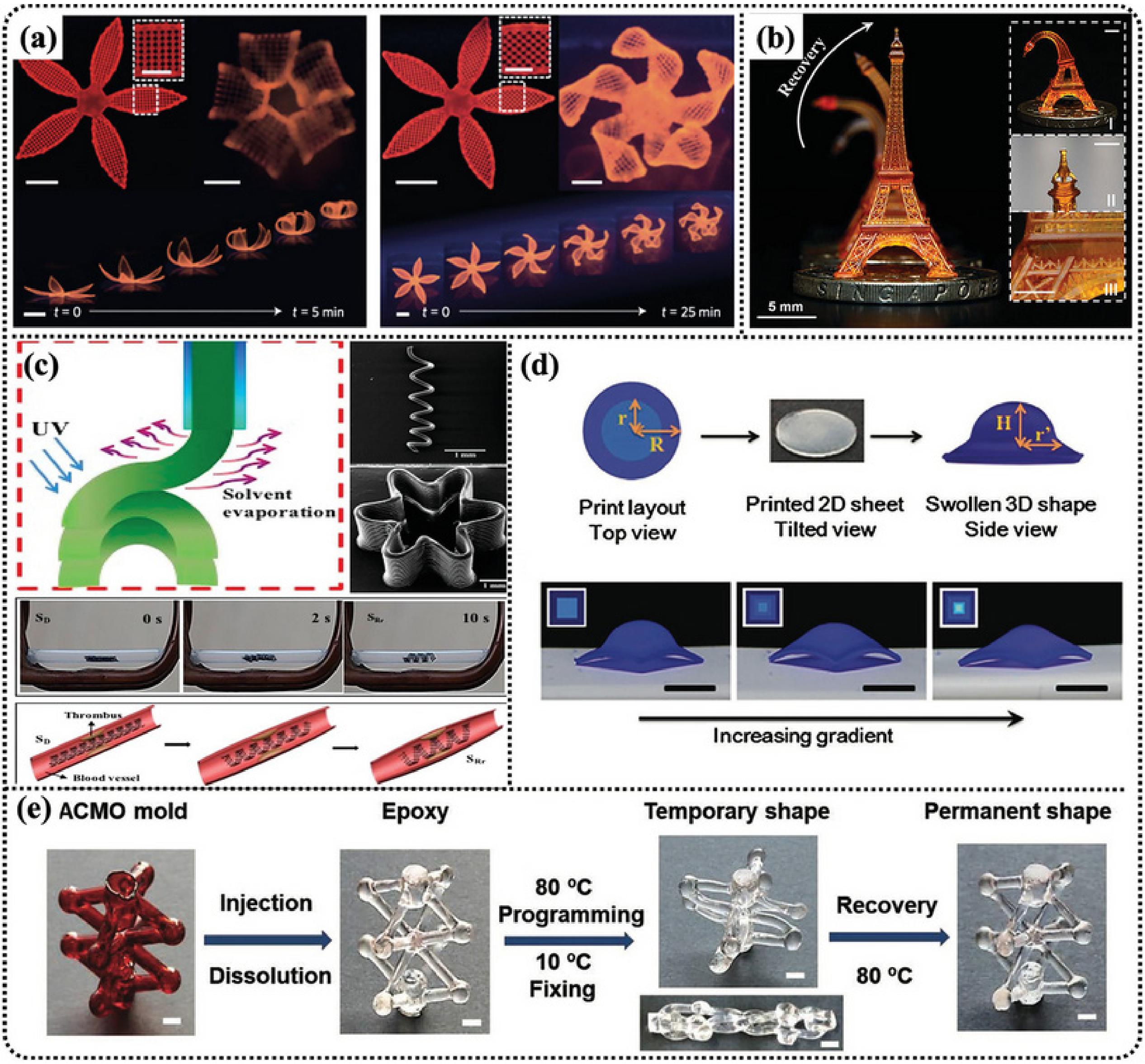


Figure 5. a) Complex flower morphologies generated by biomimetic 4D printing. b) 4D-printed shape memory Eiffel tower. c) Schematic illustration of the direct ink writing of active shape-changing architecture that can be actuated under a magnetic field. d) Process illustration from a planar sheet with patterned concentric circles swollen into a cap-shape 3D structure and cap geometries controlled by crosslinking density distribution. e) Construction of an epoxy SMP structure. (X. Yuliang et al., 2021)

2.1.3. Shape Memory Hybrids

Shape memory hybrids are material systems that are based on the combination of atleast two materials with different thermo-mechanical properties that enable the creation of a shape memory effect by the simultaneous action of both materials (Huang et al., 2010). An example of this is a system with an elastic material and a transitioning material, when the system is heated, the transitioning material softens and the stored elastic energy is released (Wang et al., 2017). Shape memory hybrids are a vast category which incorporate multiple combinations of materials and techniques to achieve a desired shape memory result.

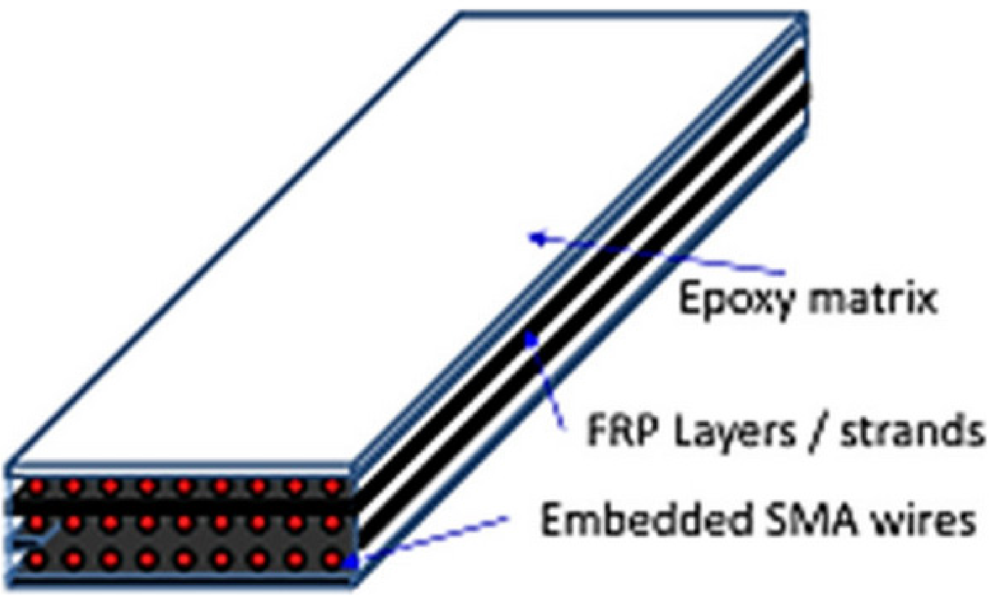


Figure 6. an example of shape memory materials part of a composite used to achieve novel properties for the system as a whole (Zafar & Andrawes, 2014)

2.1.4. Magnetic Memory Materials

Magnetic Memory Materials are a subset of shape memory materials that can be actuated by magnetic fields. The most common type of Magnetic Memory Materials are subsets of SMPs made of carbon or silicon based polymers combined with magnetic microparticles based on either iron or neodymium (Jokinen et al., 2001). These microparticles are mixed with the polymers to impart magnetic properties to the material. This material can then be cured and shaped to the final shape through various processes detailed in the next section. The magnetic particles inside the polymer matrix also need to be aligned as this is the process by which controlled deformation of the final part is achieved.

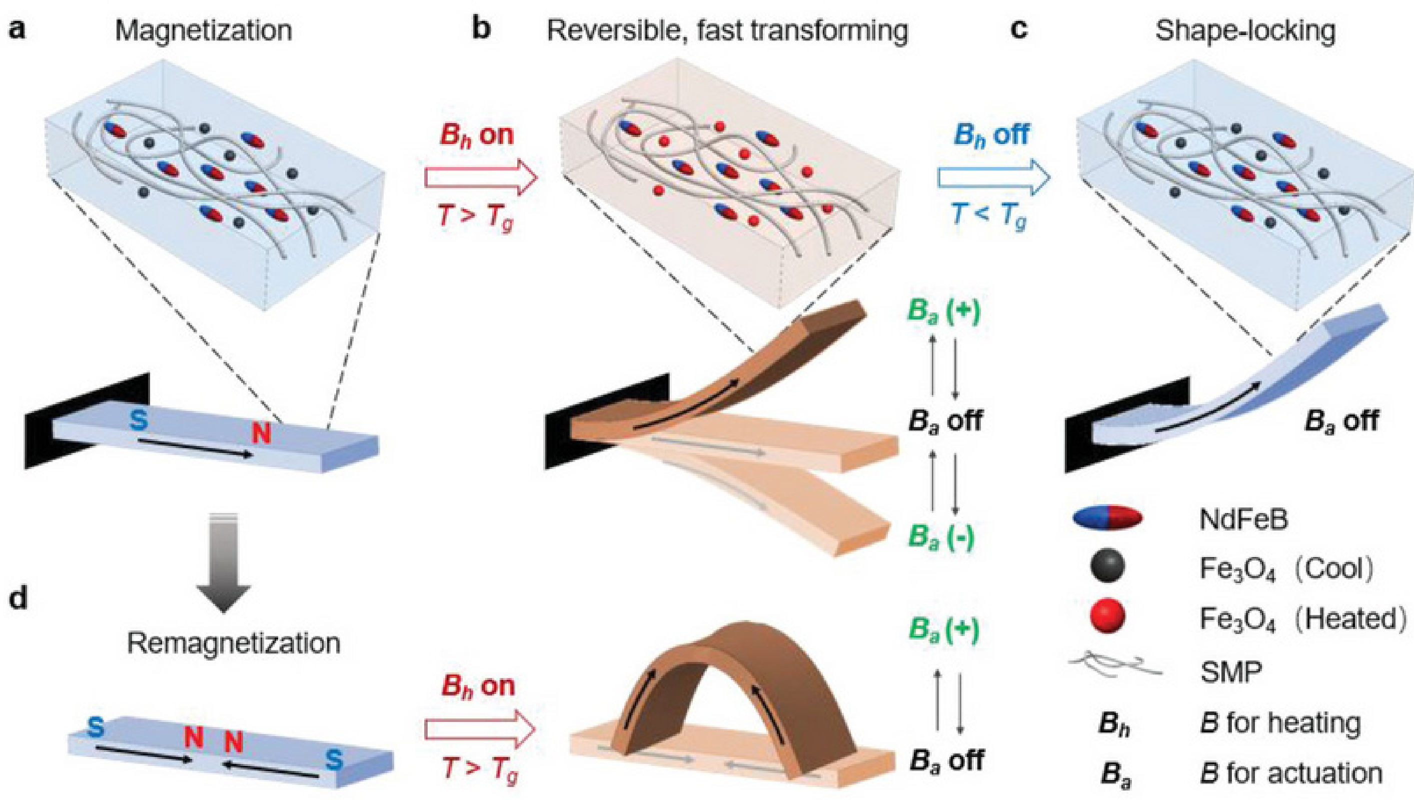


Figure 7. Working of shape memory polymers with integrated magnetic microparticles (Ze et al., 2020)

2.2. Methods of making shape memory polymers

2.2.1. Fused Deposition Modelling:

FDM is an additive manufacturing technique involving the melting and deposition of material, usually thermo-plastics, combined with an X-Y-Z motion system to create parts in a layered manner. This method of manufacturing has been popularised by the FFF (Fused-Filament-Fabrication) method, which involves having the raw material in the form of a thin filament that can be passed through a heating extruder and deposited onto a bed.
This same technology can be used for the manufacturing of SMPs by having the SMP made into a filament that can be fed into the machine. This technology has been applied by (Hu et al., 2017) using a Polyurethane-based thermo-responsive SMP to create structures that deform when heated past their glass transition temperature. The structures can be designed so that their final deformations could be controlled during the printing of the material. For better control over the final results, it is recommended to have a layer height of 0.2-0.4, printing speed of 30mm/s, 0.6mm nozzle diameter and temperature of 210-260 celsius (Akbar et al., 2022)
Ly and Kim (2017) also created their own SMP filament using SMP pellets and a composite with CNTs, which they then used to create their own printed samples. They showed that shape memory behaviour is retained even after FDM printing and confirmed this with both a water bath and voltage test.

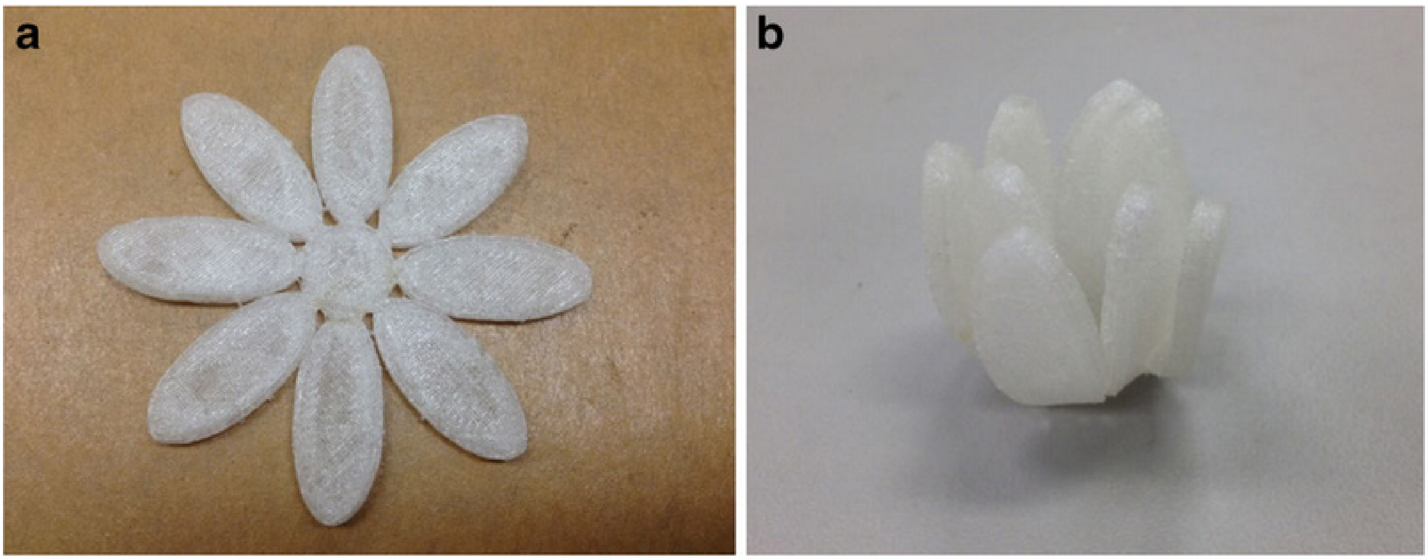


Figure 8. Yang et al.,(2016) demonstrated shape memory effect using FDM wherein the petals of the flower fold when subjected to heat

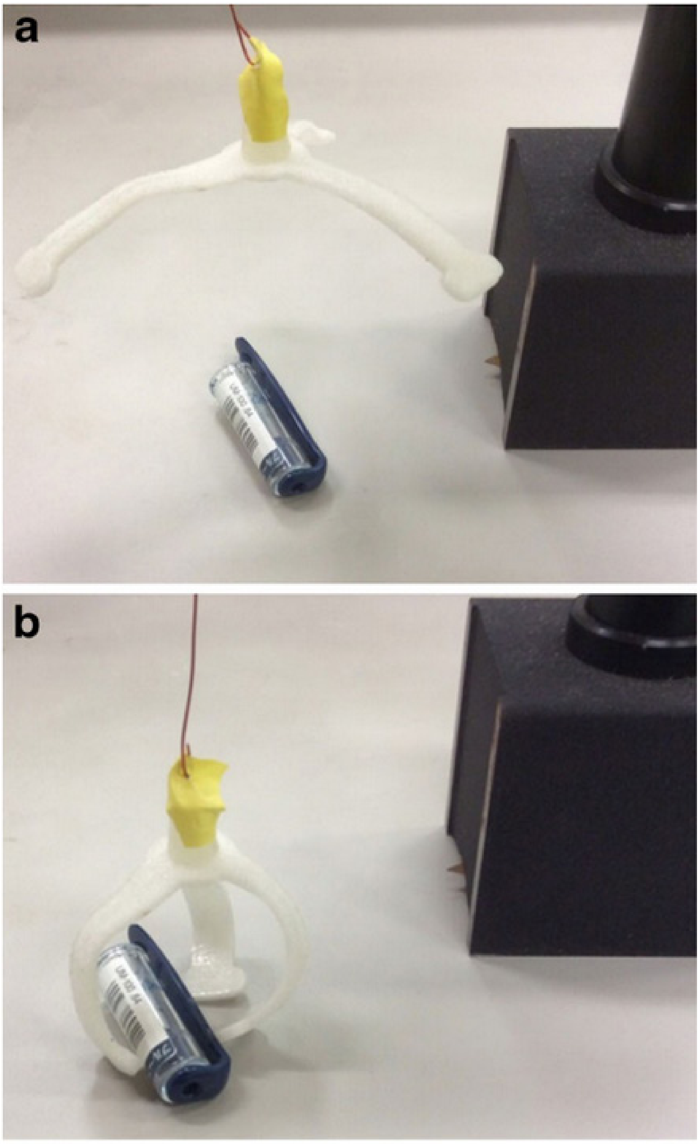


Figure 9. Yang et al., (2016b) demonstrated gripping effect using heating on a shape memory polymer part which was produced using FDM

2.2.2. Direct Ink Writing:

Direct ink writing is a manufacturing method that is similar to FDM in that it is based on the deposition of ink onto a surface using a 3D gantry system. There are mainly 2 types of DIW, the first being filament writing, where an unbroken stream of liquid is deposited to progressively create structures. This method works well with viscous liquid polymers whose flow can be controlled. The second method being the deposition of droplets on a substrate to progressively build up the structure (Lewis, 2006).
For the purposes of this review, filament writing will be the focus.
With DIW, since the material which is used as the ink is usually a liquid of varying viscosity, it needs to be cured to harden into something more solid, this process can be done with multiple methods like a chemical catalyst, UV light or heating to a high temperature.
The use of chemical catalysts or heating as methods of curing allow for much simpler manufacturing as a photo-sensitive polymer is not a necessity, at the same time, they have their own constraints which need to be considered when using them. For example, by using a chemical catalyst there is generally no requirement for any post processing as the deposited ink is able to self cure over a given period of time, but this restricts the amount of printing time available to the setup, especially if the ink is pre-mixed before being loaded into the deposition system.
There is another constraint that is common between chemical and temperature based curing inks, after the deposition of the ink, it can be difficult to build on multiple layers as each layer is printed as a liquid and no curing has taken place to give strength to the printed structure (Wan et al., 2020b).

There are many methods that are derived from the use of UV light for curing as methods of manufacturing SMPs, like SLA,

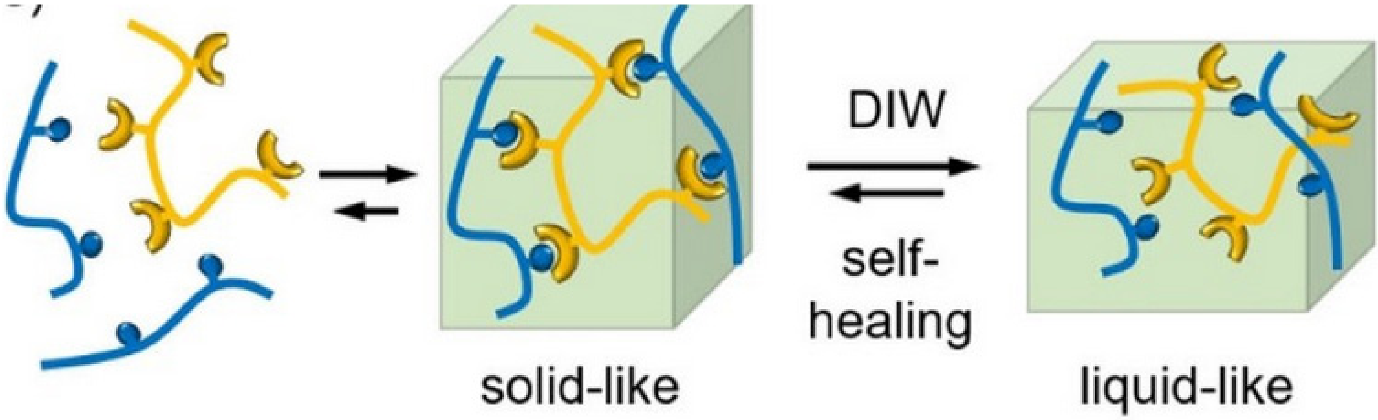


Figure 10. Illustration of the action of 3D printing DIW (Li et al., 2019)

DLP, PolyJet printing.
In SLA and DLP, both which are commonly used for Vat-Photo-Polymerization, a UV LASER(SLA)/UV light (DLP) is used to selectively cure the resin layer by layer allowing for the construction of structures. These methods can only be used with polymers that are photo-sensitive to UV light.
The methods of DIW that have been developed till date represent combinations between the two DIW methods of filament writing and droplet deposition with UV curing, temperature based and chemical based curing. Further development on this has been by changing the method of delivery of UV light or the involved resins.

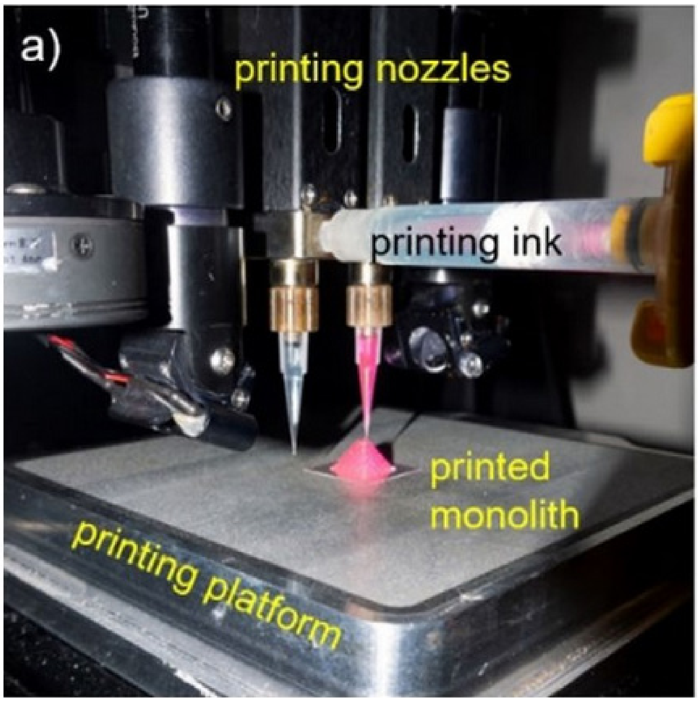


Figure 11. Direct Ink Writing using 2 extrusion nozzles (Li et al., 2019)

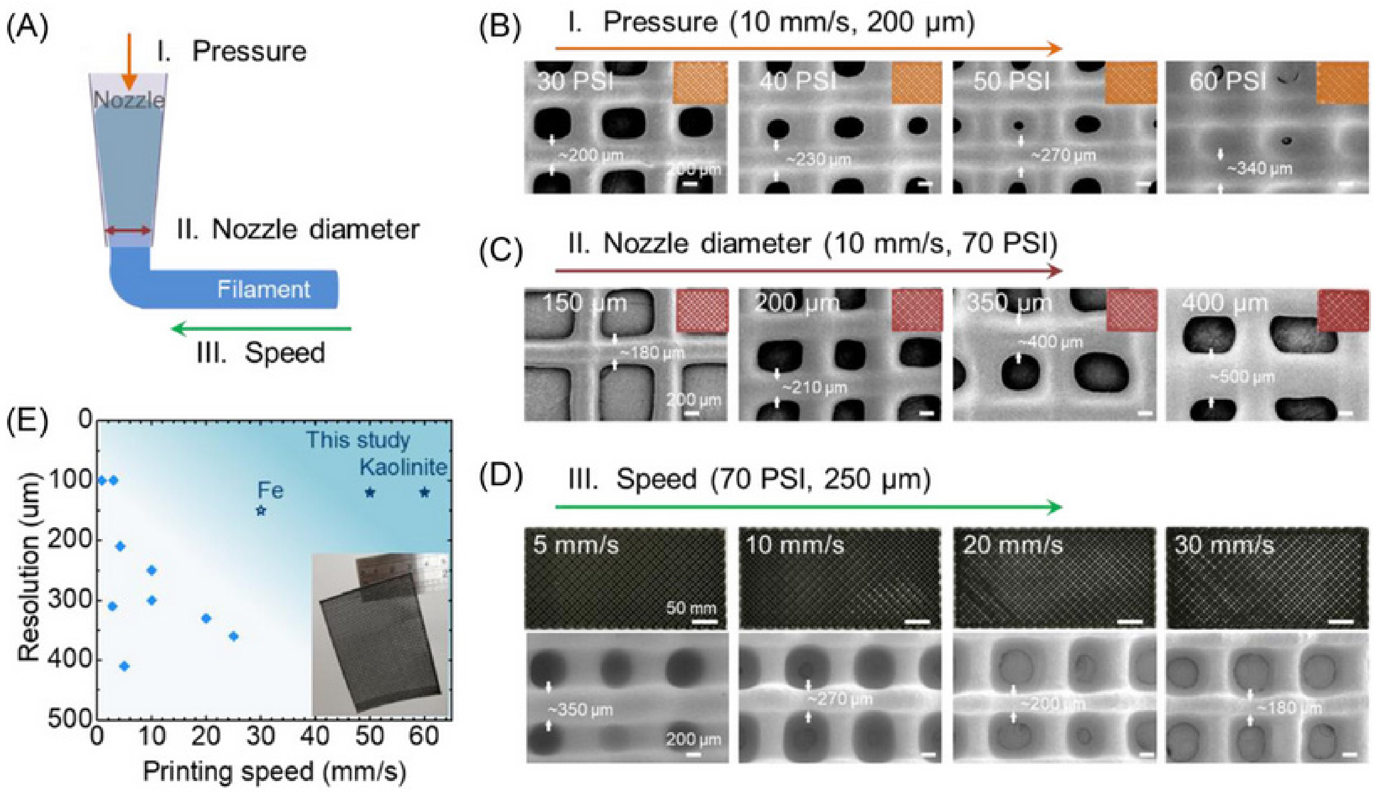


Figure 12. Illustration of process of DIW with effects of various parameters as observed by Lyu et al. (2022)

Material	Material type	Print condition	Physical properties	actuation	Reference
PLA/BP/Fe3O4	SMPC	UV-assisted at RT	Tga): 71 °C Rf: >90% Rr: ≈95%	Shape memory behavior	Wei et al., 2017
Polyacrylamide/ poly(N-	Hydrogel	Print at RT with post-UV irradiation	Ttrans: 35–37 °C	Sol–gel phase transition	Chen et al., 2019
NdFeB/PDMS/SiO2	Ferromagnetic Domains	Print with a magnetic field	Power density: ≈22–309 kW m−3	Magnetic polarity	Kim et al., 2018
PUA/HEMA/ SiO2/alumina/ photoinitiator	Ferromagnetic domains	UV-assisted print with a magnetic field	E: ≈2–8 MPa, σc: ≈4–8 MPa εb: ≈150–380%, s.g.: 1.1 g cm−3	Different swelling strains in	Kokkinis et al., 2015

Table 1. Different shape memory methods applied (Wan et al., 2020)

2.3. Effects of printing parameters on shape memory polymers

2.3.1. Using Fe Microparticles

Iron microparticles are a very common additive used in imparting magnetic effect to create shape memory materials. The ferromagnetic particles work by acting as tiny magnets which are trapped in the polymer matrix, when the magnetic moments of these magnetic particles are all aligned in the same direction, they will react to an external magnetic field simultaneously in the same manner, allowing for an overall deformation of the structure as long as the polymer matrix in which the particles are suspended is able to accommodate that deformation.(Ze et al., 2020)
By expanding on this property and by having the magnetic moments of the ferromagnetic microparticles have different orientations in different parts of the structure, complex deformations can be designed to allow for various different shapes and motions for the structure. Given that the microparticles have a fixed orientation, an alternating magnetic field can be used which would cause the polymer structure to move constantly and be able to create motion.

Lyu et al. (2022) created magnetic shape memory materials using iron microparticles in a PDMS (Polydimethylsiloxane) polymer matrix and were able to measure the magnetization levels of different concentrations of microparticles against PDMS.
Similarly, Qing et al. (2021) experimented with using a different Fe based microparticles as a functional filler at much higher concentrations (wt%) to find the results in Fig.14.

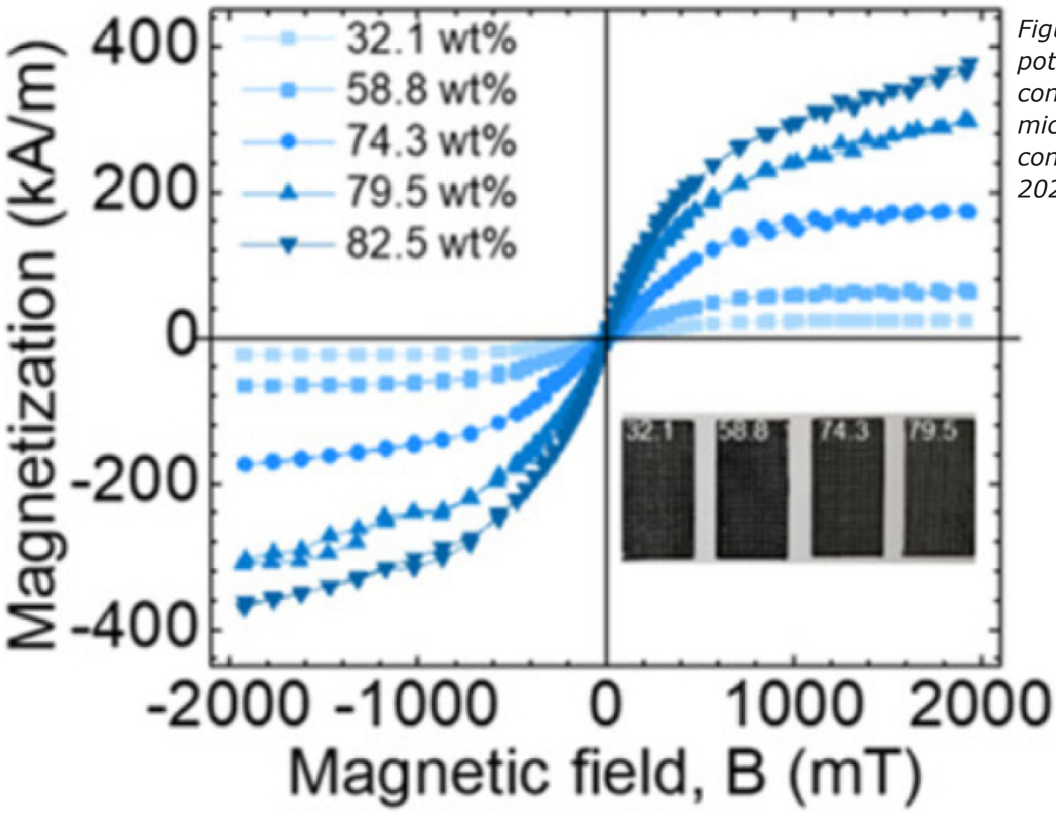


Figure 13. Magnetization potential of different concentrations of Fe microparticles at different concentrations (Lyu et al., 2022)

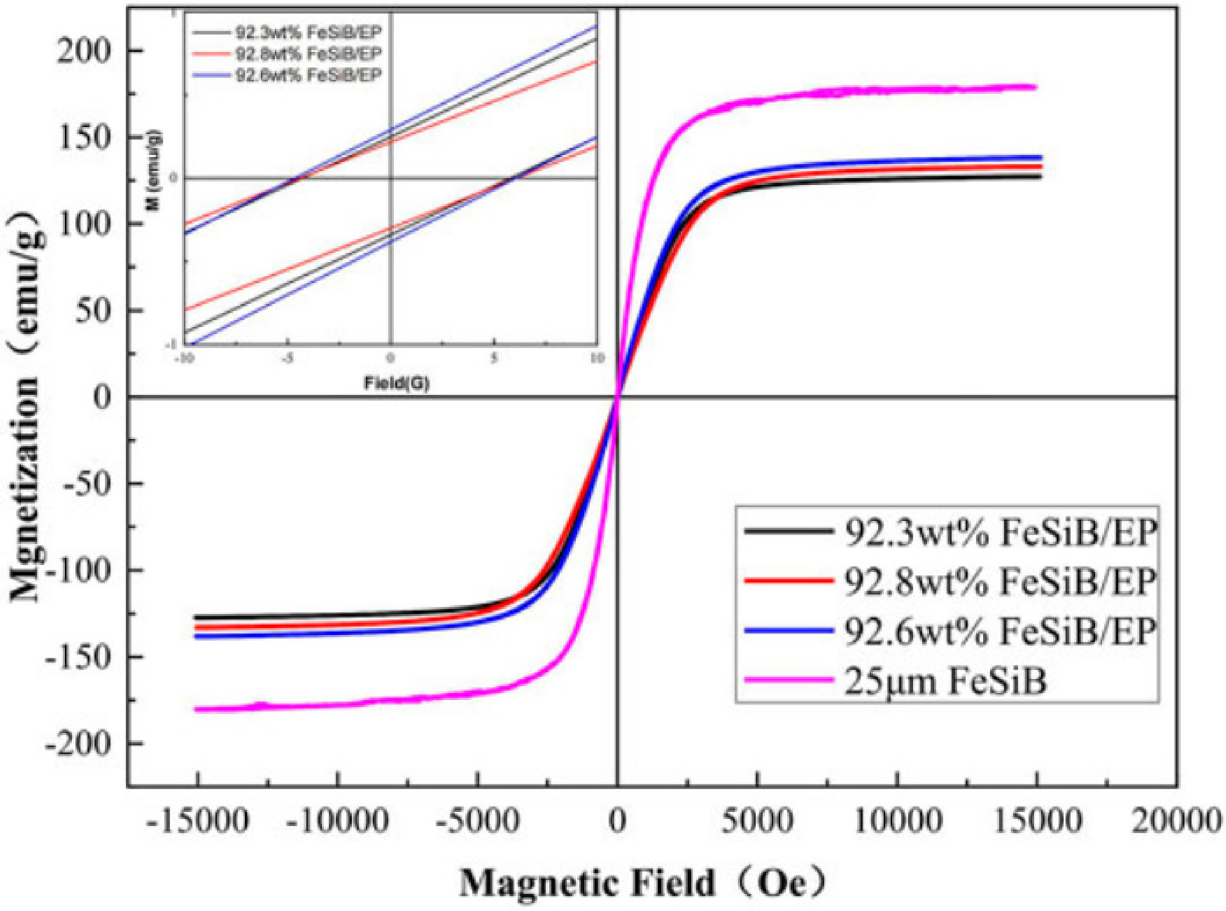


Figure 14. Magnetization of different concentrations of FeSiB at higher concentrations (Qing et al., 2021)

2.3.2. Using Neodymium Microparticles

Neodymium based magnets are much stronger than ferrous based magnets and this property extends onto microparticles as well, and that is why neodymium based microparticles (like NdFeB) are a common functional filler to impart magnetic sensitivity to SMPs.

This material has already been used to create magnetic shape memory materials in combination with various different polymers. NdFeB microparticles have been observed to have greater magnetization than iron microparticles at lower concentrations. Neodymium based microparticles tend to be more expensive than iron based ones as neodymium is a rare-earth metal and more expensive than iron, therefore making it interesting to compare the two materials to achieve maximum usability for the least cost.

In comparison between these two functional fillers, it is observed that Fe-microparticles show a magnetization of 340kA/m in a field of 1.5T at a concentration of 82.5%wt whereas NdFeB microparticles are observed to have a magnetization of 110kA/m in a field of 1.5T at a concentration of 15%wt, indicating that there is much greater magnetization potential in using NdFeB particles over Fe-microparticles.

It can also be inferred from both the tests (Fig. 15 & 16) on the NdFeB microparticles that they retain some level of magnetization even in the absence

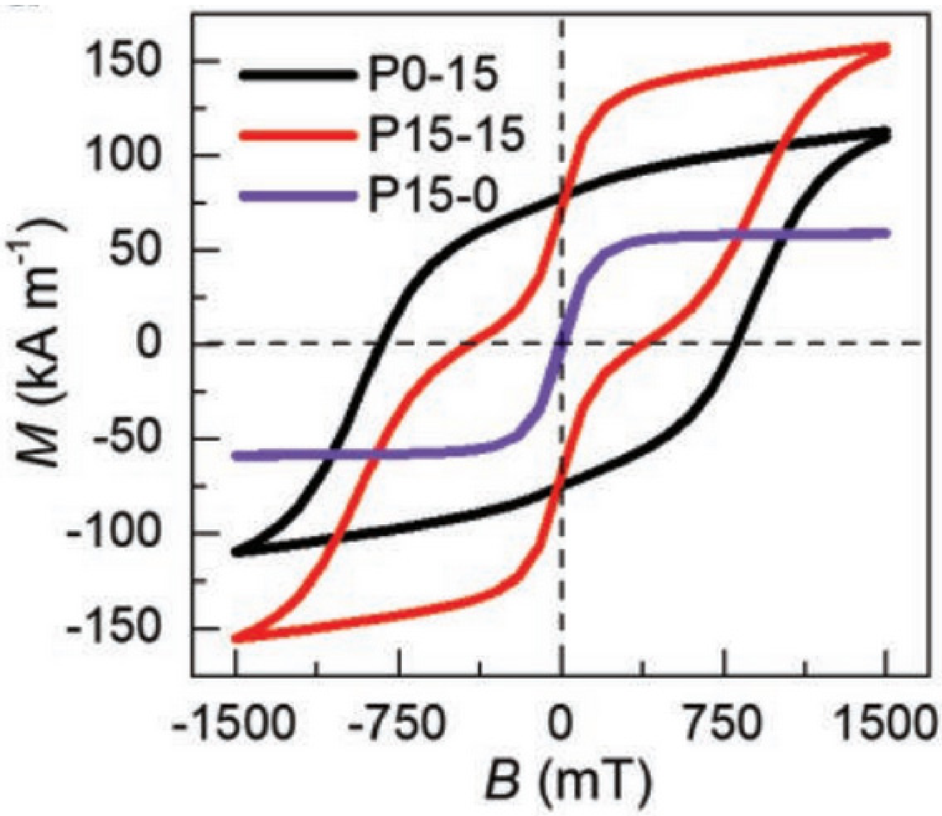


Figure 15. Magnetization of Fe3O4 and NdFeB microparticles at 15%wt concentration black-15% NdFeB, red-15% NdFeB+15%Fe3O4, blue-15% Fe3O4 (Ze et al., 2020)

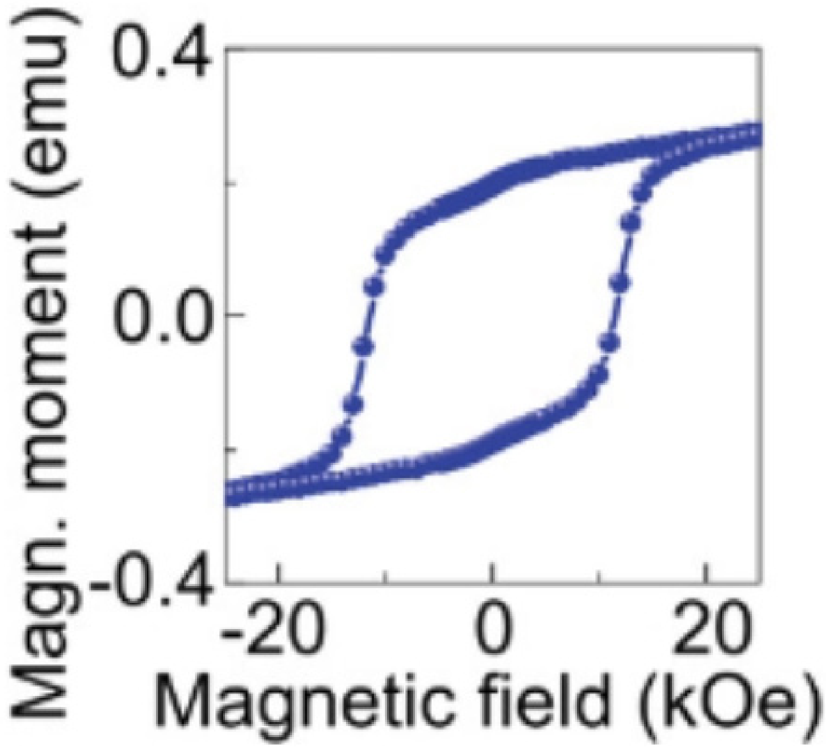


Figure 16. magnetization of 40% NdFeB particles (Ha et al., 2021)

of an external magnetic field, which is something not exhibited by the Fe microparticles as seen in Fig. 13, 14 and 15.

2.3.3. Different polymer bases

There are multiple different polymers that can be used as a base for creating magnetic shape memory materials as the main requirement for them is the ability to be cured rapidly without affecting the ability to actuate. For this reason it is generally preferred that the polymer in its cured form is flexible and capable of deformation without the requirement of a large external force. This is particularly important in the case of magnetic shape memory as the strongest field humans can be subjected to for long periods of time is 60mT. Therefore the material should be soft enough to be actuated well below this limit.
Kim et al. (2018) used a recipe with the base polymer being SE1700 (DowCorning) mixed with Eco-Flex 00-30 part B (SmoothOn) mixed with the magnetic microparticles which served as a reference for multiple other experiments like (Zhang et al., 2021), this recipe is able to be extruded after mixing from a nozzle of diameter 0.4mm.
Lyu et al. (2022) instead used Polydimethylsiloxane (PDMS) as the base polymer as it has already been used in applications of soft robotics and bioelectronics. They used PDMS to create a composite with Fe microparticles and a shear thinning elastomer to provide for easier printing through DIW. PDMS is known to be soft, chemically stable, transparent and biologically compatible.

2.4. Making it 3D

The main challenge presented to direct ink writing (DIW) of shape memory polymers is that the material being printed is required to simultaneously have good

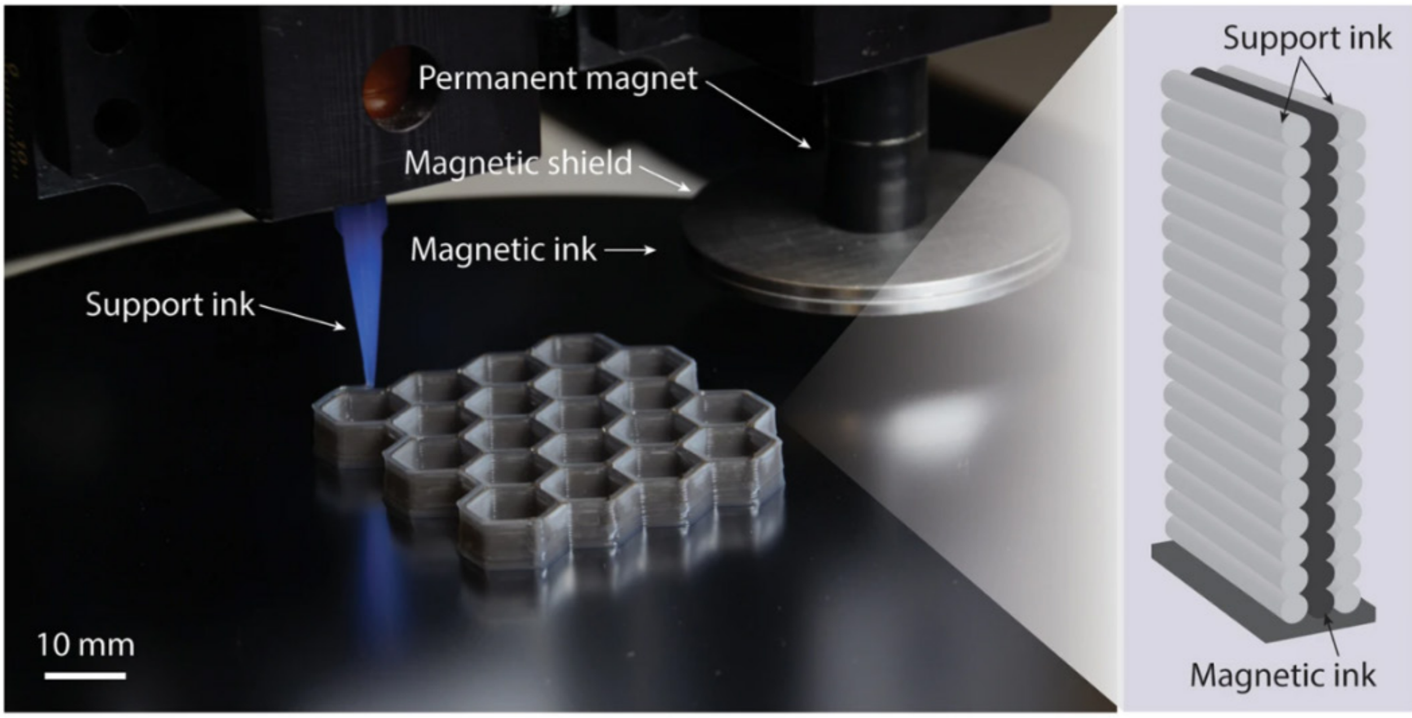


Figure 17. Printing with support inks (Kim et al., 2018)

flow properties for ease of printing, while also being able to support multiple layers being printed on top of each other without collapsing or mixing.

This has been achieved mainly in two ways in DIW applications, the first is to create an external support structure that can support the printing of the functional ink. This setup normally requires a dual extrusion setup capable of printing both inks simultaneously as well as individual control over the extrusion of both inks. The support ink used should ideally be something that is easy to remove from the main structure either physically or chemically, in this scenario of printing with polymers, chemical removal is generally preferred as the main printed structure is usually made with soft polymer bases which would not be able to resist the stresses required for removal, especially in the case of more complex geometries. Kim et al. (2018) were able to achieve successful prints by sandwiching the magnetic ink between the support inks (Figure 17) providing lateral support during printing.

The second method of creating 3D structures in DIW is to allow for the ink to immediately cure when it is deposited, allowing for enough structural strength for printing of multiple layers while also creating an interface layer that prevents the mixing between the printed and deposited inks. This method is widely applied in the additive manufacturing of photo-polymer resins where UV sensitive resins are deposited (Figure 18) and exposed to UV light to cure the resin simultaneously with its deposition. (Saadi et al., 2022)

Since the required effects during DIW are structural strength and immiscibility, as long as the deposited polymer is able to cure itself before the next layer, the printing will be successful, therefore, chemical curing, aided by heat, is also a method that can be used to create 3D structures.

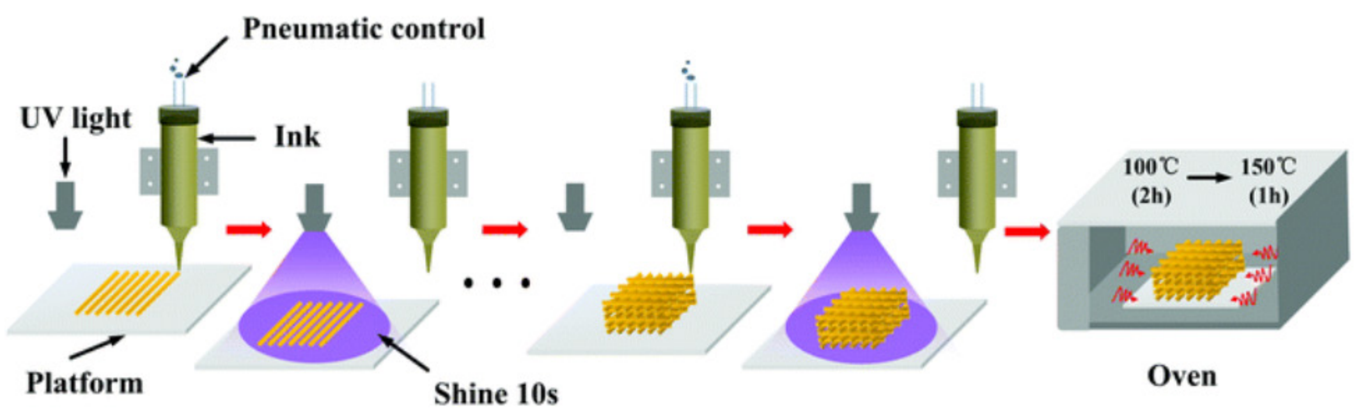


Figure 18. Schematic of 3D DIW printing with UV light and photopolymer resins (K. Chen et al., 2018)

2.5. Effects of printing directions

Direct ink writing of magnetic shape memory polymers allows for changing the orientation of the magnetic microparticles in the deposited material by placing an electromagnet near the point of extrusion that causes all the microparticles passing through to orient in the same direction. This method allows for creating segments in the printed structure that would all deform in a magnetic field in the same manner and this method can be used to create complex motion. Since this deformation is caused by magnetic fields, by alternating the polarity of the applied magnetic field, the printed structures can be designed to move or oscillate which is a useful property for designing applications.

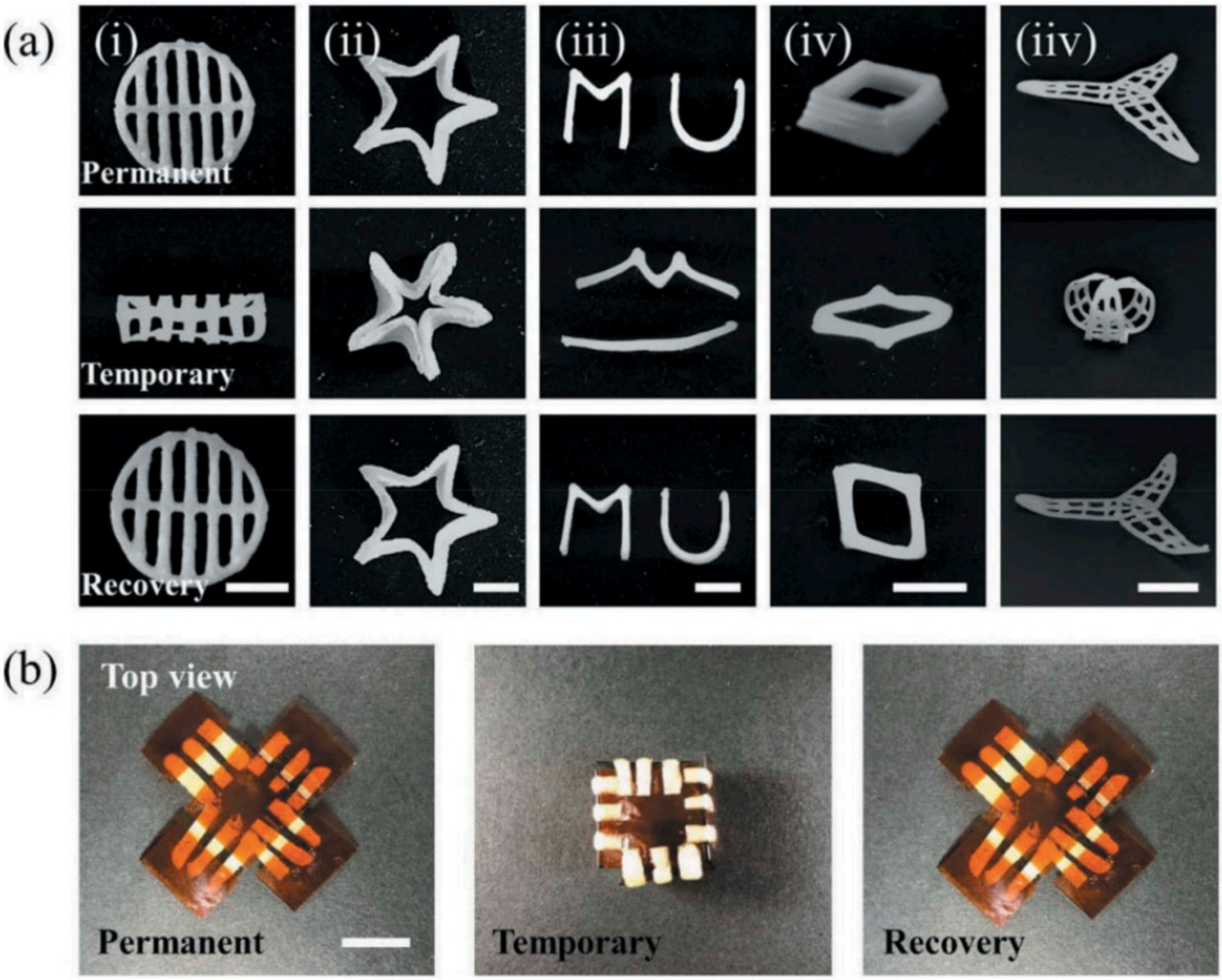


Figure 19. a) Deformations of various shapes and their recovery. b) using SME as a muscle to create folding structures (Su et al., 2019)

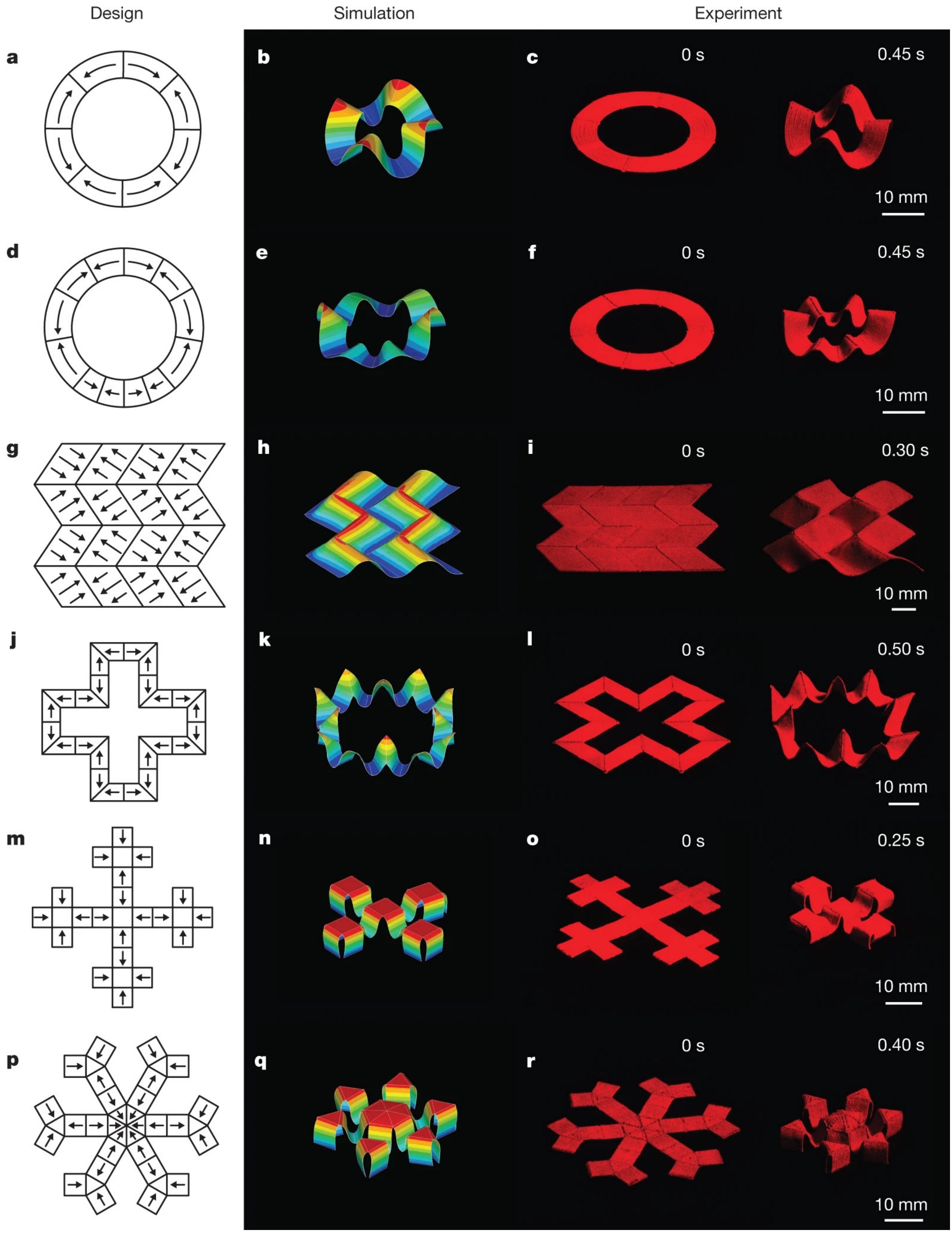


Figure 20. Various printing patterns and the structures that are created when a magnetic field is applied. (Kim et al., 2018)

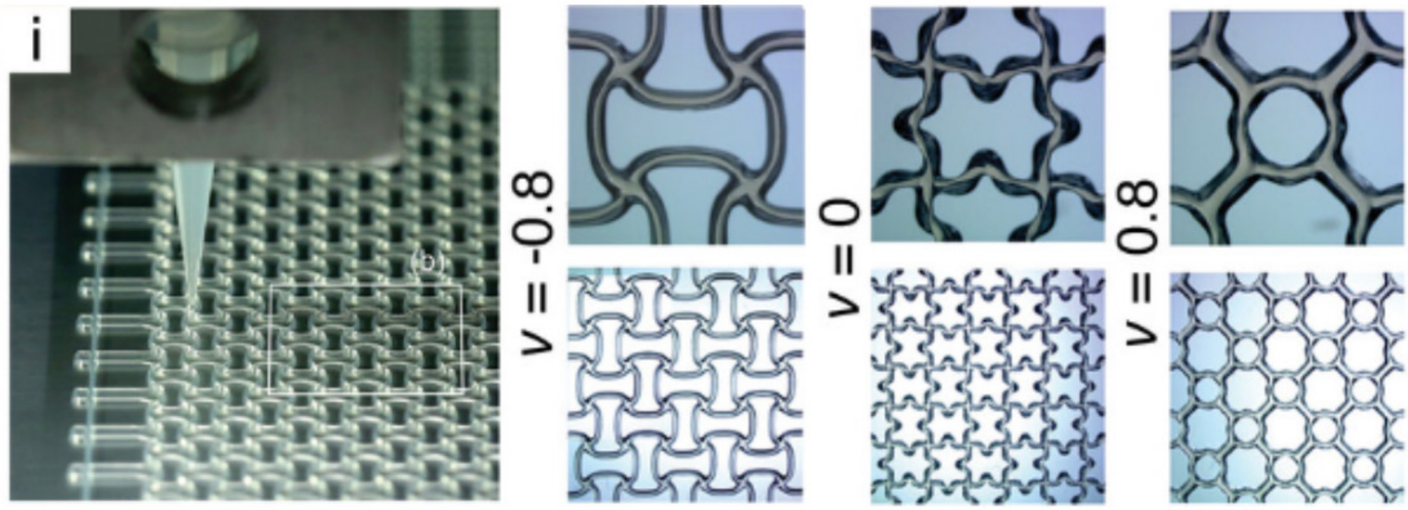


Figure 21. different geometry patterns can also be used in the infill to achieve different reactions to external loading, in this case, different poisson's ratios (M. Saadi et al., 2022)

2.6. Applications of magnetic shape memory polymers

Magnetic shape memory materials being a new set of materials that have been developed, their applications are still being explored and developed, these applications are to serve as further inspiration for the possible functionalities of these materials. Magnetic memory materials can also be combined with other shape memory materials (eg. thermo-responsive) to create compound systems where both functionalities complement each other to create complex motion. Q. Ze et al. (2020) used this functionality to create a compound material that can both be deformed under heating and under magnetic fields, allowing for the material to be set into particular shapes using both these methods together.

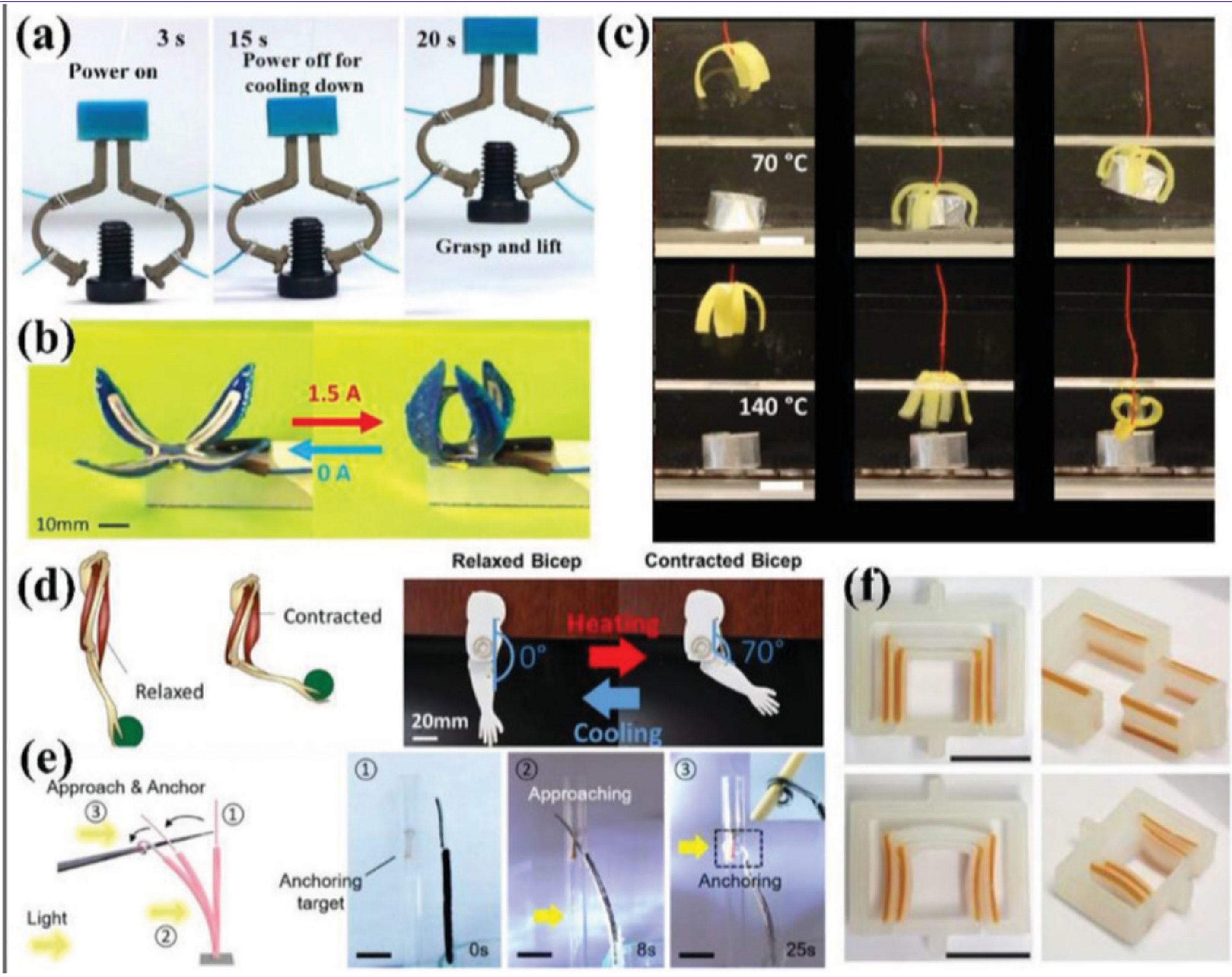


Figure 22. Shape memory effect based actuators a) robot pincers to pick up objects, b) two way shape change grippers, electrically actuated, c) temperature dependant gripping ability, d) muscle inspired actuator, e) Biomimetic bending and anchoring behavior of an artificial tendril consisting of photoresponsive hydrogel/PDMS, f) magnetic assisted clamping behaviour (X. Wan et al., 2020)

2.6.1. Figure 22a:

Clamp Style Gripper - This design features a thermally actuated clamp-style gripper with two jaws. When heated, the jaws open up with a larger distance between them. After heating stops and the system cools down, the jaws can close and grip objects placed between them. A similar concept can be achieved using a magnet switch, where the grippers are initially free to move without a magnetic field. Once a magnetic field is applied, they are attracted to each other and can softly grip objects. This can be a very useful mechanism when combined with a robotic arm to create a soft gripper robot that can be actuated from a distance.

2.6.2. Figure 22b:

Petal-Like Gripper - Inspired by the blooming of a flower, this design utilises petal-like parts instead of jaws to create a gripping mechanism. This concept can be replicated using magnetic memory materials wherein, depending on the

magnetic orientation, the petals can be opened or closed around an object, similar to the action of a Venus flytrap. This gripping mechanism can also be used with a robot arm.
A similar example of a petal based shape memory system can be seen in Figure 21c.

2.6.3. Figure 22d:

Bicep and Tricep Muscle System - This example demonstrates the use of shape-memory materials to replicate the human bicep and tricep muscle system. The materials can act simultaneously as muscles do to lift objects when appropriately activated. The example described in the picture uses thermally actuated shape memory materials. Magnetic materials can also be used for this application, for this, the two muscles can be designed to compress and expand in opposite magnetic fields so that under the same field direction, they would show opposite actuation and this can be used together as a muscle.

2.6.4. Figure 22e:

Photo-Responsive Attachment - The system shown in this figure involves a photo-responsive polymer that can approach and attach to a wire when exposed to light of a specific frequency. A magnetic alternative wire can also be used to generate a magnetic field that attracts and attaches the shape-memory material sample when impacted by the magnetic field.

2.6.5. Figure 22f:

Exhibits a different clamping mechanism that functions as a sealed clamp. Magnetic materials in the walls of the clamp can come together and create a clamping force when affected by a magnetic field. This mechanism provides a unique way to achieve controlled clamping and release

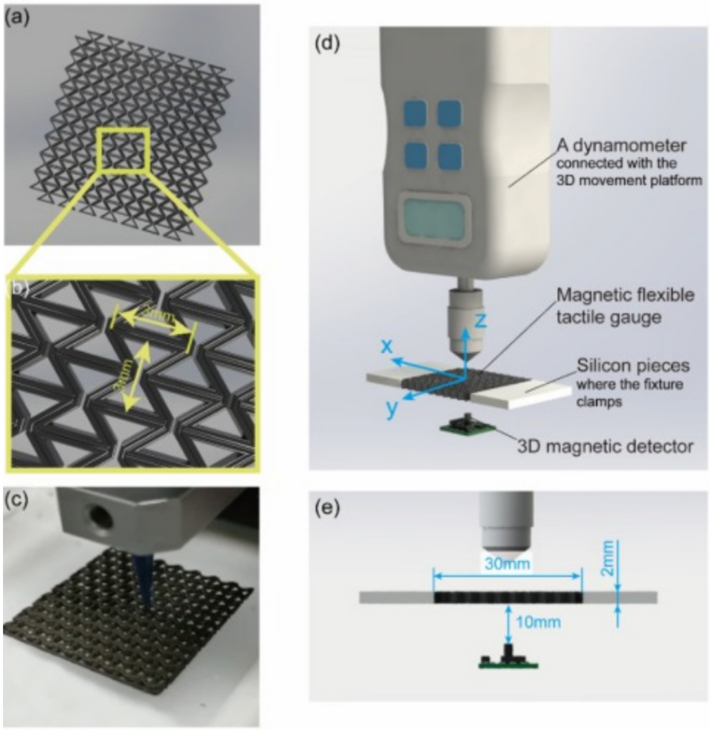


Figure 23. Magnetic flexible tactile sensor using flat pattern and 3D hall effect sensor to recognize pressure at different points in the pattern (X. Zhang et al., 2021)

actions.

2.6.6. Figure 23:

A magnetic flexible tactile sensor is presented. This sensor employs a mix of a Hall effect sensor and a specially drawn grid of magnetic memory materials. When force is applied to specific parts of the magnetic actuator sensor, it generates changes in the magnetic field, which can be sensed by the Hall effect sensor. This arrangement allows for remote sensing of touch or force at various points on a surface or plane.

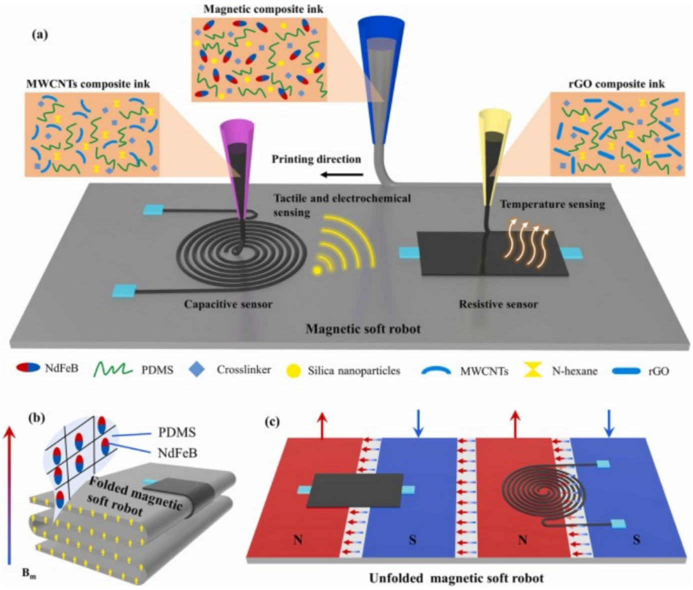


Figure 24. Soft magnetically activated soft robot with thermal and electrochemical sensing used for intravascular drug delivery (Z. Wang et al., 2023)

2.6.7. Figure 24:

showcases a complex system of magnetic and electroactive materials. The base of this system comprises magnetically activated material, which can be actuated to move like a wave forward. On top of this base, electrochemical and thermal sensors are placed. This combination of materials and sensors finds potential application in biomedical fields for drug delivery, where the wave-like motion can act as a propulsion system.

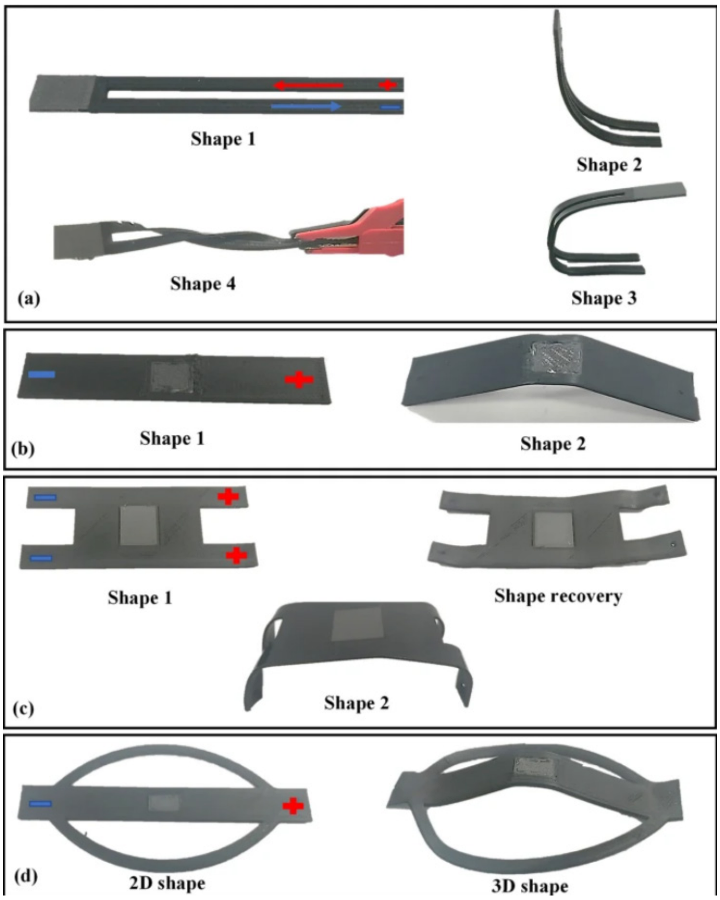


Figure 25. compound structures made with magnetic and conductive PLA capable of simultaneous electro-sensitivity and magneto-sensitivity (Dezaki & Bodaghi, 2023)

2.6.8. Figure 25:

a compound structure made of magnetic and conductive materials is presented. This structure possesses the ability to be both magnetically and electrically sensitive, allowing it to deform differently under magnetic and electrical stimuli. This property opens up possibilities for various functional applications, such as adapting to different conditions or responding to changes in the environment.

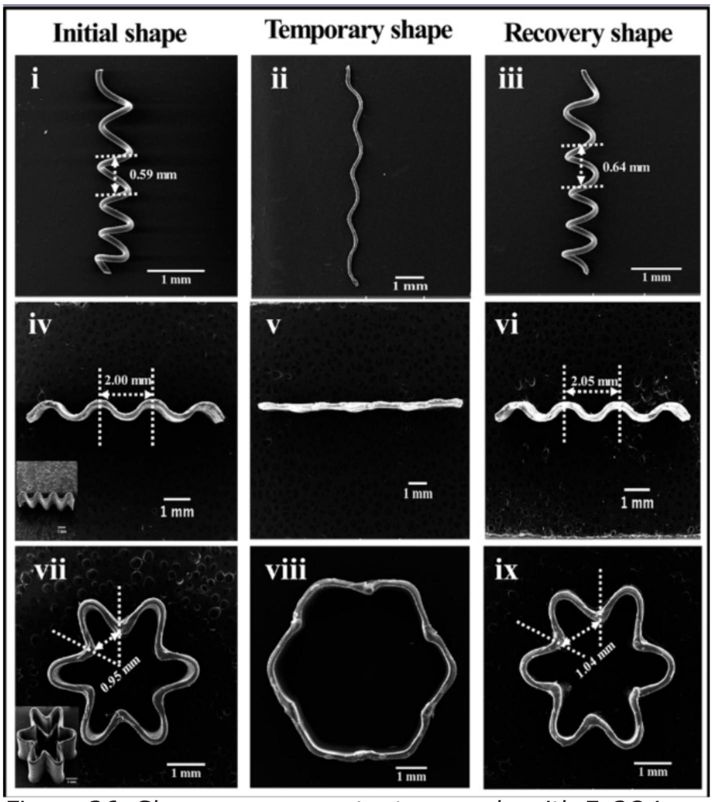


Figure 26. Shape memory actuators made with Fe3O4 microparticles and their shape changing behaviour (H.Wei et al., 2017)

2.6.9. Figure 26:

displays a thermally actuated shape memory material designed in different patterns to act as different shapes. Some segments transform from a simple line to a coiled spring, making it useful for applications requiring spring-like behavior. Other segments resemble a closed flower-like shape, which, upon actuation, opens up into a more hexagonal shape and can exhibit valve-like closing motion. This versatile design allows for the creation of structures that change shape in response to thermal stimuli, offering a wide range of applications.

Table 2. Learnings for different parameters of ink and printing methods

Parameter	Material	Test Scenario	Observation	Inference	Reference
Magnetic material concentration	NdFeB	5, 10,15,20% by vol NdFeb Magnetization in a magnetic field	Magnetization ability linearly increases with vol%	Greater concentration of magnetic microparticles will result in better actuation	(Kim et al., 2018)
	FeSiB/EP	92.8-100% by wt FeSiB in EP Magnetization in a magnetic field	FeSiB has maximum magneitzation of about 175(emu/g), not a linear relationship b/w wt% and magnetization	Addition of any mixing in pure material causes appreciable reduction in magnetization	(Qing et al., 2021)
	Fe3O4+NdFeB	0-15,15-15,15-0%vol Fe3O4-NdFeB Magnetization in a magnetic field	15-15% shows greatest magnetization, 0-15% shoes magnetization at 0mT field	Combining Fe3O4 and NdFeB can result is multisensitive materials	(Ze et al., 2020)
Actuation time	NdFe-	63%wt NdFeB in silicone sample Actuated by a magnetic field	Actuation times between 0.1-0.7s	As long as the material is soft and magnetic, actuation is almost immediate	(Kim et al., 2018)
	Ag@CNF+PLA (Thermally actuated)	10.6% Ag@ CNF in PLA sample Actuated by an electric current which causes internal heating	15 seconds for heating and shape change. 5 seconds for cooling and fixing of new shape	If thermal actuation is only source of actuation, even with efficient heat transfer cycle type for shape change is about 20s	(Wei. et al., 2019)

Parameter	Material	Test Scenario	Observation	Inference	Reference
	Fe3O4+NdFeB in PLA	15-15%vol Fe3O4-NdFeB in PLA sample actuated by magnetic field and inductive heating	15 seconds to heating and shape change, after which as long as temperature is maintained, shape change takes about 7s	Combining thermal and magnetic sensitivity allows for quicker shape change once the material has been heated past glass transition temperature	Ze et al., 2020)
Viscosity	NdFeb+Ecoflex 00-10	63.1%wt NdFeB in Ecoflex 00-10 Part A and B In Rheometer	Part A and Part B individually and mixed Maxima <10000 Pa.s Minima ~50 Pa.s	Shear rate of 1 s-1 or greater is preferred	(Kevin, 2022)
	Fe+PDMS	82.5% wt of Fe in PDMS+Fe In Rheometer	Maxima ~30000 Pa.s Minima ~50 Pa.		(Lyu et al., 2022)
	FeSiB/EP	FeSiB at high wt%(>90) mixed in epoxy resin In Rheometer	At ~92%wt Maxima 50000-100000 Pa.s Minima <100 Pa.s	Very high material wt% causes drastic increase in viscosity	(Qing et al., 2021)
Layerability	NdFeB +SE1700+Ecoflex 00-30	DIW with support ink	Material is soft and needs support inks to prevent collapse and allow for layering		(Kim et al., 2018)
	Fe3O4+PLA	DIW with UV light	Material is able to cure with a combination of UV curing and solvent evaporation. Smaller diameter nozzle allows for quicker curing		(Wei et al., 2017)

2.7. Conclusion

This literature survey has been done to serve as a guide and reference for the optimization and improvement of the printing capability of the magnetic shape memory materials being made with the printer setup which is also part of this graduation project, and to also serve as an inspiration point for the applications and the capabilities of magnetic shape memory materials.

From the literature survey conducted, it was observed that for the printing of magnetic shape memory materials, DIW is as ideal choice as it allows for flexibility in terms of the materials used to achieve the flexibility as well as the magneto-sensitivity of the material as well as allow for the creating of precisely designed shapes by following the principles of additive manufacturing for their development.
It is preferred to have the incorporated magnetic microparticles to be NdFeB due to the much higher magnetization of the material even when exposed to weak magnetic fields (~50mT). The alternative of Fe/Fe-based microparticles have the advantage of being cheap and easy to obtain due to the absence of rare earth metals, but have very low magnetization in external fields around 50mT.
The desired properties of the base polymer/resin used would be low viscosity, shear thinning, smooth surface finish, high strain resistance, flexible after curing and biocompatibility for medical applications.
To create self-sustaining 3D structures, each method has its pros and cons, support inks are very effective but require a much more complex printing setup to accomplish, as well as complexity in support removal. UV curable resins are able to cure very quickly and are easy to implement, but are restricted in terms of the polymer bases that can be used as they need to be photosensitive. Chemical curing/thermal curing does not require any additional systems apart from resin extrusion but are time sensitive with a chance of mixing between layers. For the purposes of this project, chemical curing will be further explored for viability due to simpler setup requirements and time constraints.

3. Printer Setup

The printer setup was being developed with the goal of having the magnetic memory materials systematically manufactured, allowing for repeatability, consistency and creating complex geometries.
This process was first attempted in the graduation project of Sanne van Vilsteren and improved upon by Kevin van der Lans, this setup used a motor driven geared piston assembly with a 3D printed static mixing nozzle for the 2 part resin used. The main challenge faced was the very high pressure requirements due to a combination of high viscosity fluids and small cross sections in the flow path, particularly in the mixing nozzle.

To improve upon the existing setup, the design was changed to first use a Creality Ender 3v2 3D printer for its open construction and open source firmware allowing for greater flexibility in modification and to use a dynamic mixing nozzle instead of a static mixing nozzle, to allow for better mixing and reduction in overall the flow resistance.
The purpose of using the Ender 3v2 here is to provide the automated X-Y-Z control control using its gantry system to facilitate the automatic printing of the magnetic materials.

3.1. Modification to the Ender 3v2

The Ender 3 Printer was first fully assembled to establish the starting point for developing the rest of the modifications to the printer (Figure 27). To start off, the printer's extrusion assembly was dismantled as this was unnecessary for the 4D printer setup. The extruder was left connected to the printer as this was necessary for the functioning of the printer. The motor of the extruder was repurposed to be used as a part of the extrusion mechanism.

The second addition was to incorporate parts of a dual Z-axis kit, a modification commonly used to add a second lead-screw to the ender 3 to allow for greater stability during printing. From this kit, the extra lead screw and motor were used as parts of the piston extrusion mechanism. To facilitate dual motor control off the single available extruder port on the Ender 3 motherboard, a split wire was also used to allow for control of 2 motors from the same extruder output port.

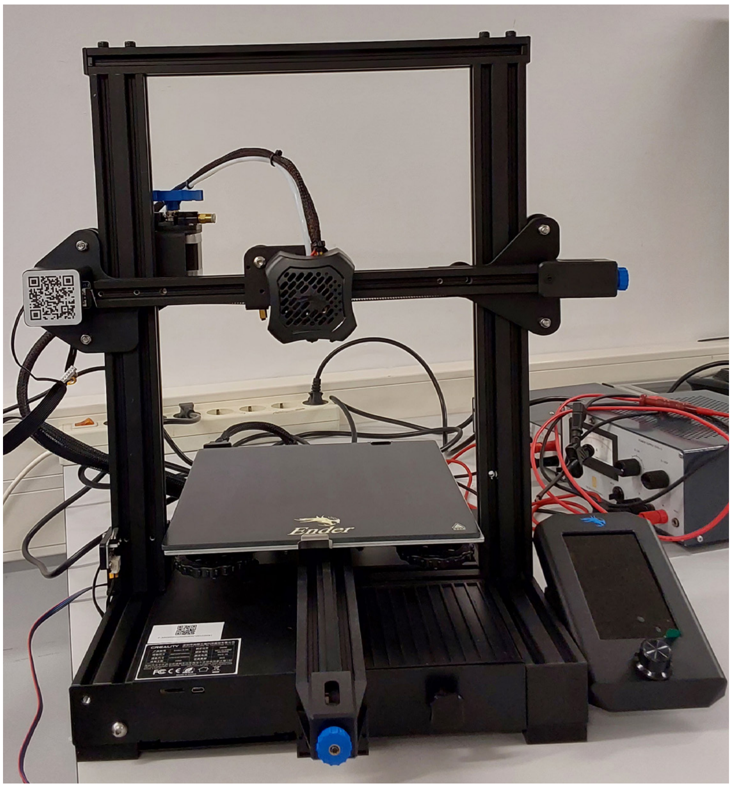


Figure 27. Ender 3v2 before any modifications were made

3.2. Super structure

The super structure here refers to the additions made to the printer which support the extrusion mechanism being added onto the Ender 3v2.
This structure was made with 9mm thick plywood as it was not expected to take excessive loading while also being inexpensive and readily available.
The vertical supports can be screwed with the printer to ensure they stay fixed together.
The assembly holders are held in place using smaller plywood blocks which allow for easy removal as well as create a strong holding force via friction and resist any bending strain placed on the assembly holders.

Figure 28. (Left) The interlocking of the support structure (Top) part part of the support structure assembly

3.3. Mixing nozzle and stirring assembly

Figure 29. Complete mixing nozzle and stirrer assembly with attached permanant magnet

The mixing nozzle assembly was one which required multiple parts to facilitate various functions, these were made using 3D printing as they had to be custom made for the 4D printer. The parts of the assembly include:

3.3.1. Extruder Casing:

The casing is the central part of the assembly which brings all the parts together, it is designed to conform to the extruder attachment of the Ender 3v2, provide channels for the tubes containing the 2 parts of the magnetic ink and the stirrer rod, provide a seal and sturdy holding for the dynamic mixing nozzle as well as have the stirrer motor mounted on it.

The casing is made out of PLA and is screwed onto the gantry of the printer, the casing went through several iterations with additions of different functionalities and fine tuning of the clearances.

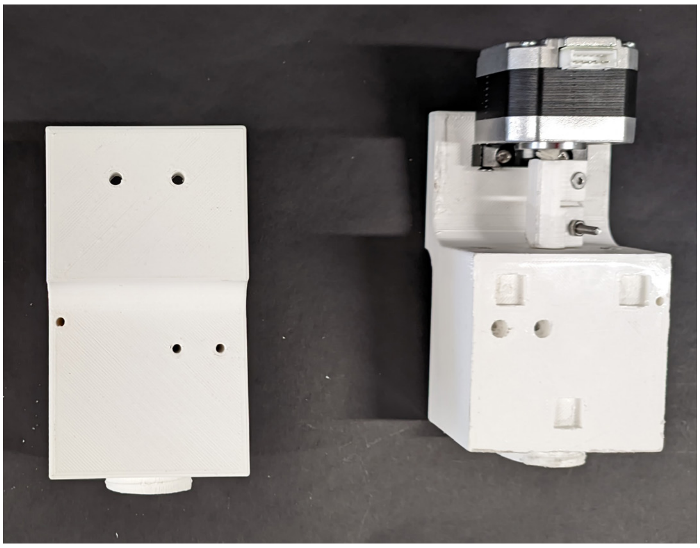


Figure 30. Front and rear of the extruder casing, also seen are stirrer motor and collet which connects to the stirrer rod

3.3.2. Stirrer motor:

The stirrer motor used is a standard NEMA 17 34-42 motor which was used originally as the extruder motor from the Ender 3v2 and it also has an attachment block attached to it which is used to mount it to the casing.

The motor is controlled by an external stepper motor controller which in turn is controlled by a Seeeduino board (see section 3.6). The motor has 2 controls, one switch to turn it off and on and an anologue potentiometer to control the speed of rotation.

3.3.3. Collet:

The collet is another 3D printed part which is used as a mating mechanism between the motor and the stirrer rod, to allow for a connection to the stirrer part of the mixing nozzle

3.3.4. Stirrer rod:

The stirrer rod connects the stirrer motor to the stirrer in the mixing nozzle. It is mated to the motor by means of the collet and to the stirrer by means of a screw.

3.3.5. Dynamic mixing nozzle:

The dynamic mixing nozzle used in this project was a standard glue mixing nozzle for 2 part epoxies sold by BOYEE TOOLS Store, China.

Length: 128mm

Inner Diameter: 12mm

Outer Diameter: 16mm

Outlet diameter: 4mm

3.3.6. Nozzle attacher:

The nozzle attacher is a part of the assembly that ensures the nozzle stays in place with respect to the casing to ensure reliable operation, it is designed to conform to the shape of the top of the nozzle and attach itself to the casing by means of mating geometry between the attacher and the casing.

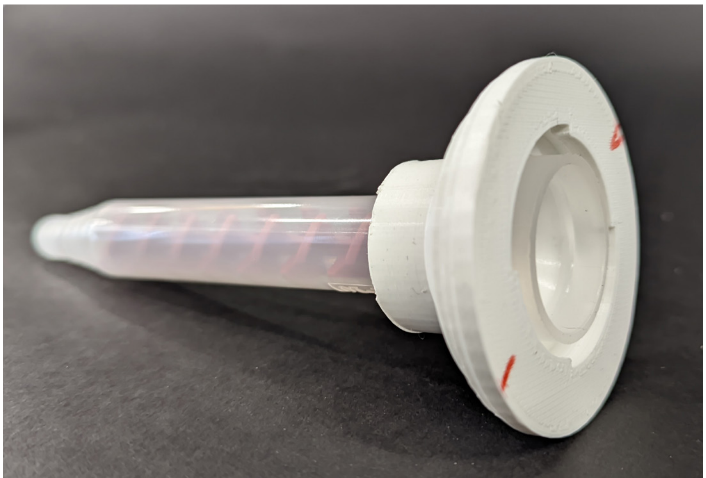
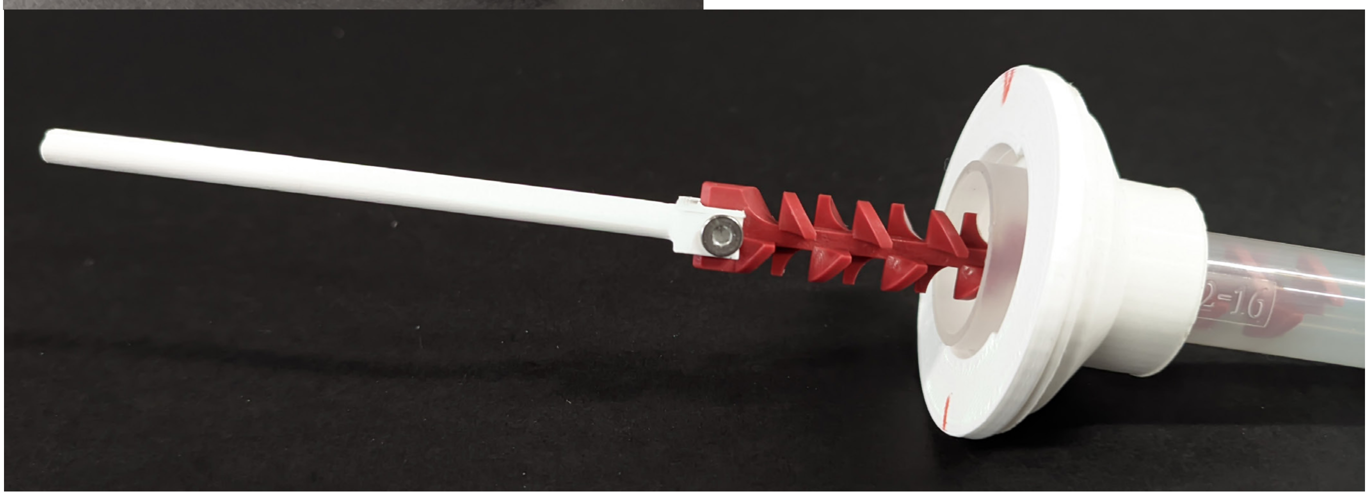


Figure 31. (Left) Nozzle attacher and mixing nozzle (Below) connection between the stirrer rod, stirrer and mixing nozzle



3.3.7. Permanent magnet:
The permanent magnet serves an important function, it aligns the magnetic microparticles in the ink in one direction allowing for the different segments printed to behave as individual magnets as long as they are printed in the same direction. The benefit of using a permanent magnet here is that the 4th dimension of printing, that is, the magnetic orientations of the printed parts can be controlled by controlling the direction of motion of the nozzle.

3.3.8. Magnetic shield:
The shield is another critical part of the assembly as it acts as a barrier for the magnetic field from the magnet, preventing undesirable effects onto the ink after it has been deposited. It is a ferritic steel disc 2mm thick, with a central hole of 10mm diameter to allow the mixing nozzle to pass through.

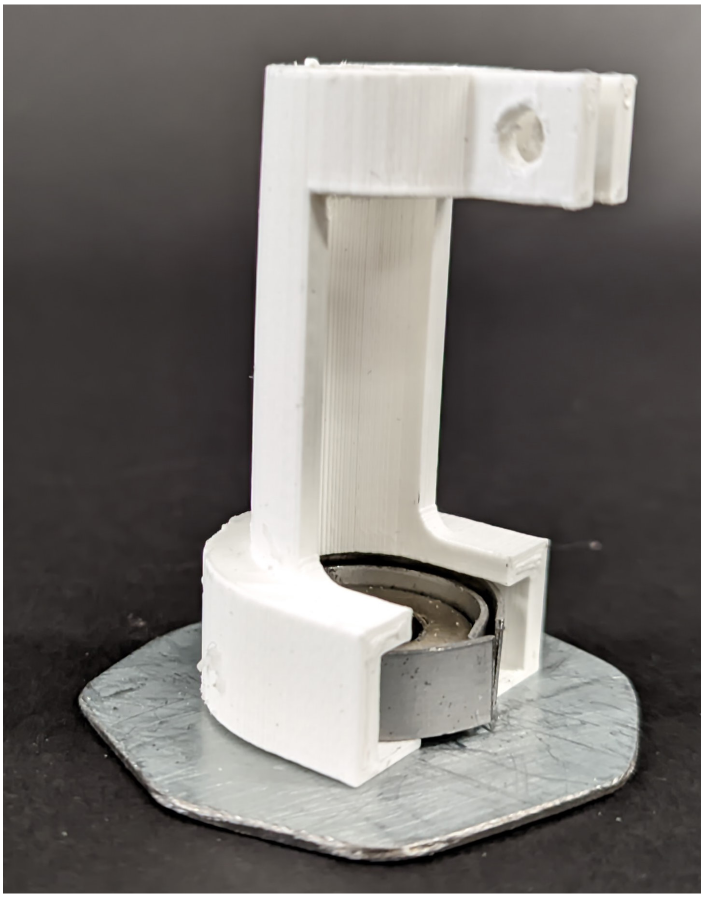


Figure 32. Magnet holder, magnet and shield

3.3.9. Magnet holder:
The magnet holder is another simple holder that attaches onto the mixing nozzle, holding the magnet as close to the nozzle end as possible to allow for most alignment of particles during printing.

3.4. Piston extrusion mechanism

The piston extrusion mechanism refers to the motor-syringe assembly that forces the viscous magnetic ink from the syringes throughout the piping to the mixing nozzle and was initially the only driving force for the ink. Through the initial printing tests it was concluded that this force was insufficient to continuously and reliably move the ink throughout the printing assembly, even with the reduction of factors contributing to flow resistance when compared with the previous setups of Kevin van der Lans and Sanne van Vilsteren. Therefore this assembly now works in tandem with the newly added peristaltic pump mechanism (see section 3.5), wherein, the piston extrusion assembly now provides the necessary positive pressure for the efficient working of the peristaltic pumps, and therefore, the assembly no longer requires fine control in terms of its motion.

The final piston extrusion mechanism consists of multiple parts.

3.4.1. motor(s):

There are 2 motors used in this assembly, both NEMA 17s which are connected to the lead screws to push the pistons of the syringe down to create positive pressure. The motors were initially controlled by the dual ports attached to extruder control on the Ender 3v2, but this has been changed to being attached to an external stepper motor controller which is also connected with the Seeeduino board. The purpose of this change was to facilitate the control of the added peristaltic pump mechanism. The motor is mounted onto the super structure by means of a L-clamp with mounting holes for both the motor and the attachment to the super structure.

3.4.2. Lead screw:

The lead screws attach onto the motors with a collet used by all creality 3D printers for their Z axis control. The lead

Figure 33. Entire piston extrusion assembly, including motors, lead screws, lead screw nut+connector block, lead screw supports, piston connectors and syringes

screw was also part of the dual Z-axis kit and the original was split into 2 to be used for the 2 pistons.
The lead screw is 200mm in length, 8mm in diameter and has trapezoidal thread geometry.

3.4.3. Lead screw support:
The lead screw support was a late addition to the design, it was observed during operation that due to the cantilever support of the motor-lead screw assembly, under load the lead screw was showing large displacement due to the feedback from the piston under pressure, this deflection was causing the threads of the lead screw and the lead screw nut to lock, preventing any relative motion. Therefore, an additional support was designed and added. This is a 3D printed part that supports the lead screw at its free tip, transferring its load onto the super structure and reducing the deflection of the lead screw and preventing the locking of the threads.

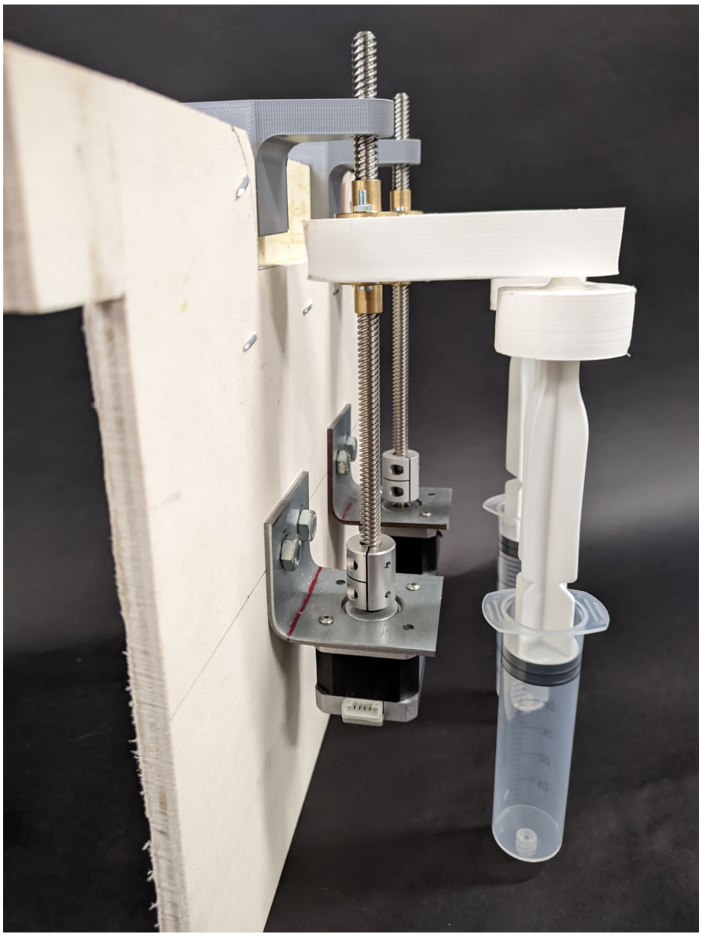


Figure 34. side view of piston extrusion assembly

3.4.4. Lead screw nut and connector block:
The leadscrew nut is what converts the rotational motion of the lead screw into translational motion which can be used by the piston. The assembly is made in a way that the connector block is sandwiched between two lead screw nuts which work together to move the connector block.
The purpose of using 2 nuts is to better handle the reaction force from the piston as 1 nut would likely lock the lead screw, preventing any motion.
The connector block is designed to move the force from the motor-lead screw over to the piston-syringe. It has a point of attachment for the piston connector on one side and the lead screw nuts on the other side. It separates the lead screw nuts by an exact distance so as to match the threads of both nuts with the lead screw and ensure a tight fit.

3.4.5. Piston connector:
The piston connector connects the connector block to the piston, it is friction fit into a hole in the connector block and there is a T channel cut out below it corresponding to the geometry of the top of the piston. The piston slides into the connector and is moved upwards or downwards depending on the motion of the lead screw.

Figure 35. syringe holders with syringes, piston connectors and connectorion blocks

3.4.6. Syringe and Syringe holder:

The syringe used is a 60ml syringe with a luer lock tip for quick attaching and detaching. The 2 syringes used are filled with the ink and the piston pushes the ink through the system. The syringe holder serves multiple functions, it connects itself and the syringe to the super structure by means of screws, it has geometry that allows for the syringe flanges to lock and prevent removal.

3.4.7. Luer lock attachment:

The luer lock attachment is an adapted luer lock nozzle which can easily and securely connect to the syringe, the nozzle is friction fit to the tube and has been drilled through to allow for maximum through flow of the material.

Figure 36. Luer lock attachment in place and its connection to the peristaltic pump

3.4.8. Tube:

The tube to be used needed to meet certain design considerations, in the initial phase, it had to have a rigid wall to prevent expansion under pressure, match the diameter of the syringe nozzle and have an outer diameter smaller than 6.5mm as that was the largest size at which 2 tubes and one stirrer rod could fit inside the top of the dynamic mixing nozzle. Therefore a tube with an OD of

Figure 37. (left) old tube with inner diameter 3mm, (right) new tube with inner diameter 4mm

6mm and an ID of 3mm was chosen. Later on, with the addition of the peristaltic pump, the design requirements changed, the tube now had to be soft walled since the pump mechanism needed to squeeze the tube to move the ink through the pump. Therefore, a polyurethane tube of 5mm OD and 4mm ID was chosen as it was sufficiently soft enough to work with the peristaltic pump while being stiff enough to hold the pressure from the syringe.

3.5. Peristaltic pump

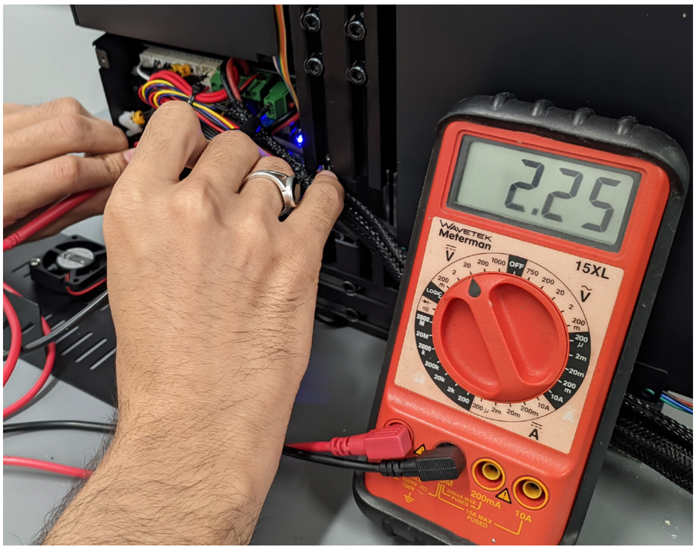
The peristaltic pump was an addition to the extrusion system to solve 2 major problems faced by the pure piston extrusion system:

- Lack of control during extrusion, this refers to the phenomenon where once the pressure has be removed, flow is still observed, this was referred to as ghost flow (Kevin, 2022)
- High flow resistance causes the flow to be very slow, slow flow in the mixing nozzle causes the resin to react and solidify within the nozzle before it is able to exit the nozzle.

The solution was to use a peristaltic pump as it is particularly useful for viscous fluids, also the pump does not physically interact with the fluid, which is particularly useful as the ink is quite expensive and direct contact will cause losses due to ink being stuck on the pump impeller.

The peristaltic pump comprises of 3 parts, the casing, the rotor and the motor.

The motor used is a higher torque NEMA 17 42-47 motor with a holding torque of 5kg/cm at peak power of 2.2A and 12V. Unfortunately, since both motors of the peristaltic pumps are driven off the same port, they do not receive full power as the peak output of a single port itself is 2.25A.



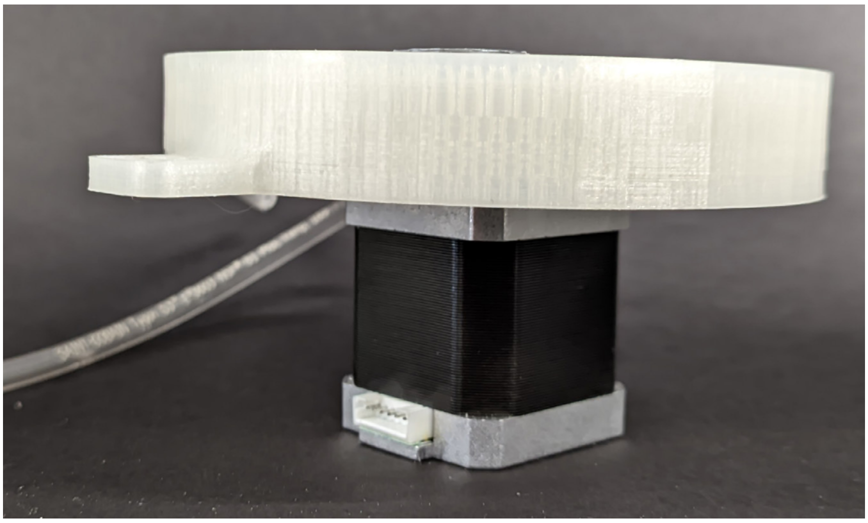


Figure 38. (Above) changed Vref of extruder on Ender 3v2 motherboard to 2.25V, indicating peak current of 2.25A. (Below) peristaltic pump attached onto high power NEMA 17 motor

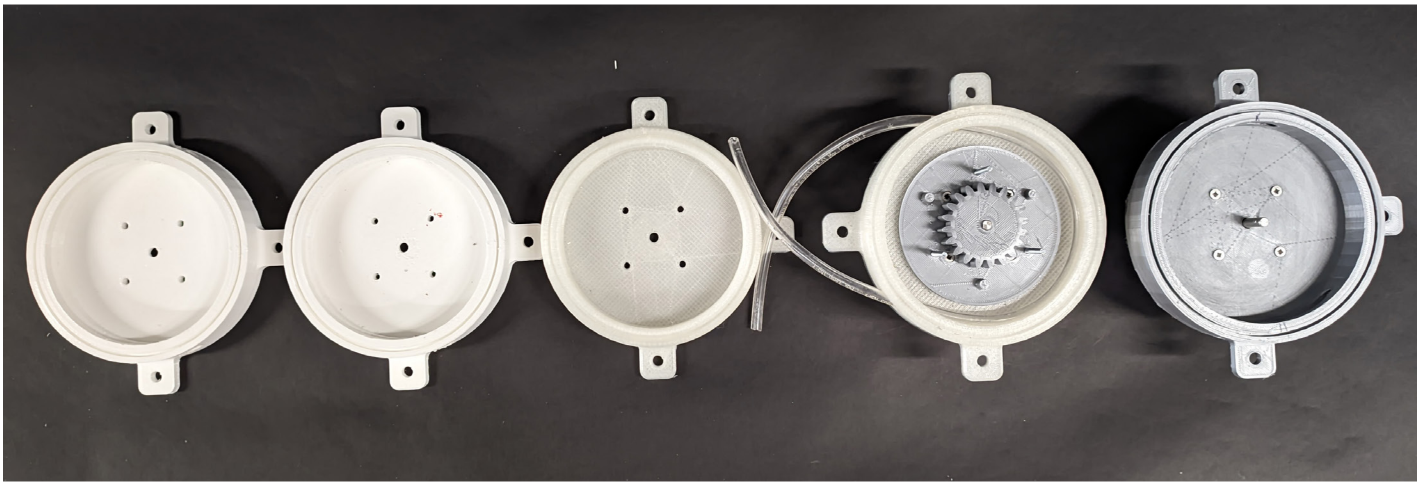


Figure 39. Evolution of casing


Figure 40. front view of the peristaltic pump assembly

3.5.1. Pump casing:

The casing of the peristaltic pump serves to act as a mounting point for the assembly to the super structure as well as provide a wall for the tube to be pressed against by the rotor. In the first iteration of the casing, it was observed that having the inlet and outlet of the tube 180° from each other caused a point of very high resistance for the rotor as the rotor had to simultaneously squeeze as well as leave the tube at the same instant, therefore a modification was made to have the exit of the tube 210° of arc from the entrance of the tube, creating a longer arc of travel as well as having the tube exit at a more natural angle since the nozzle assembly is situated higher up than the base of the peristaltic pump. Along with this, the inner wall geometry was also changed to have a more gradual engagement between the bearing and the pipe.

This setup was observed to initially provide desirable results with minimal skipping of steps and even extrusion of both materials as long as adequate lubrication was provided, but there were still instances of the motor skipping steps.

Therefore the next design change was to reduce the diameter of the casing and correspondingly reduce the rotor size. This change will increase the torque output at the point as torque (N.m) is a function of force (N) and distance (m), and for the same torque, a reduction of distance will result in an increase in force. Therefore, the size of the pump was reduced from an inner wall diameter of 100mm to an inner diameter of 64.6mm. (See Appendix 8.2 for further details)

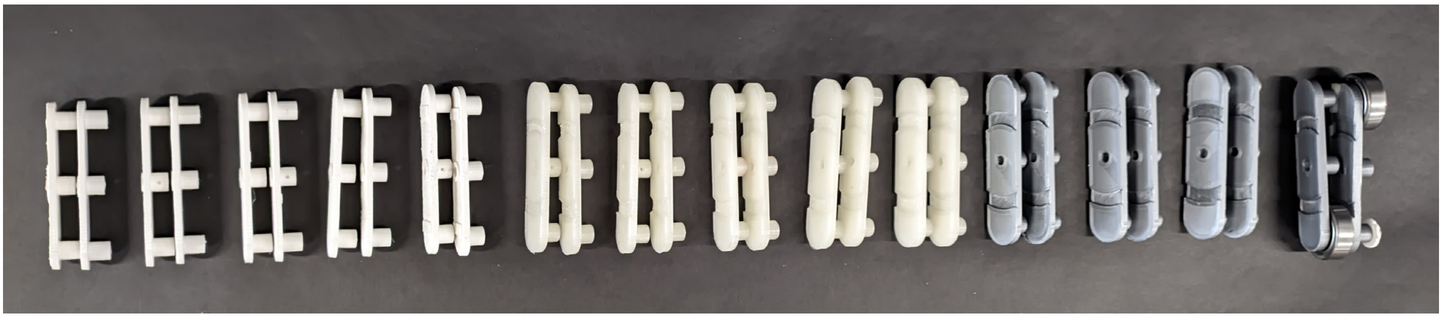


Figure 41. (Top) side view of the evolution and iterations of the rotor design. (Left) rear view showing the changes made to the bottom geometry

3.5.2. Rotor:

The rotor is a 3D printed part that attaches onto the shaft of the motor, it is made to hold 2 bearings that press against the tube, which in turn squeeze it and push the ink along as it rotates.

The rotor was one of the most iterated parts as it has multiple parts that had to be fine tuned, these included that mate with the motor, the distance of the bearing holders from the center and the bearing locking mechanism.

The rotor was initially designed to be used with the flat surface moving against the base of the pump casing, but testing revealed a high amount of friction between the two surfaces, also it was observed that the bearings were being subjected to an upward force by the pipe which caused them to be dislodged from the holder despite a sealing mechanism. Therefore, after testing it was determined that it was more efficient to turn the rotor to have the flat surface outside, which solved the problem of the upward force on the bearing as well as reducing the contact area between the rotor and the pump casing base, with only the sealing caps being the points of contact.

To solve the problem of the slightly higher

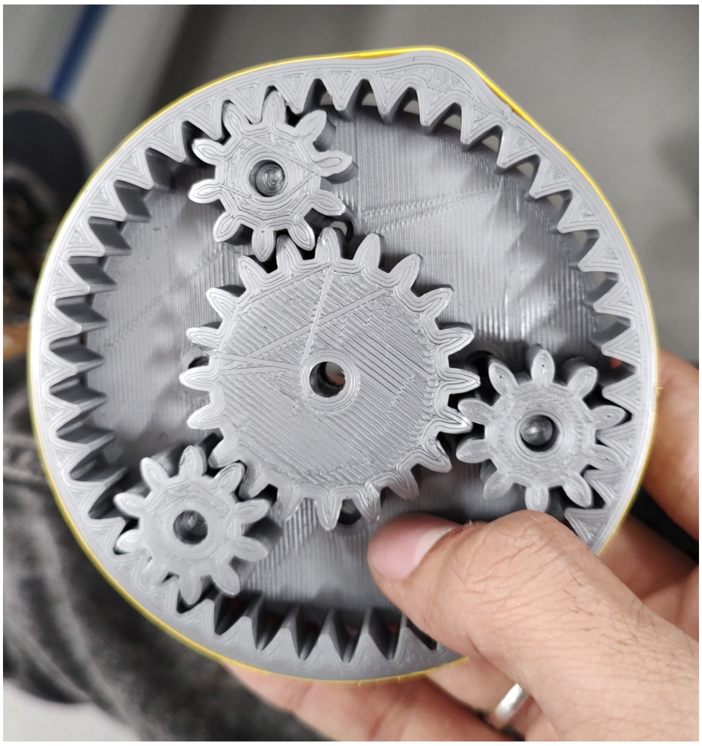


Figure 42. 3D printed epicyclic gear train with protruding lobe

torque requirement, another approach was first used, which was to replace the original rotor with an epicyclic gear train which would provide a reduction ratio to the motion solving the torque problem. With the setup, a 1:-2 ratio was achieved (-2 implies the direction of motion is reversed). Since a bearing could no longer be used, the outermost gear (internal spur gear) was designed with a lobe protruding from one point which would be the point of contact with the pipe and move the material forward.
When this setup was tested with the motor, it was observed that even with the improved gear ratio, the motor was still unable to move the outer gear due to the high torque requirement, although, the point of contact which caused a problem was not the initial point of contact, but midway through the arc. The problem with this setup turned out to be the change in the nature of friction. Initially, with the rotor-bearing system it was a smooth steel surface and a rubber surface in contact and the nature of friction was rolling friction as the bearing was able to freely spin and move through the arc of the pipe. With the new epicyclic gear train, the nature of contact changed to contact between 3D printed PLA and rubber, and the type of contact was sliding contact, an inherently higher friction form of contact. Even with lubrication, the gear train was not able to overcome the friction and would cause the motor to constantly skip steps.
Therefore a decision was made to revert back to the usage of a rotor with bearings to press against the wall of the pump. With the reduction in the size of the pump, the size of the rotor was also reduced while maintaining the determined effective gap of 4.2mm between the end of the bearing and the wall of the pump. Also the bearing size was reduced from the initial 30*10*9mm to 26*10*8mm which also helps in reducing the distance between the motor and point of contact. before this, a pump with a diameter of 75mm too was tested but it was observed that while it was able to move the material through the tube without any problems, due to the back pressure generated in the mixing nozzle due to the presence of more material that had to be pushed out of the way, it was skipping steps and unable to

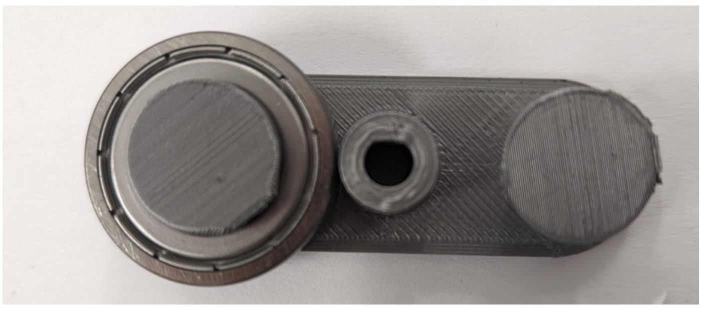


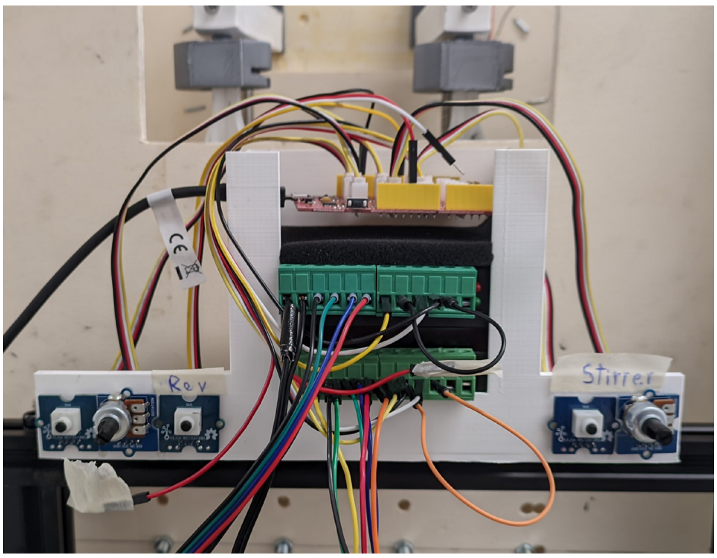
Figure 43. Final rotor-bearing assembly

compress the tube at the initial point of contact of the arc. This was then solved in the aforementioned final diameter of 64.6mm. (See appendix 8.2 for more details)

3.6. Control electronics

The control electronics used for this 4D printer were all controlled by a single Seeeduino Lotus board. This system was needed as the Ender 3v2 had limited expandability in terms of motor control and other input output. The Lotus board serves to control 2 major functions of the 4D printer system, the control of the stirrer motor and the control of the piston extrusion motors.

The Seeeduino lotus board is quite similar to an Arduino board, it has grove connectors as well as the standard pin connectors making it very convenient for quick connections. It is powered by a standard 5V 1A power supply over a micro-USB connection.
For the multiple systems that the Lotus board needs to control, it has multiple switches and potentiometers to control the various aspects of the 4D printer.
For the control of the stirrer motor, there were 2 controls that were required, an on/off control as well as a speed control for the rotation of the mixing nozzle stirrer.
For the control of the piston extrusion system, there were 3 controls required, an on/off control, a rotation direction control to also allow for the reverse motion of the pistons, and speed control for the actuation of the pistons.
Since the Seeeduino Lotus board cannot directly control and power the various motors on the system, stepper motor drivers are necessary to control the motors. For this purpose, 2 TB6600 stepper motor drivers were used as they allow for micro-stepping of the stepper motors allowing for greater control in the rotation of the motors. They also can control the current output of the motors which is useful as for the piston extrusion system, 2 motors will be connected onto the same controller for simultaneous control.
From the Seeeduino Lotus board, there are 2 types of commands sent to the



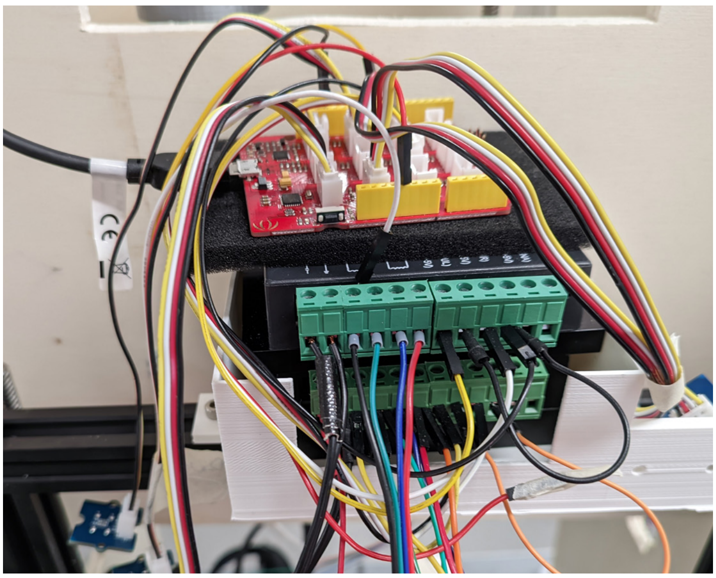


Figure 44. (Left) Control switches for the Piston extrusion system and control switches for the stirrer motor. (Right) Control electronics setup, seen in picture are Seeeduino controller and 2 stepper motor drivers for controling the 2 sets of motors

drivers, the pulse rate and the direction of rotation. The each pulse sent commands the motor to move by 1 step, and this stepping can be controlled by the driver to result in ½ steps or ¼ steps or other fractions of steps for finer rotation control. The direction control determines whether the motor will spin clockwise or counterclockwise.

3.6.1. Coding the Seeeduino Lotus board

Since the Seeeduino Lotus board is an arduino based board, it can be coded on the Arduino IDE (Integrated Development Environment).

The coding the board was rather straightforward, there were 4 outputs needed (stirrer motor (Pulse and direction control) and Piston extrusion motors (Pulse and Direction control)) 2 analogue inputs needed for the speed control of the 2 motor systems and 3 switch inputs needed for the 2 on/off controls and the one direction reverse control. This last part of the 3 switch inputs was a little challenging to tackle as a Seeeduino lotus can only accept 2 pin interrupts (activations of switches), the command that was being used to read the actuation of the switches. For this, the Seeeduino lotus board had to be commanded to reprogram some of its pins to read interrupts and only then could a third interrupt be executed successfully.

3.7. G-code

G-code is the method of instruction used by the Ender 3v2 to control the various motors to and other aspects of the printer to generate the requisite designs.

There are 2 main parts to the G-code, the header and the body, the header contains an initial set of guidelines for the printer to make it ready to print and the body refers to the commands guiding the actual printing.

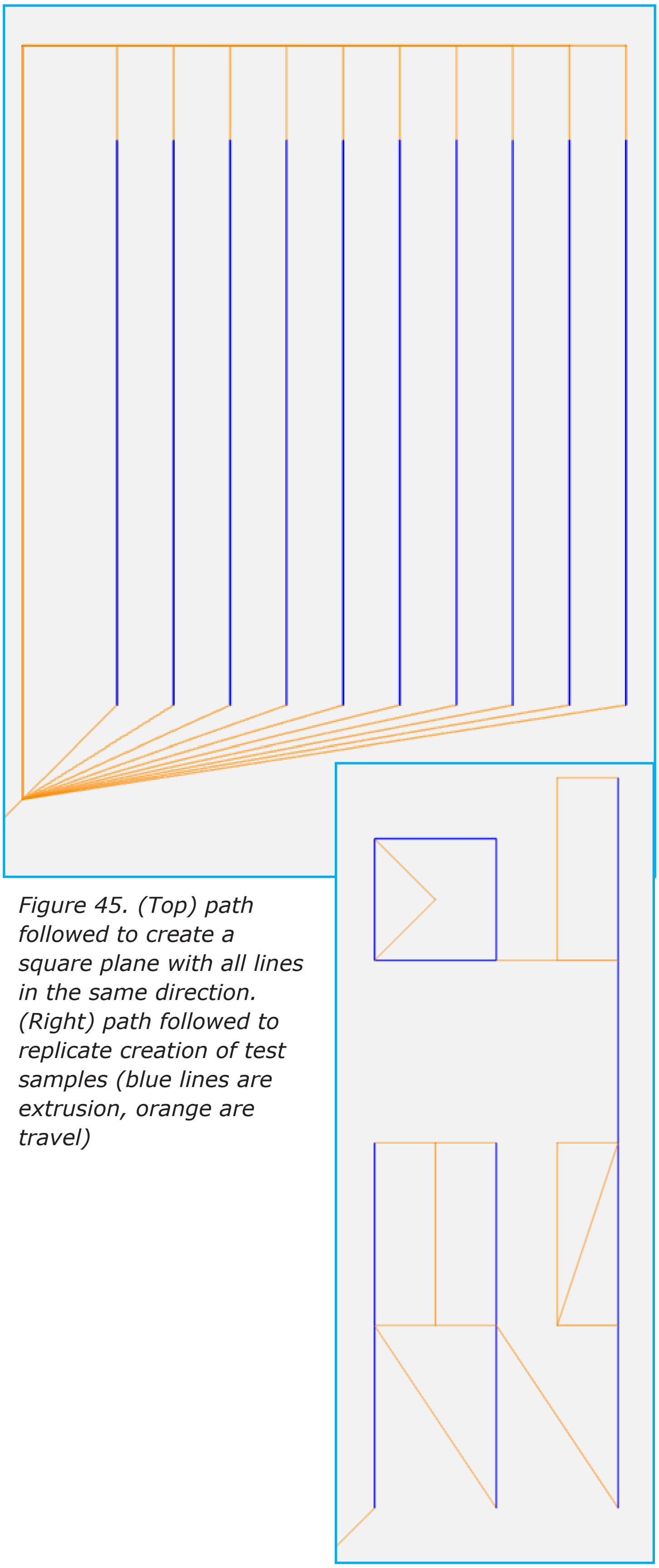


Figure 45. (Top) path followed to create a square plane with all lines in the same direction. (Right) path followed to replicate creation of test samples (blue lines are extrusion, orange are travel)

In the case of 4D printing of magnetic materials, there is particular importance placed on the direction the extruder moves to print each line as this direction will be the determining factor of the magnetic orientation of that segment of material. Therefore, the body of the G-code needs to be written in such a way that the lines are drawn as desired so as to together create the desired actuation.
This is difficult to achieve with the common slicer softwares used for normal 3D printing like Ultimaker Cura, Prusa slicer, etc. as they are programmed without any consideration of printing direction of individual lines. Therefore, for the testing and the prototyping, the G-code was either manually written or with the assistance of custom code developed specifically to generate the required G-code instructions automatically.

Figure 46. Material curing before it was able to reach the bottom of the entire extruder during testing the piston extrusion system

3.8. Printer testing

In the first step of testing the printer's functionality, pure EcoFlex part A and part B were used to test the printer. This test served as an initial check for the printer's systems, allowing them to verify the printer's capability to handle the resin and ensuring that all the components of the printer were functioning correctly. This test was successful and the printer was able to mix and print the Ecoflex without any trouble, the curing within the nozzle too did not happen to an extent of hindering the printing.
However, during the testing with ink made by incorporating iron microparticles with the Ecoflex resin, an issue was encountered with the Piston extrusion

Figure 47. material clogging around the connection point of the mixing nozzle as well as travelling up between the tubes, stirrer rod and inner walls of the casing

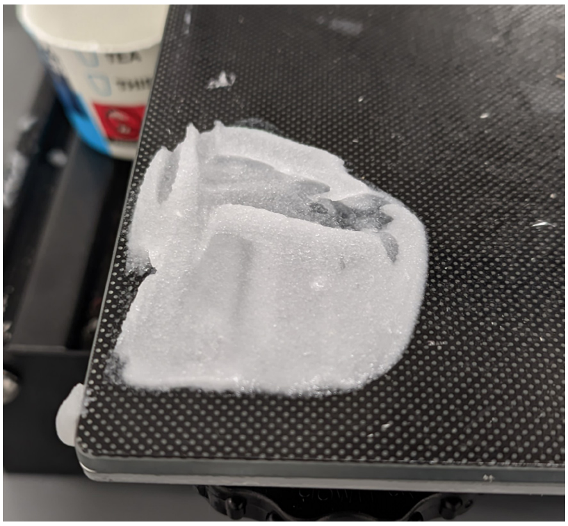


Figure 48. First successful print done using baking soda analogue, material was spread out due to the magnetic shield combined with high flow rate

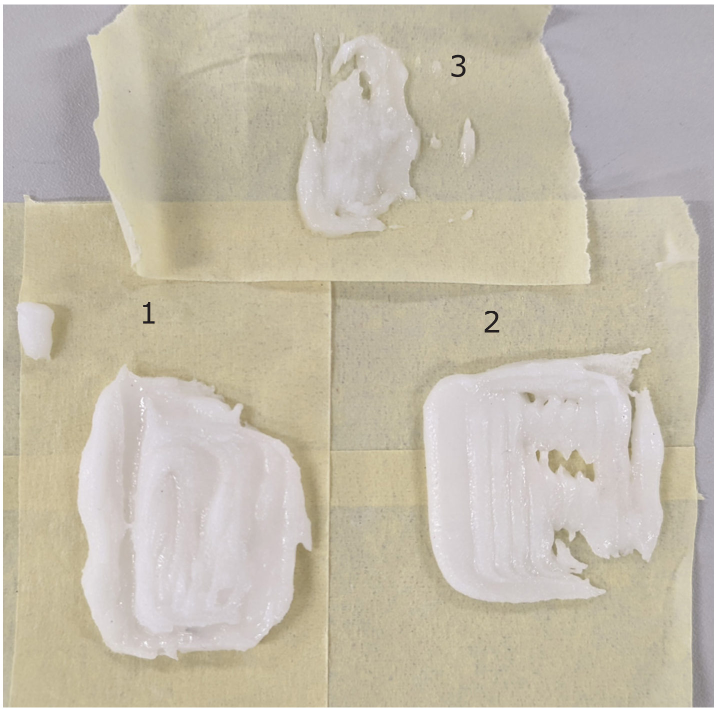


Figure 49. Successive prints showing the gradual decrease in flow theough the nozzle to a point of freezing of the stirrer

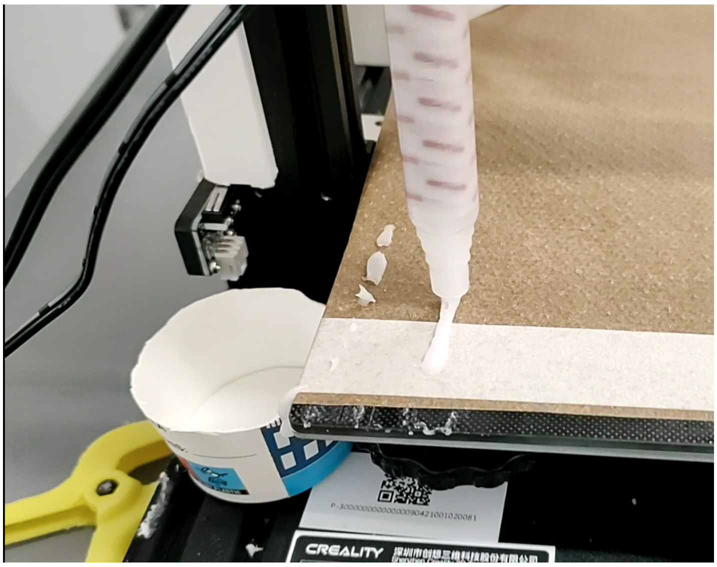


Figure 50. Successful printing using the baking soda analogue and test samples G-code

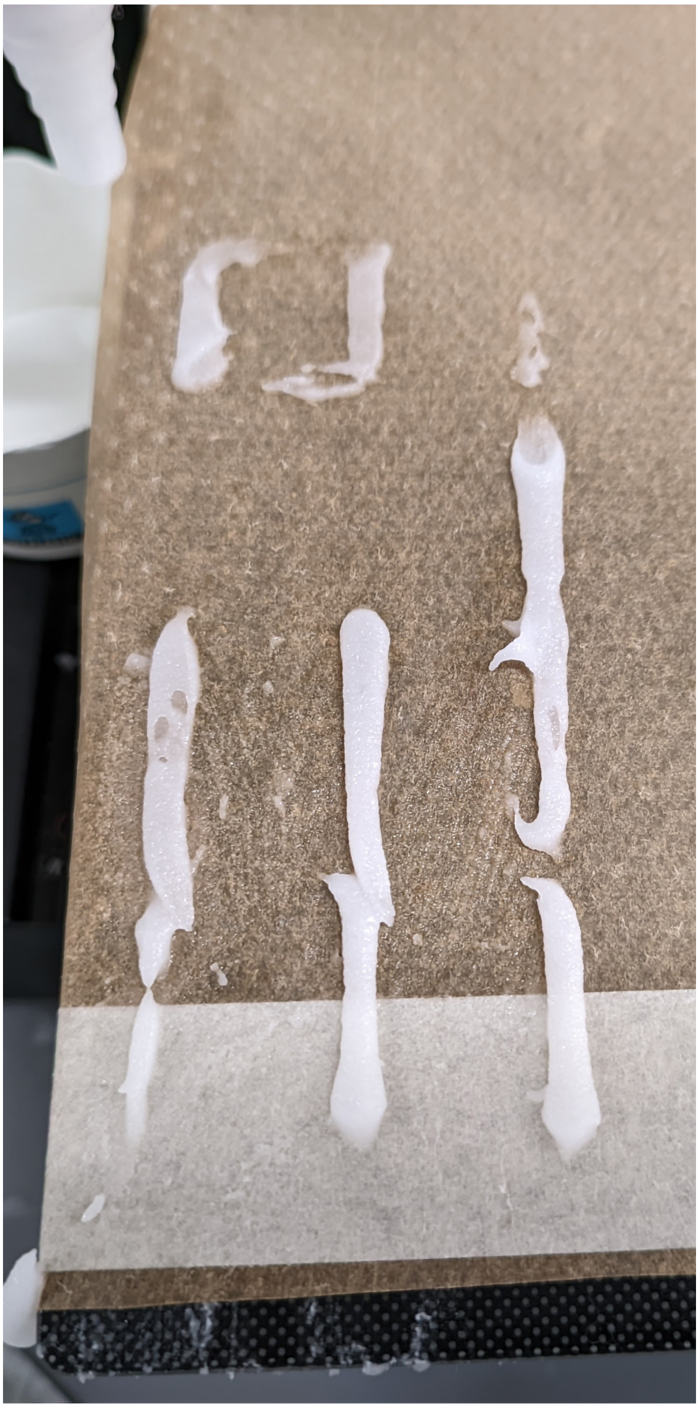


Figure 51. Final result of the test samples G-code, towards the end flow rate significantly dropped

system, which was initially intended to be the sole driver for the system, it was no longer capable of extruding the ink quickly enough before the curing of the magnetic in the mixing nozzle (Figure 46). This was due to the higher viscosity of the ink with the incorporated microparticles. The system's failure led to the modification of the printer design by adding a peristaltic

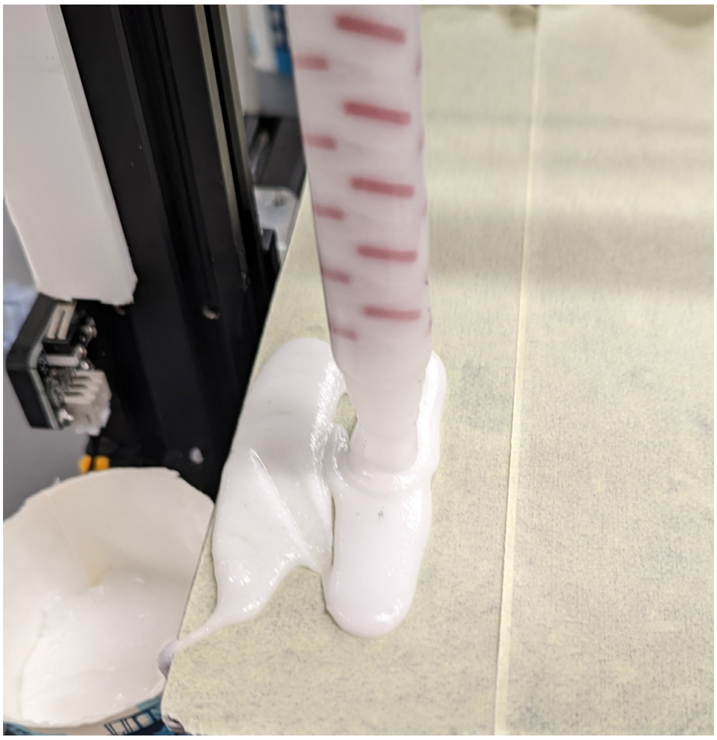
Figure 52. Third attempt with baking soda analogue resulted in improper flow along with significant step skipping, material did not cure (lack of either part A or part B)

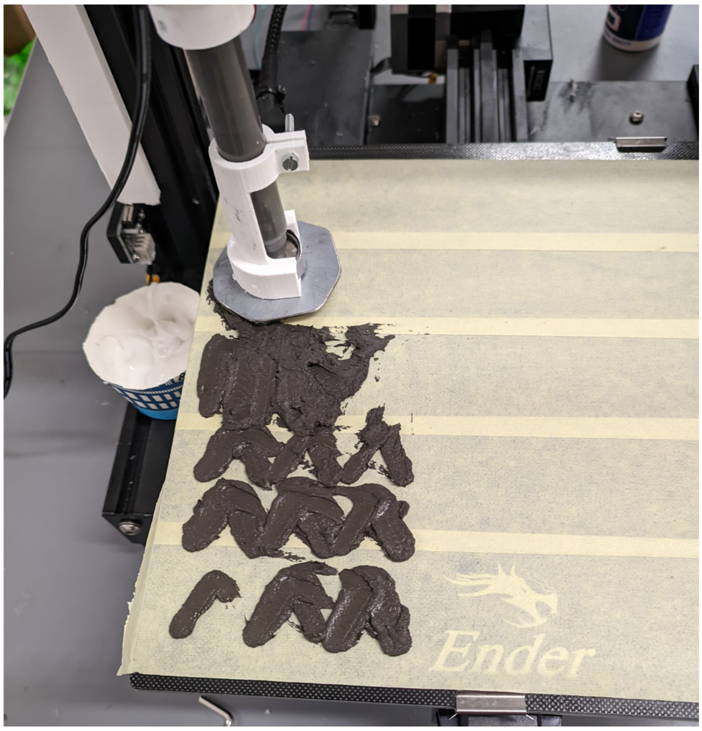
pump assembly. This change required adjustments in the extrusion command within the G-code used for printer testing. Initially, the extrusion command in the G-code relied on the Piston exrusion system, which required a gradually reducing rate of actuation due to the non-linear relationship between the linear actuation of the piston and the flow of material through the pipes. However, with the introduction of the peristaltic pump assembly, the extrusion command was modified to allow for a linearly increasing activation of the extrusion process, ensuring a proportional motion of the fluid through the pipes with each revolution of the peristaltic pump.

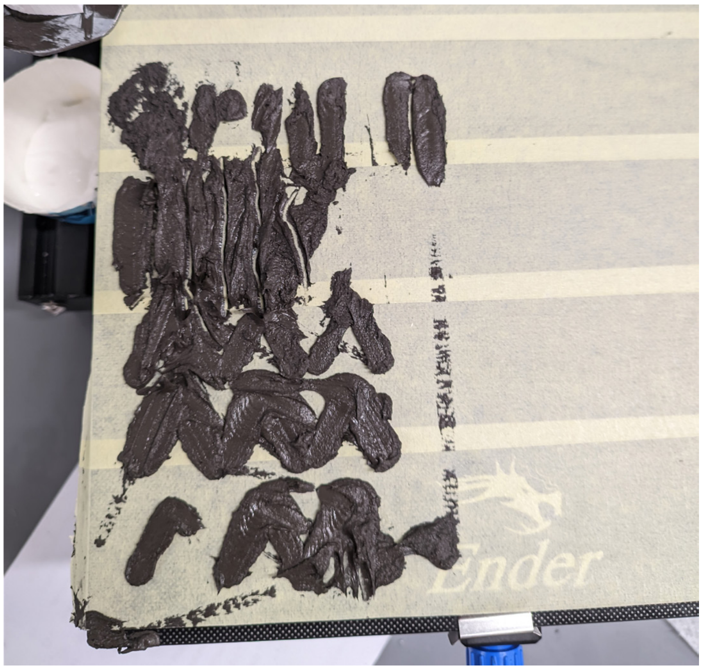
The modified G-code, which incorporated the changes in the extrusion command, was used to test various printer part prototypes. This testing aimed to determine the system's capability to move the material within the liquid in the pipes reliably and without any observed step skipping in the motor, which could occur when the torque requirement exceeded the motor's capacity to move.

In order to conduct the tests, analog materials were initially used as substitutes for the costly neodymium magnetic micro particles present in the original magnetic ink components. Iron carbonyl microparticles were chosen as an alternative because they exhibited attraction to magnets, though they themselves did not possess magnetic activity. This choice allowed for the testing of the printer's functionality and validate the overall system without the added expense of using the original magnetic particles.

Furthermore, during the testing of the complete printer extrusion system, baking soda was used as a mixer material. This choice was based on the need to ensure that the material could pass through all the parts of the extrusion system, from the extruder to the nozzle, in a consistent manner. Multiple viscosity tests were conducted with both the analog and magnetized material to ensure printability







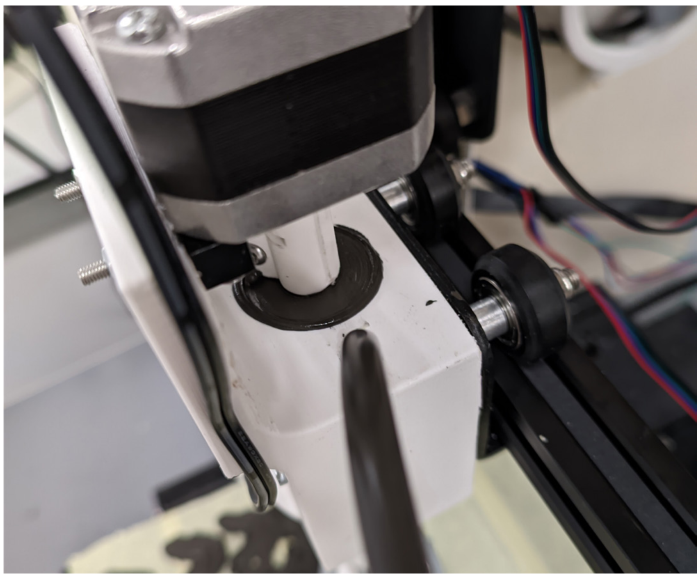
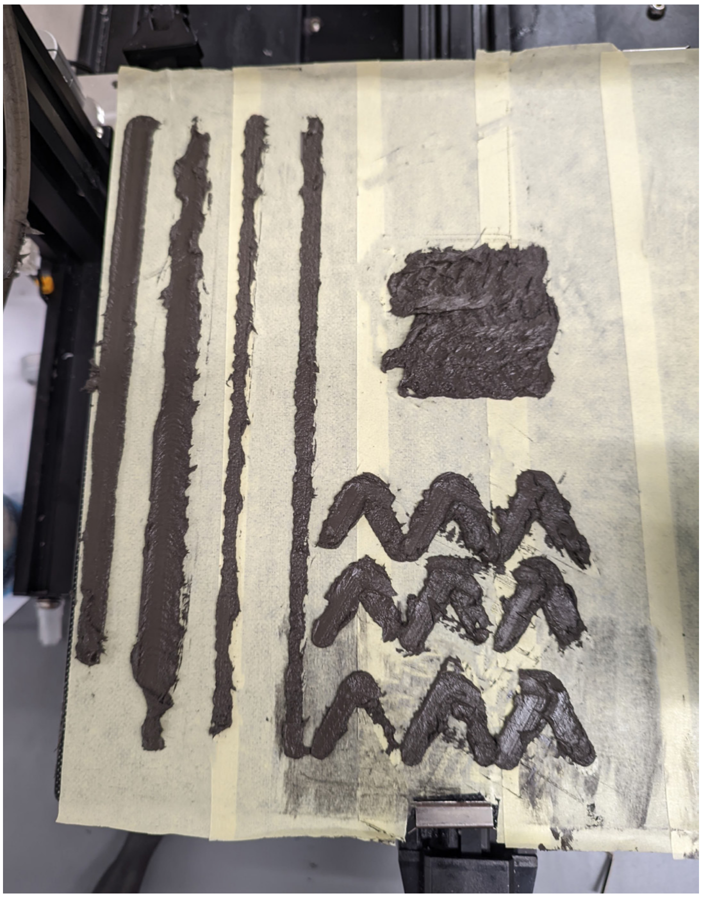


Figure 53. (Top left) Further printing with analog material showing more promising results than previous testing, overflow observed. (Bottom left) 2 cured prints with the one on the right being made with a slower flow rate. (Top Right) improper printing seen during first test with magnetized material. (Right centre) final result of first print with magnetized material, the mixed together material was manually separated in an attempt to recover some usable samples. (Bottom right) overflow seen wherein the material flows up the stirrer rod between the motor collet and stirrer, through the casing due to the pressure generated inside the mixing nozzle.

of the material. (see Section 4.3 for further details)

After the printer was tested with the analog material made using baking soda, it was then used with the magnetized neodymium microparticles ink to print the prototypes. The first attempt at printing began well but as the printing progressed, the flow of the material was very high causing a lot of overflow (Figure 53 Top-right), this combined with a large magnetic shield caused a situation where the shield would spread the already printed material and create unsuitable results (Figure 53 right-centre). This was particularly prominent in the printing of the flower and suction parts of the prototype, where the overflow and speading resulted in a large amount of mixing of the already extruded and aligned material. To remedy this, the flow-rate was reduced for the next round of printing, the printing pattern was simplified, the magnetic shield was made smaller and the distance between the printed parts was increased to prevent cross mixing.

These adjustments were implemented in the second printing round, resulting in significant improvement (Figure 54 Top), particularly in reducing the flow rate. However, it’s worth noting that the flow remained larger than the nozzle diameter, leaving room for further optimization.



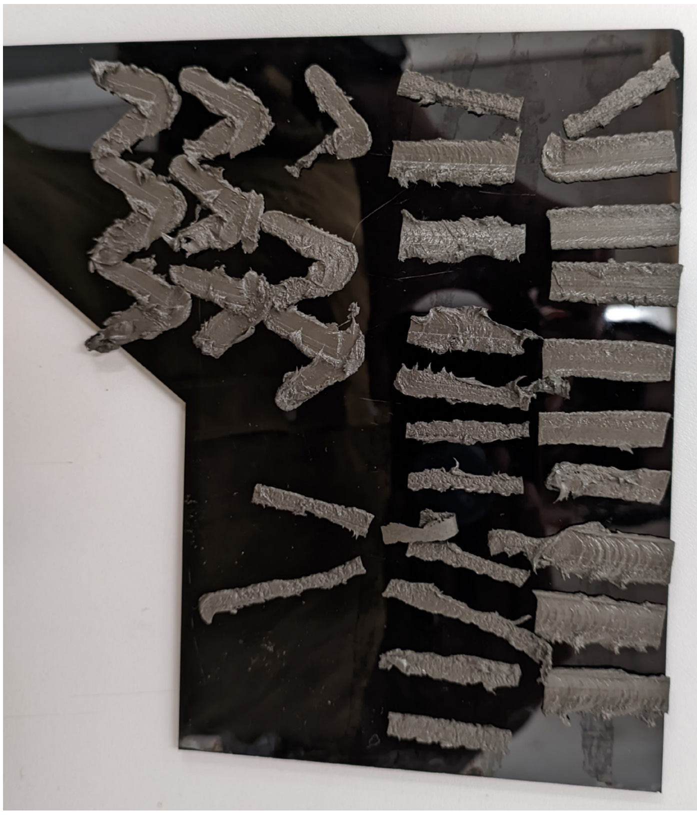


Figure 54. (Top) result of second print session with magnetized material incorporated best practices identified from the first round of printing. (Bottom) working samples obtained from the second print session segmented into 30mm long pieces.

3.9. Printer Usage Guidelines

The usage guidelines for the 4D printer involve several important steps to ensure its proper functioning and minimise ink wastage during printing.

1. **Ink Loading:** The first step is to load the ink onto the printer by manually filling the syringes with the appropriate ink components. It's crucial to ensure that the part A and part B of the ink are placed in the same syringe to prevent cross-contamination.

2. **Piston Engagement:** After loading the ink, the piston is placed in its most extended position to allow air pressure generated within the piston to assist in pushing the material forward. The piston is engaged with the extrusion assembly using a piston attacher, securely fixed with a set screw.

3. **Motor Connections:** Ensure that the motors of the extrusion assembly and peristaltic pumps are correctly connected to the stepper motor controller. This ensures proper control and operation of these components.

4. **Tubing Connection:** Connect the luer lock on the tubing to the syringe luer lock, ensuring a tight engagement to prevent overflow at the connection point.

5. **Peristaltic Pump Setup:** Properly route the tubing through the peristaltic pump casing, ensuring good contact between the rotor of the pump and the tubing. Connect the peristaltic pump motors to the printer.

6. **Extrusion Assembly Setup:** Secure the connections between the collet on the stirrer motor, connecting rod, and dynamic mixing nozzle using screws. Put the casing of the dynamic mixing nozzle in place and engage the nozzle locking mechanism for a sealed fit. Connect the stirrer motor to the corresponding stepper motor driver. Attach the magnet holder and the magnetic shield to the mixing nozzle.

7. **Power Connection:** Plug in the two stepper motor drivers and the printer's controller to the power outlet.

8. **Engage Piston extrusion System:** Periodically engage the piston extrusion system to maintain positive pressure in the system and assist the peristaltic pump in efficient material flow.

9. **Prime Nozzle G-Code:** Run the G-Code for priming the nozzles. This involves heating the printer's hot end, homing the printer's axes, and spinning the extruder motors to prime the tubes and mixing nozzle.

10. **Execute Prototype G-Code:** Once the nozzle is primed, immediately execute the prototype G-Code to ensure smooth flow throughout the operation. Failure to do so may result in increased material wastage.

By following these usage guidelines, the 4D printer can operate effectively, with minimised ink wastage and smooth material flow during the printing process.

4. Material Experimentation

The recipe used in this project was a modified version of the recipe originally developed by Y Kim from MIT. The original recipe utilized SE 1700 material from Dow Corning as the resin base for creating magnetic memory materials.
The recipe was initially referenced during the graduation of Sanne van Vilsteren (Sanne, 2021), Sanne further tweaked and tested the recipe, iterating upon it to optimise the desired magnetic properties and printability.
However, due to difficulties in obtaining the SE1700 material, he modified the recipe to use EcoFlex 00-10 resin instead, which was easier to obtain.
After Sanne's contributions, the modified recipe was used as the base for the graduation project of Kevin van der Lans, who played a crucial role in finalising the recipe for the project. He made additional modifications to ensure that the recipe would meet the specific requirements of the magnetic memory materials they intended to create.
This project aims to build upon that research by further investigating these material properties, with a specific focus on their impact on printability. The project will examine how changes in the concentrations of microparticles and improper mixing ratios of resin components affect the printing process. Additionally, to meet the printer's requirements, the magnetic material undergoes magnetization in a magnetizer up to 3 Tesla. This process imparts magnetic properties onto the microparticles. Both iron carbonyl and neodymium powders are magnetized, and their magnetization is tested to understand the expected variations achieved using these materials.

4.1. Non-magnetized material testing

To test the non-magnetized materials, the first step involved replicating Kevin Van der Lans' ink recipe, which served as a baseline for comparison. This recipe consisted of 100% carbonyl and helped in understanding the process of making magnetic ink. The initial testing included manual mixing and extrusion of the ink in different geometries to observe their effects.
The next test examined the differences between using ink with a 63% micro particle concentration and a 50% micro particle concentration (See Figure 55). The objective was to determine if altering the concentration would adversely affect the magnetic properties, viscosity, and printability of the material. It was found that the material with a 63% concentration was significantly more viscous, allowing it to support additional layers, indicating its suitability for three-dimensional prints. On the other hand, the material with a 50% concentration exhibited lower viscosity and resulted in ineffective layer adhesion.
Based on these results, it was concluded that maintaining a 63% micro particle concentration was optimal and should not be changed.
The subsequent test compared the results of improper mixing of the two parts (A and B) of the silicone magnetic inks at a 70/30

concentration (Figure 56). It was observed that at a higher concentration of Part A, the material remained viscous, similar to the 63% concentration ink. However, at a 70% concentration of Part B, the material resembled the 50% concentration ink, displaying lower viscosity and slower curing.

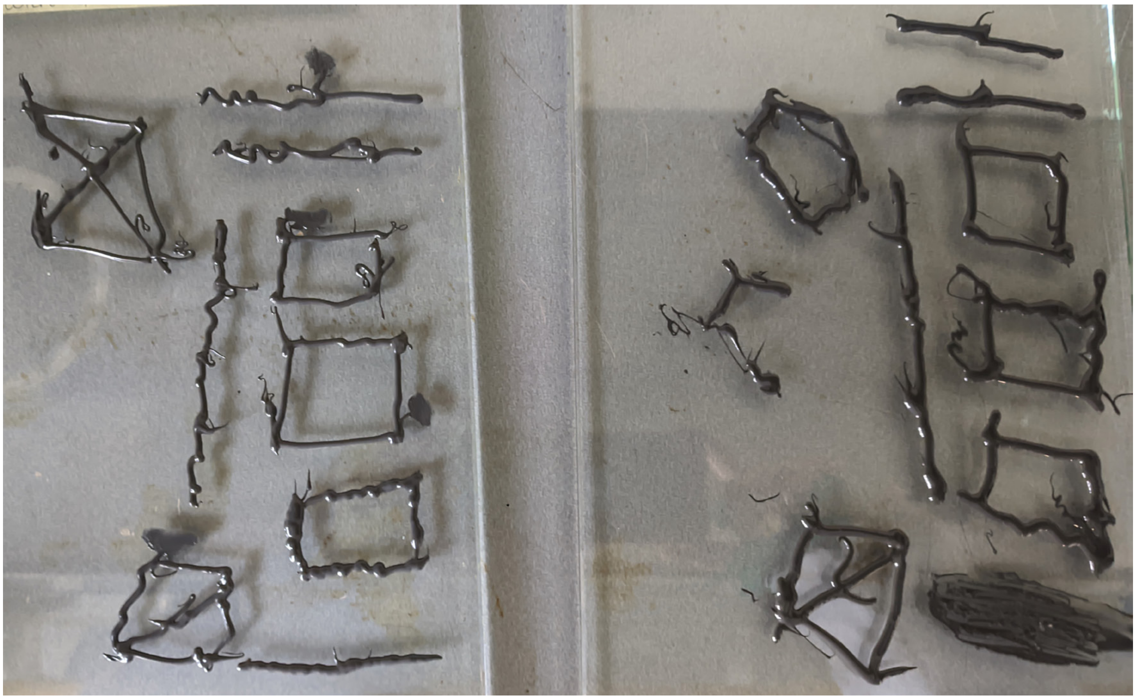


Figure 55. Manual extrusion of 63% (left) and 50%(right) by weight of Iron-carbonyl microparticles

Figure 56. Results of (70-30) (left) and (30-70) mixing ratios of Parts A and B resins

4.2. Magnetized material testing

Next, larger quantities of ink were magnetized to impart magnetic properties. This magnetization process was conducted at the TU Delft’s Reactor Institute using a magnetizing machine. Parts A and B of the ink, consisting of neodymium and iron carbonyl, were mixed in a 63% concentration. Samples were taken from this magnetized ink to test the success of magnetization and investigate shape memory effects (Figures 58 and 59). The results showed that Neodymium, when cured, retained its magnetization, and different segments of the ink printed in the same direction acted as

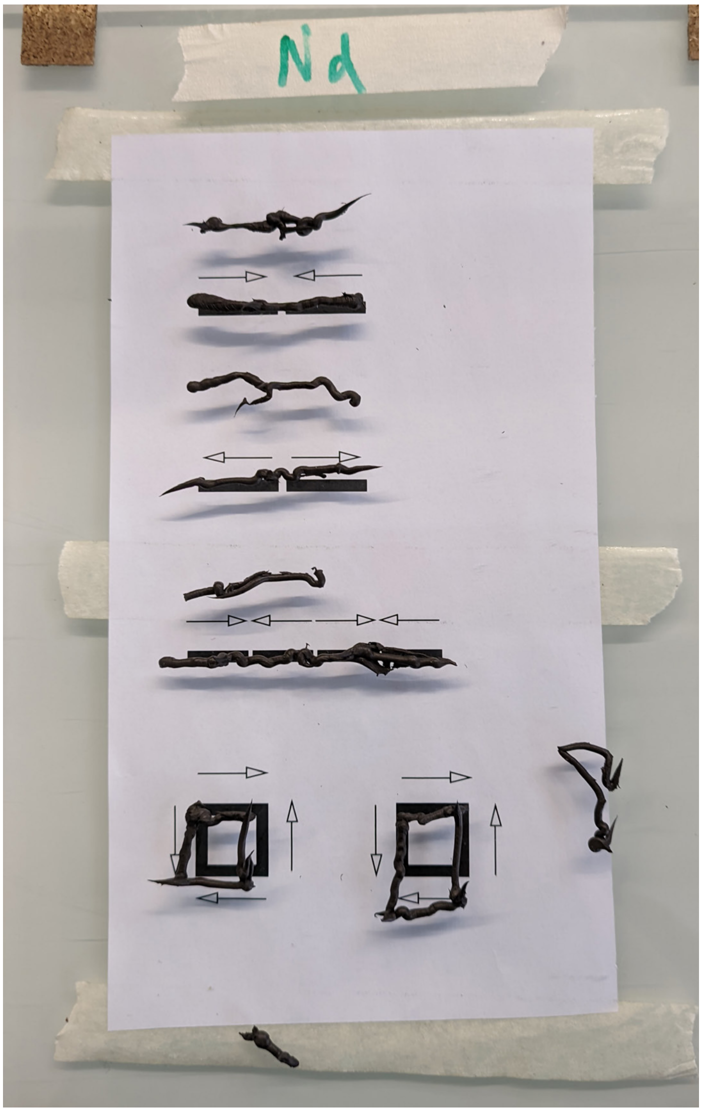
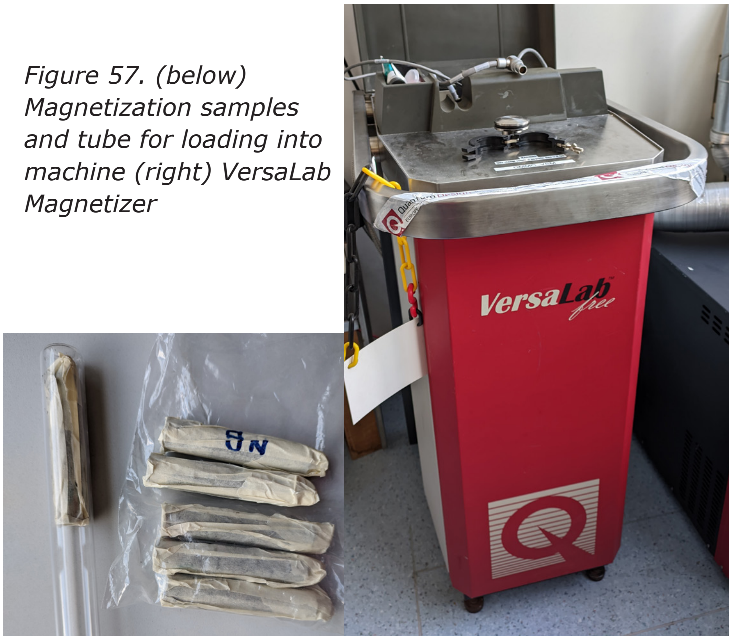


Figure 58. manual extrusion and template used to print samples using magnetized material of both Neodymium and Iron

Figure 57. (below) Magnetization samples and tube for loading into machine (right) VersaLab Magnetizer



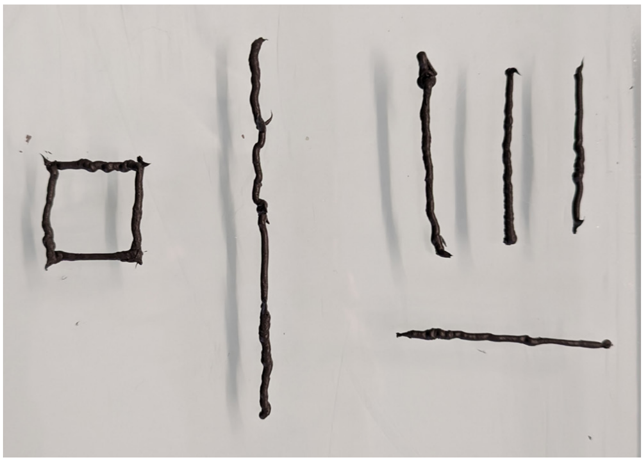


Figure 59. Second set of manual extrusion magnetized samples for material testing

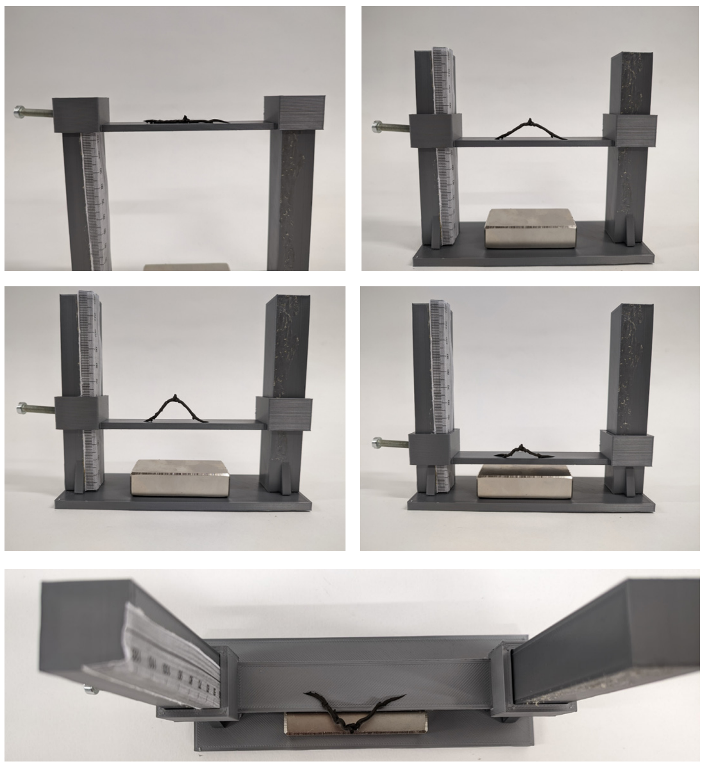


Figure 60. 2 Segment sample shape change 100,50,25 and 10mm from a strong magnet surface

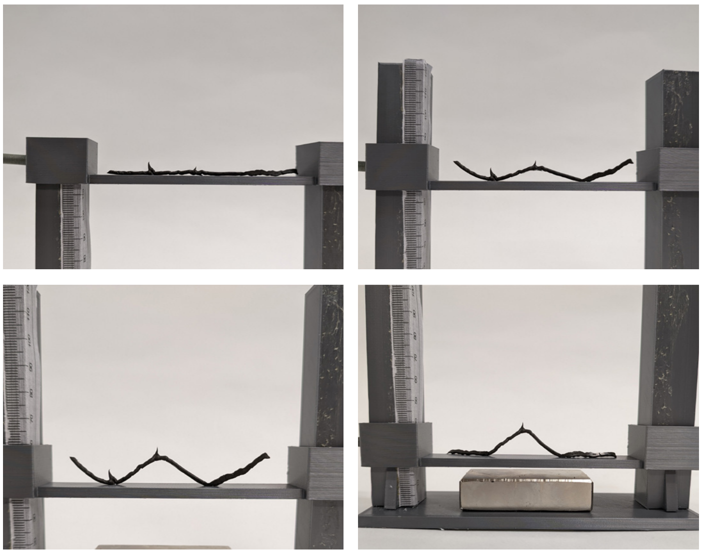


Figure 61. 4 Segment sample shape change 100,50,25 and 10mm from a strong magnet surface

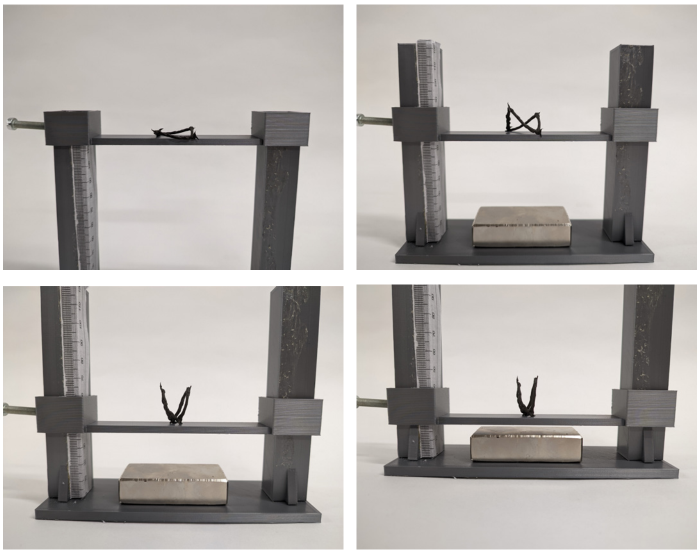


Figure 62. 4 Segment square sample shape change 100,50,25 and 10mm from a strong magnet surface

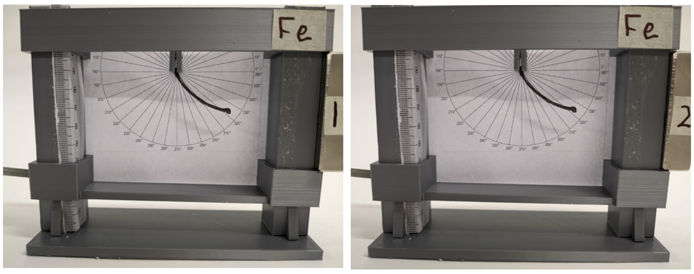


Figure 63. Angular deflection of magnetized Iron Carbonyl sample under opposite magnetic fields

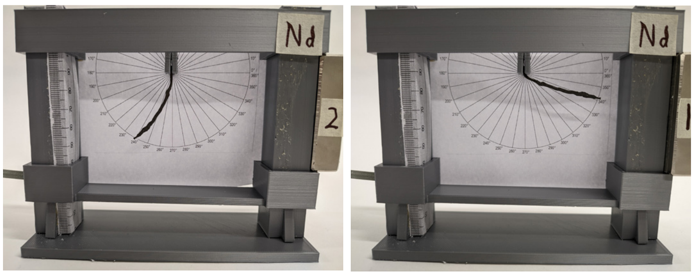


Figure 64. Angular deflection of magnetized neodymium sample under opposite magnetic fields

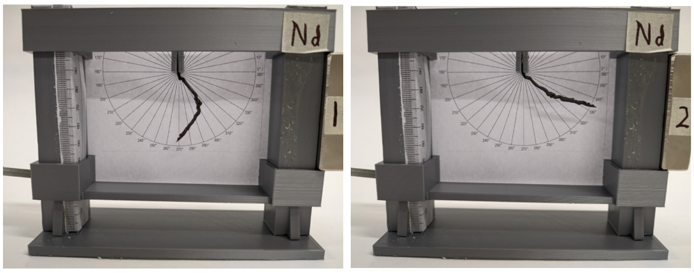


Figure 65. Angular deflection of 2 segment magnetized neodymium sample under opposite magnetic fields

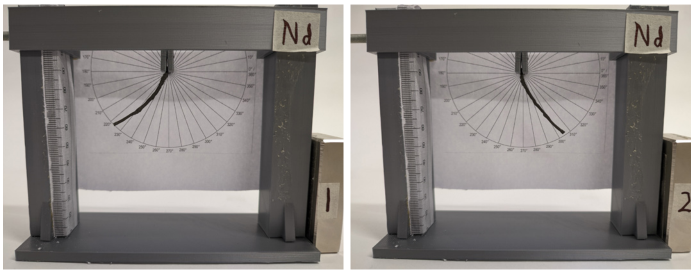


Figure 66. Angular deflection of magnetized neodymium sample under weaker opposite magnetic fields

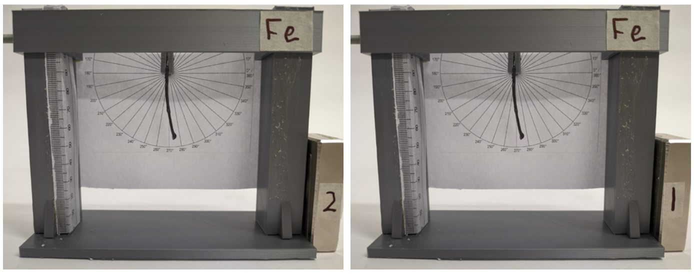


Figure 67. Angular deflection of magnetized Iron Carbonyl sample under weaker opposite magnetic fields

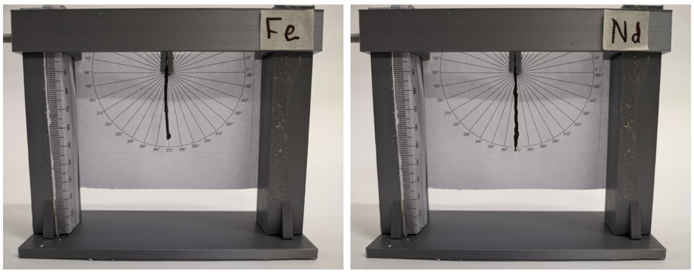


Figure 68. Deflection under no magnetic fields

independent magnets. Testing involved assessing the shape change of samples at varying distances from a fixed magnet, revealing that the iron ink only exhibited ferromagnetic behavior and lacked magnetization, while the neodymium ink acted as magnets in the presence of a

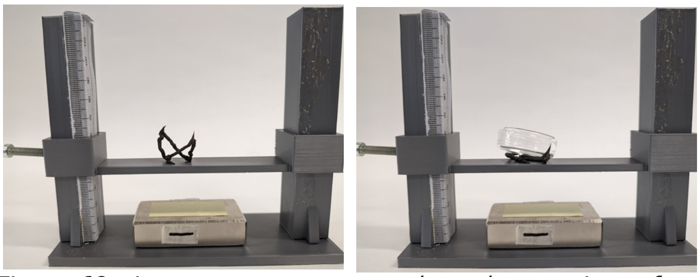


Figure 69. 4 segment square sample under a weignt of 7.8g at a distance of 25mm from magnet surface

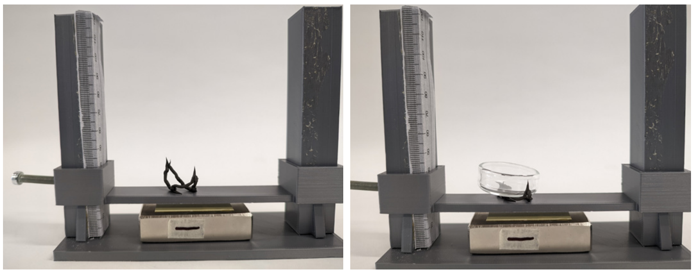


Figure 70. 4 segment square sample under a weight of 7.8g at a distance of 10mm from magnet surface

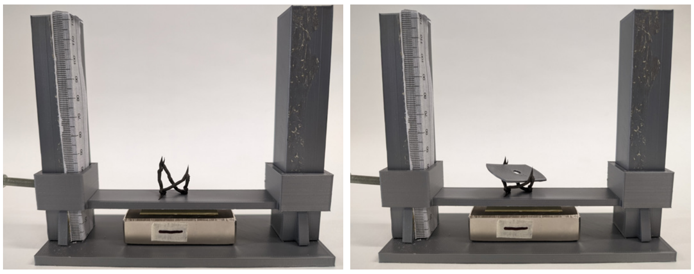


Figure 71. 4 segment square sample under a weight of 0.9g at a distance of 10mm from magnet surface

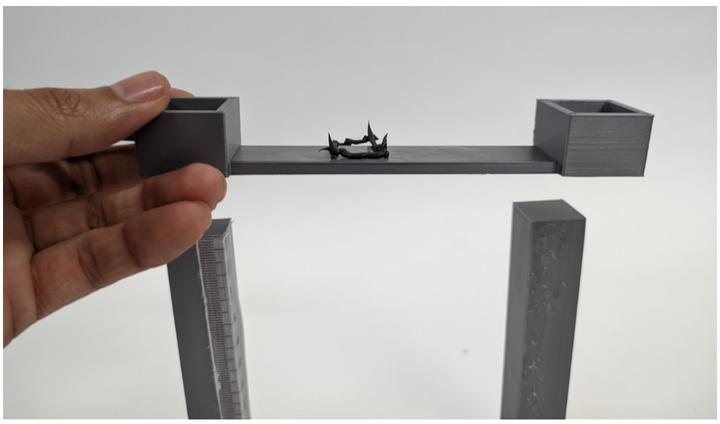


Figure 72. Material shows complete immediate shape recovery upon removal of magnetic field

magnetic field.

Multiple types of samples were created using both inks, and they can be categorized into three types. The first type consisted of a sample with two straight lines meeing in the centre whose magnetic moments are in opposite directions, which theoretically should generate a V-shaped structure (Figure 60).

The second type involved four consecutive line segments, each drawn in alternating directions, which could create an M or W shape when exposed to a magnetic field (Figure 61).

The third type focused on square geometries, where two adjacent line segments started from the same point, and the other two line segments started from the diagonally opposite point (Figure 62). This configuration should result in a double V structure, with two points of the square moving away from the magnetic field and two points moving towards it.

The final type comprised a single line segment drawn in one direction, which acted as a single magnet. This sample was used to test the angular deflection in the presence of a magnetic field.

From the various pictures testing the deflection based on proximity to the magnet, it is observed that the behavior of the sample is mostly as expected as it is coming closer to the face of the magnet, but when the material is very close to the magnet, its shape changes again as now, due to the shape of the magnet, magnetic fields of the opposite face too come into picture attracting the ends of the sample that were supposed to be deflected away. This is particularly a problem if the sample is an open geometry with free ends that can show anomolous deflection behavior (as seen in Figure 60 and 61).

From the various pictures testing the angular deflection (Figure 64-66), it can be inferred that the Nd-magnetized samples are strongly attracted to the magnet as long as the free tip is magnetized such that it attracts to the magnet face, when the polarity of the magnet is reversed, the material is deflected away from the magnet, but to a lesser angle, this is due to the fact that the effectiveness of the magnet reduces following the inverse-square law and it is not able to push away the tip if it moves too far away from the magnet face.

Another important aspect to test is the weight holding/force exertion capability of the material. During this testing it was seen that while the material is able to hold weights close to its own weight (~0.9g) as seen in Figure 71, it struggles to hold heavier weights due to the fact that the material used (Figure 69 and 70), EcoFlex 00-10 is a soft resin and is not able to provide a lot of structural strength to properly be able to exert the force it experiences through the interaction of the magnetized particles and the magnet.

4.3. Viscosity testing

To refine the printing process, an investigation into the viscosity properties of both analog and magnetized materials was conducted. The purpose was to better understand these materials' behaviors and ensure consistent and reliable printing outcomes. The analysis involved following the viscosity tests conducted by Kevin Van Der Lans, focusing on studying viscosity in relation to shear rate.
The test was conducted on a TA Instruments AR-G2 machine. The test was conducted with a 40mm stainless steel peltier plate, 25 centigrade temperature, shear rate from 0.01/s to 100/s, 3 steps for every order of magnitude and 30s of data collection for every step.

Initial viscosity tests on the analog material revealed unexpected results. It was discovered that contamination in part A of the resin caused clumping, resulting in a viscosity significantly higher than anticipated. The subsequent filtration of the material through a sieve rectified this issue, yielding a maximum viscosity of around 3000 Pa.s. Similarly, part B of the resin-analog material too showed peak viscosity in the range of 3000 Pa.s. These values were observed to be significantly less than those observed by Kevin (2022) which were in the range of 8000 Pa.s.
To bring the analog material closer in viscosity to these results, more baking soda was added to increase the viscosity with relatively successful results of viscosity in the 7000 Pa.s range.
Next to also ensure that the magnetized material produced in this project was similar to that of Kevin (2022), the magnetized material was also tested and it was found that the peak viscosity was in the order of 100000 Pa.s, this was an order of magnitude greater viscosity in the lower shear rates, but it was observed that the viscosity became similar to that of Kevin's material and the analog material in the higher shear rates. Compared with the analog material, higher shear rate was an

expected side effect of the magnetization of the microparticles in the ink which would cause the attractions and repulsions of the microparticles to contribute to the higher resistance to shear.
Simultaneously with the viscosity tests, flow tests using the 4D printer too were conducted to see whether the material was able to flow at a adequate and consistent rate. This testing showed a key difference between the analog and the magnetized material, wherein, the analog material would stick to the walls of the tube and flow like a viscous fluid, the magnetized material was observed to not stick to the wall and flow through more like a solid, holding a cylindrical shape during its exit from the tube. This testing also served to see how well the material was able to flow using the current printing apparatus
To solve this problem of significantly higher viscosities, a resin thinner (Smooth-on Silicone Thinner) made for the EcoFlex 00-10 resins was used to bring the viscosity down. While the manufacturer recommended an addition of only 10% by weight of the silicone used, this was not enough at still showed a high amount of viscosity, therefore this limit was exceeded with the reasoning being the additional microparticles added to the material that let the ink incorporate more thinner. After testing a value of 25% by weight of the resin was finalized which had a much more reasonable viscosity in the order of 10000 Pa.s.

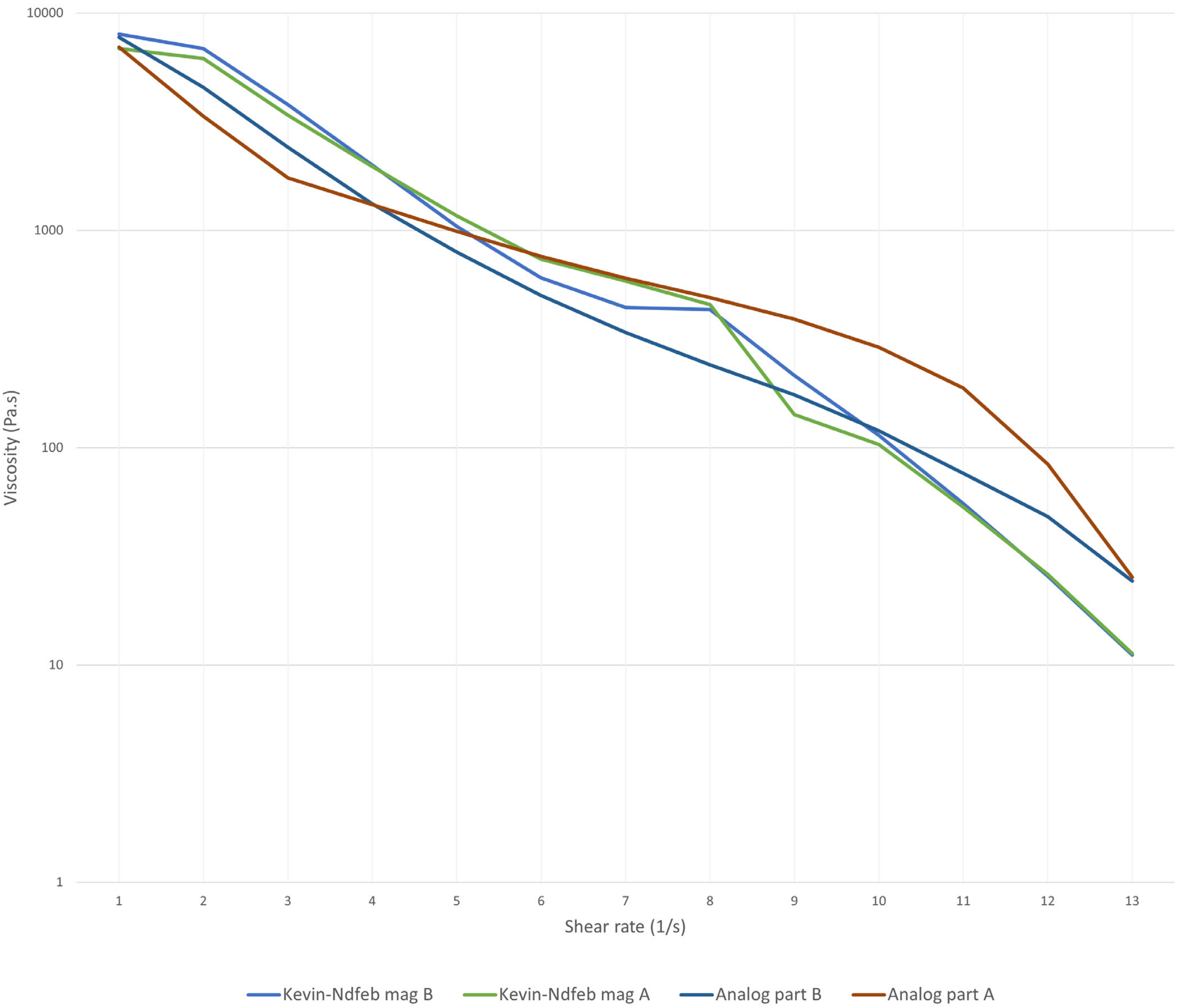


Figure 73. Graph comparing viscosities of refernce ink of (Kevin, 2022) and Analog inks used

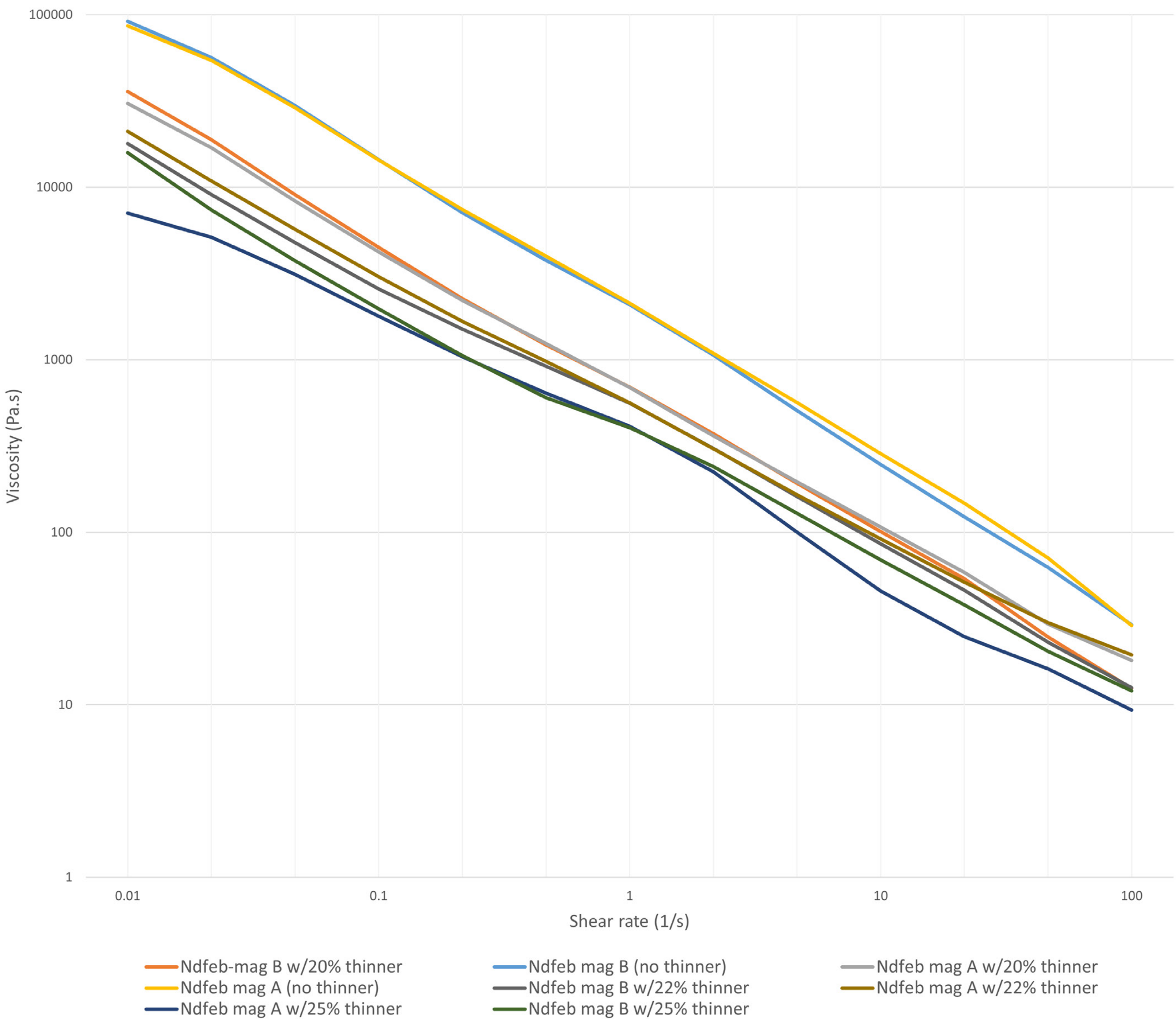


Figure 74. Graph comparing viscosities of various progression of addition of thinner to the magnetized inks (0-25% by weight of base resin used)

5. Concept Development

The graduation project has two primary focuses. The first objective is to create a 4D printer capable of working with magnetic materials. This printer aims to produce objects that can change their shape over time in response to external stimuli. The second objective is to utilize the capabilities of the 4D printer and magnetic materials to develop a functional prototype or demonstrator that showcases the potential of this technology. By combining magnetic materials with other substances, the project seeks to create concept prototypes that serve useful functions. By exploring the combination of materials, the project aims to create

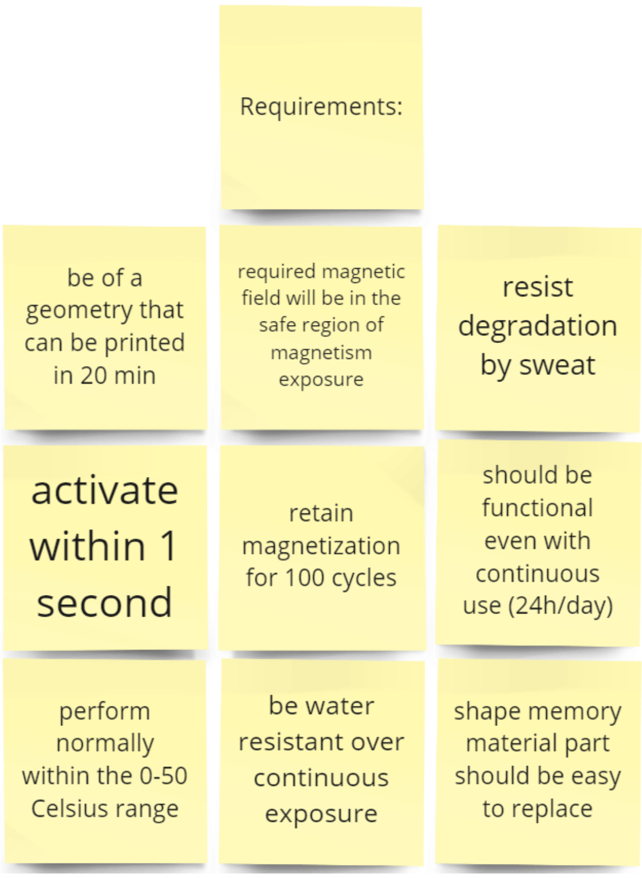
motion and mechanical systems that can demonstrate the capabilities of the technology and inspire other designers. The goal is to provide a tangible example of the diverse applications and directions in which magnetic materials can be implemented.

5.1. Requirements and wishes

The wishes and requirements are essential components of the graduation project. The requirements establish the necessary guidelines and benchmarks that the 4D printer and the printed material must meet to be considered successful products. They outline specific performance criteria and functional attributes, ensuring that the final product aligns with the project's objectives and delivers the expected performance, durability, and usability.

5.2. Ideation

During the ideation phase, several brainstorming sessions were conducted to generate ideas for potential applications of magnetic memory materials.
The first round of ideation involved a group session where participants from different departments were introduced to the material's capabilities. They then individually generated ideas for 10 minutes, followed by a group discussion to consolidate and refine the concepts using techniques like SCAMPER and morphological charts.
The second round of ideation focused on individual ideation using the Flower ideation method. Participants explored different domains of potential application and developed solutions within each domain.
The third round of ideation drew inspiration from biomimicry, examining nature's efficient designs that actuate at low power requirements. The shapes created by nature were considered as



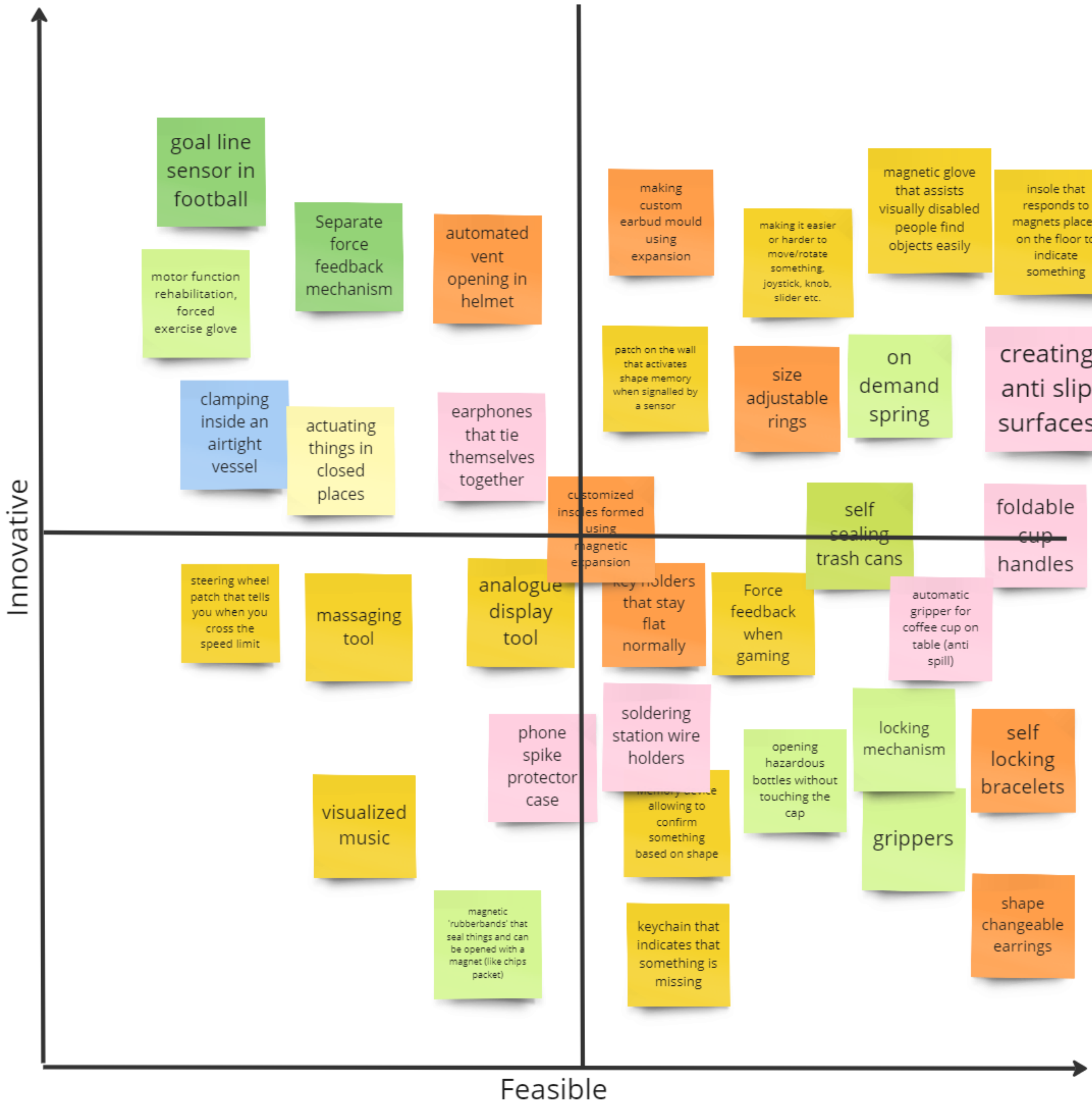


Figure 75. C-Box matrix used to compare the various generated ideas

possibilities for leveraging magnetic memory materials.

5.3. Conceptualization

After generating a range of ideas across different domains, a selection process was conducted to choose the most suitable demonstrators. The ideas were compared based on their innovativeness and feasibility, and the wishes (evaluation criteria) were used to assess their alignment with project objectives. A matrix was created to compare the ideas, considering their innovativeness and feasibility. Sketches of the most promising ideas were then evaluated against each other.
Ultimately, four demonstrators were selected from various domains, including

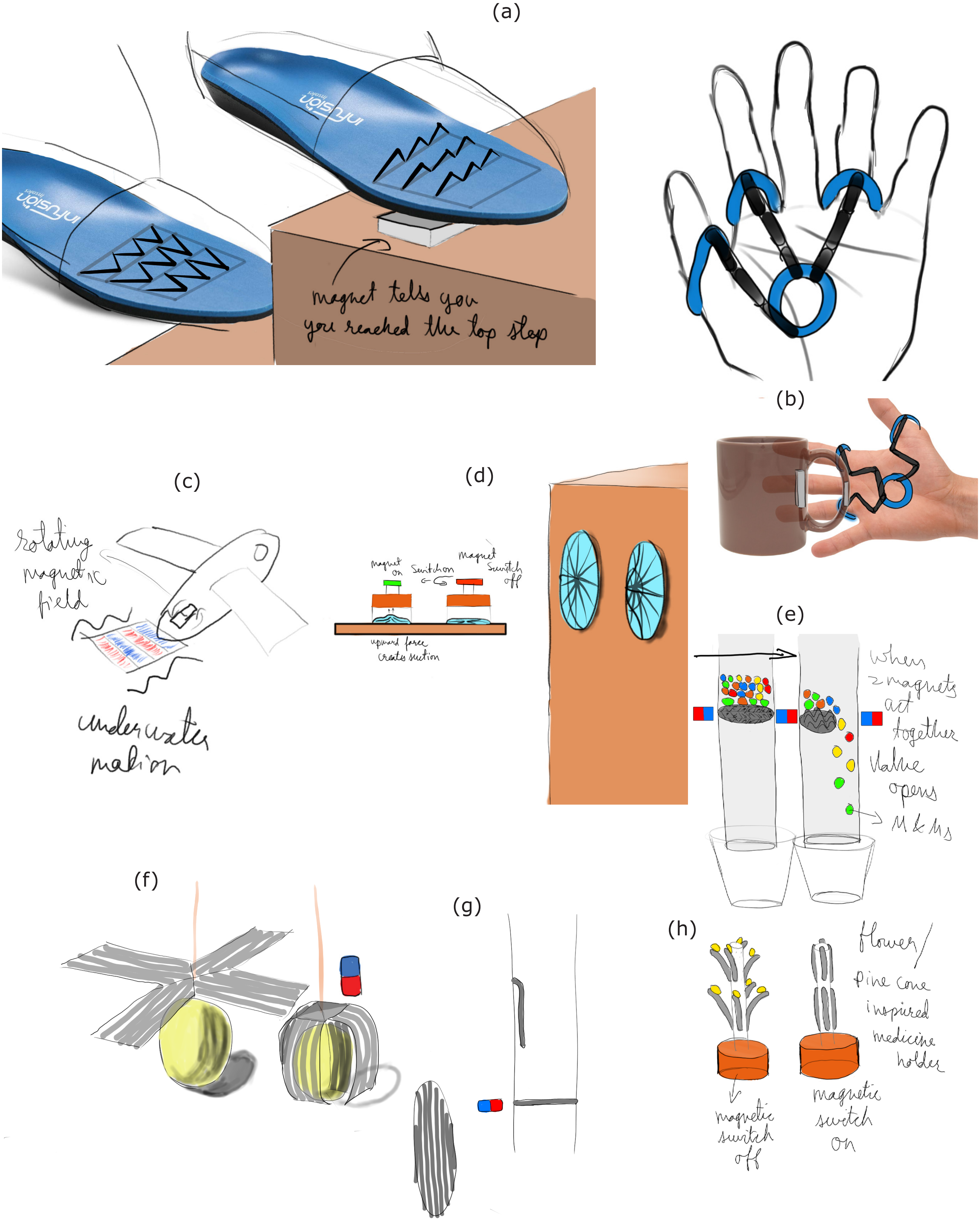
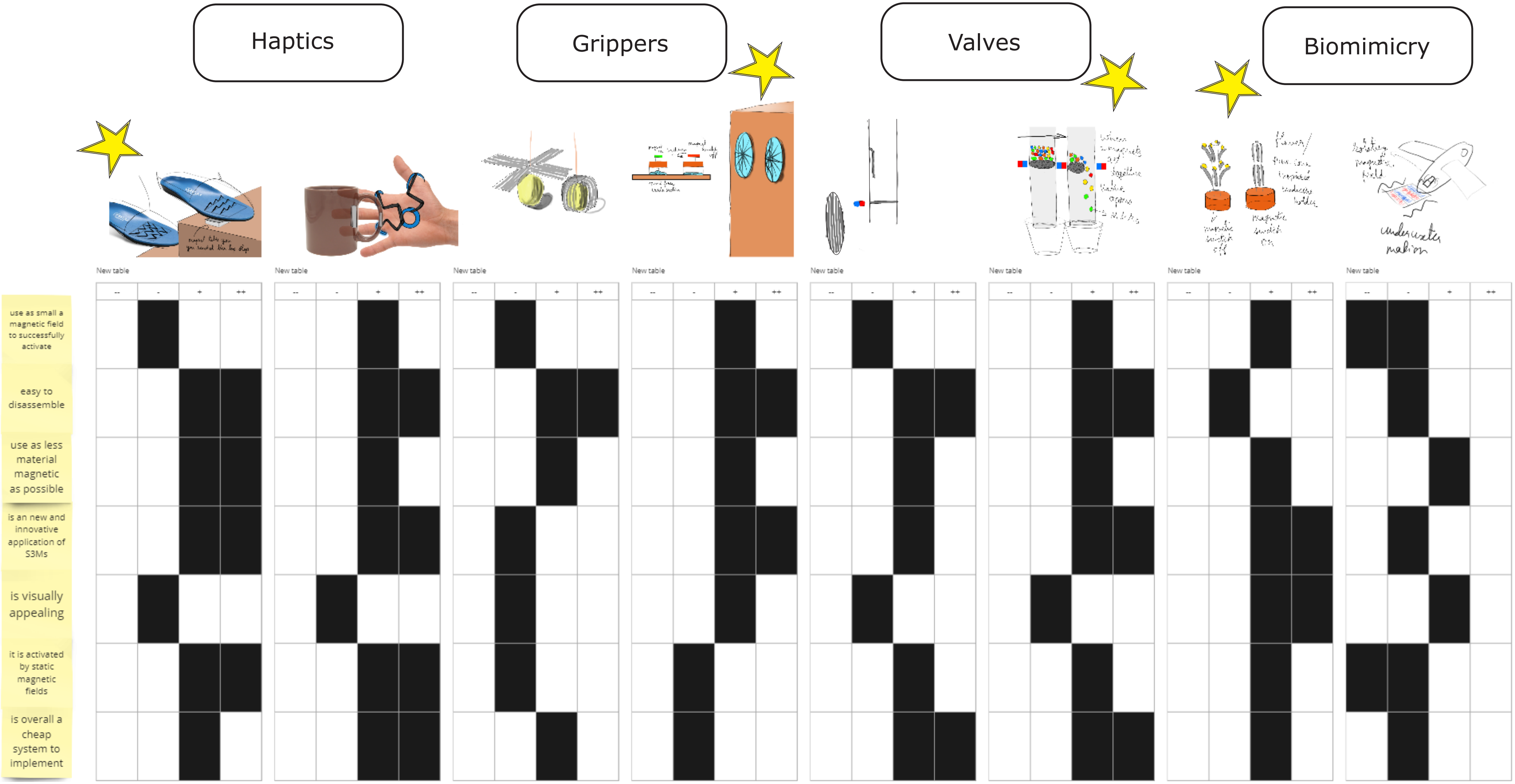


Figure 76. Various concepts illustrated (a) insole actuator that can help visually disabled people naviagate spaces more easily (b) wearable glove that can help visually disabled people find objects more easily (c) an underwater robot propelled by a sheet of magnetic materials that can be made to create motion by changing shape in the presence of an alternating magnetic field (d) vacuum suction cups that can be made to pull up and stick to flat surfaces in the presence of a magnetic field (e) a flat sheet valve that crumples itself in a magnetic field to create an opening in a pipe (f) a gripper that actuates its fingers in a magnetic field and grip strength can be controlled by moving the magnet (g) another simple plate valve that normally falls under gravity but can be made horzontsal in a magnetic field (h) a pinecone/flower inspired medicine holder system that can open up when a magnetic field is removed



Haptics
Grippers
Valves
Biomimicry
underwater nation
New table
--
-
+
++
use as small a magnetic field to successfully activate
easy to disassemble
use as less material magnetic as possible
is an new and innovative application of S3Ms
is visually appealing
it is activated by static magnetic fields
is overall a cheap system to implement

grippers, haptics, biomimicry, and valves. These demonstrators represented innovative and feasible applications of magnetic memory materials and served as tangible examples of their capabilities for the project.

The selected Demonstrators are the feet sensors under haptics, the suction style wall gripper, the flat pipe valve and the pine cone style medicine holder. These concepts now need to be better defined in terms of the way they are magnetically programmed.

5.4. Prototyping

The printing of the prototypes was conducted in two rounds. In the first test round, the designs of the suction gripper and pine cone were transformed into small vertical line segments, each measuring 30 mm, spaced 10 mm apart. V-shaped spikes were created, consisting of two segments at a 60-degree angle from each other, converging at a common point. These spikes were arranged in a 3*3 grid pattern.
The geometry of the pipe cover followed Kim et.al (2018)'s design. It included alternating line segments with opposite directions. This geometry was mirrored above and repeated to establish a 60*60 mm grid.
The initial printing round highlighted challenges, such as higher-than-expected material flow rates leading to overflow, and interference from the magnetic shield disrupting printed material distribution. Also, a pause command triggered accidentally during printing caused issues, and a similar pause just before printing the pipe cover resulted in progress loss.

The conclusions from this testing prompted changes. The flow rate had to be reduced. Initially, the G code directed 26 mm of extrusion for every 10 mm of actual printing distance was then altered to 20 mm of extrusion for the same 10 mm of printing. The large magnetic shield's size was decreased to a 28 mm outer circular diameter. The printing geometry was also simplified, consolidating short line segments into longer lines of 200 mm, spaced further apart.

5.4.1. Pine Cone-Style Demonstrator:

This prototype merges form and function seamlessly. By utilizing magnetized segments, it simulates the dynamic motion of flower petals in response to magnetic stimuli. The two sets of 4 30 mm segments represent petals of a pine cone which can be made to open or close based on the polarity of the magnetic field applied. These magnetized segments are stuck to the stem and the petals are glued on to better show their motion.

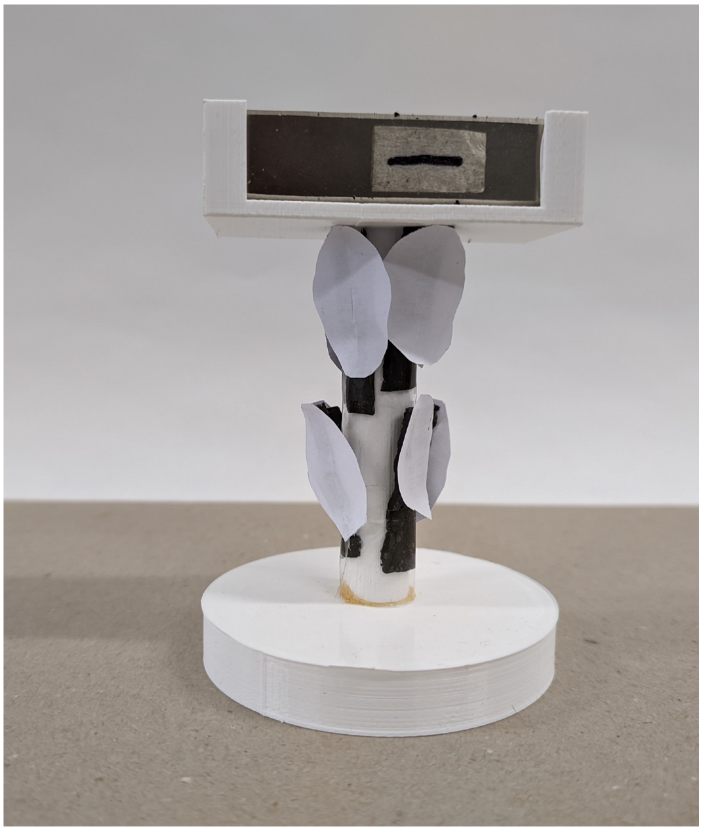
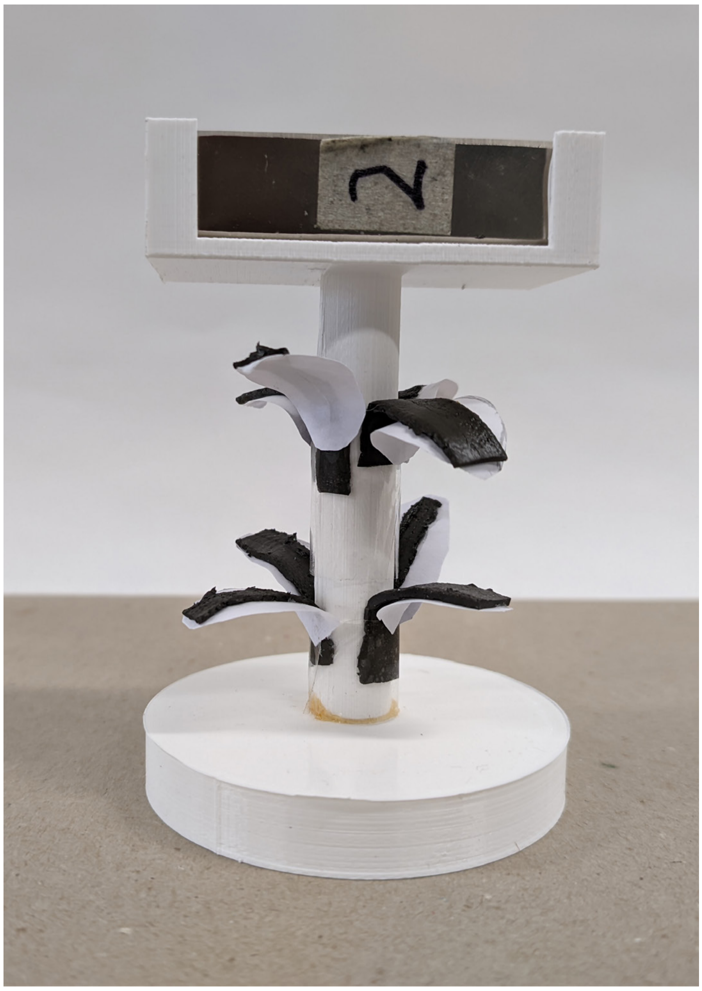


Figure 77. (Top) Pine cone demonstrator at resting position (Top right) Demonstrator when magnet attracts the free tips of the magnetized segments. (Right) Demonstrator when free tips repel the magnet



5.4.2. Haptic Feet Spikes:

This prototype serves a functional purpose for the visually impaired. The incorporation of unobtrusive spikes inside a shoe’s sole allows for the creation of tactile feedback. In response to magnetic fields, the spikes lift, creating a pressing force allowing for possibilities of enhanced spatial awareness. This is done by embedding magnets into the environment where they can signal danger to the user.

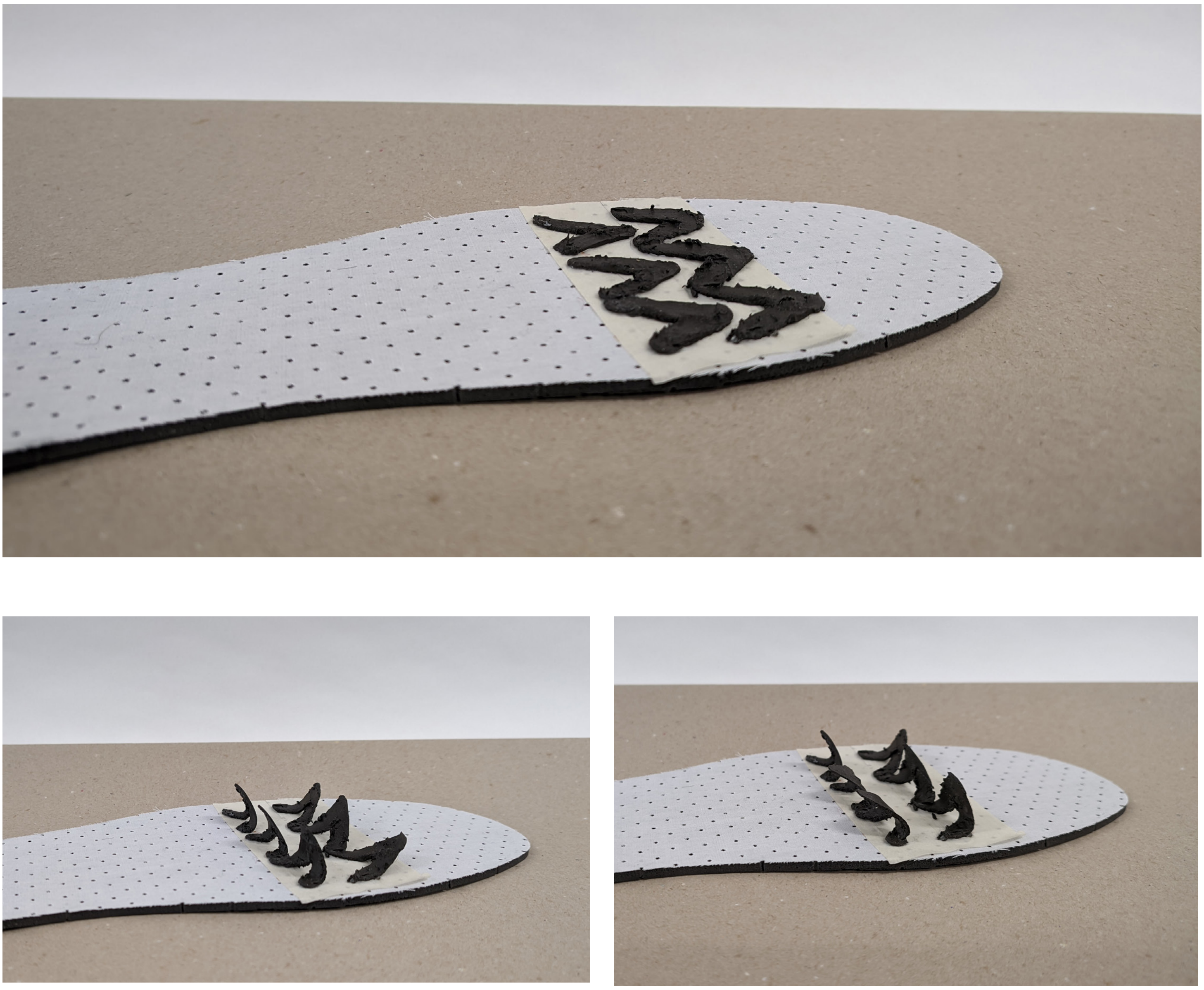


Figure 78. Haptic feet spikes demonstrator in its resting postion (Top) and progressively actuated positions (Left-Right)

5.4.3. Suction-Based Gripper:

This prototype demonstrates practical gripping applications. The magnetized segments are aligned to point to the centre of the 60mm circular mold which is then filled with EcoFlex 00-10 resin to a height of 2.5mm and set to cure, the final result is a gripper that that creates a vacuum at its centre when impacted by a proper magnetic field. This demonstrator is capable of lifting smooth flat surfaces as long as the resin is able to maintain a seal around the edge of the demonstrator. To better ensure a seal, and also proper magnetic actuation, a spacer was 3D printed that is used to press down the edges of the demonstrator and then a magnet can be placed on top of it for the actuation.

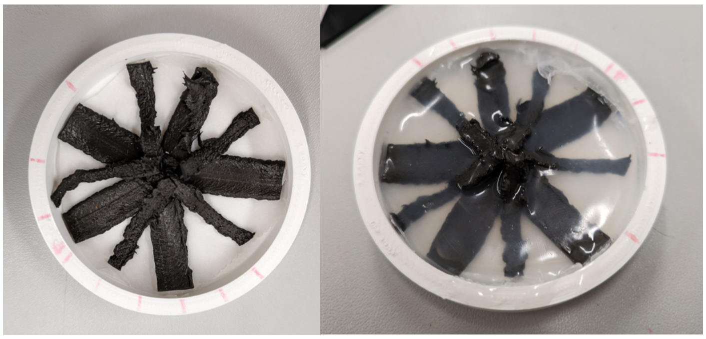
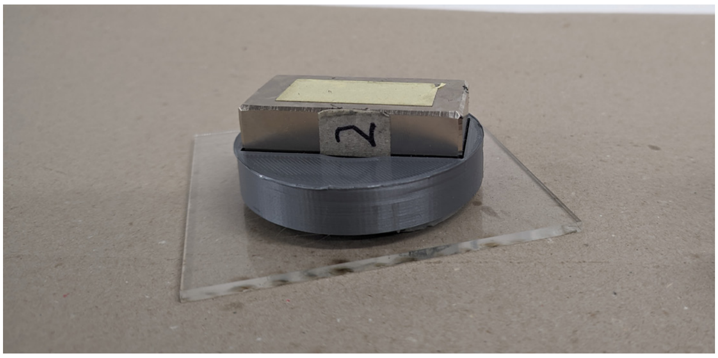
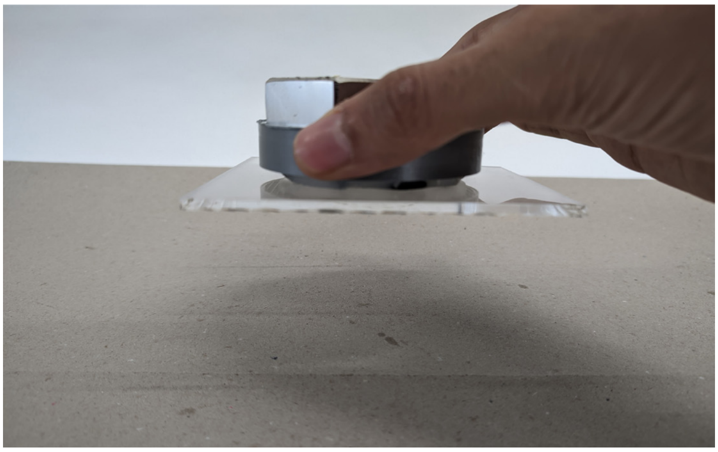
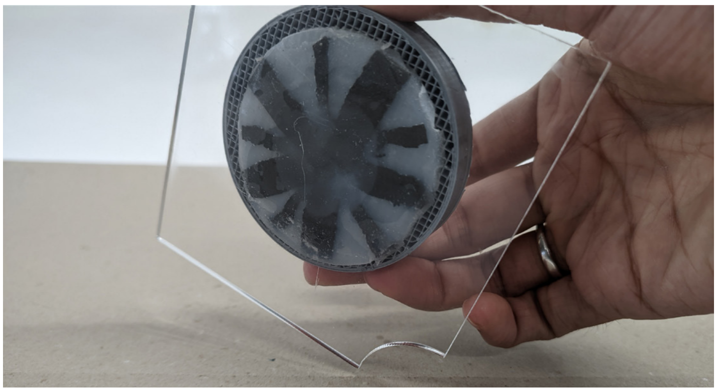


Figure 79. Suction Demonstrator being cast in resin (Top). (Right) progressive steps to actuate the demonstrator



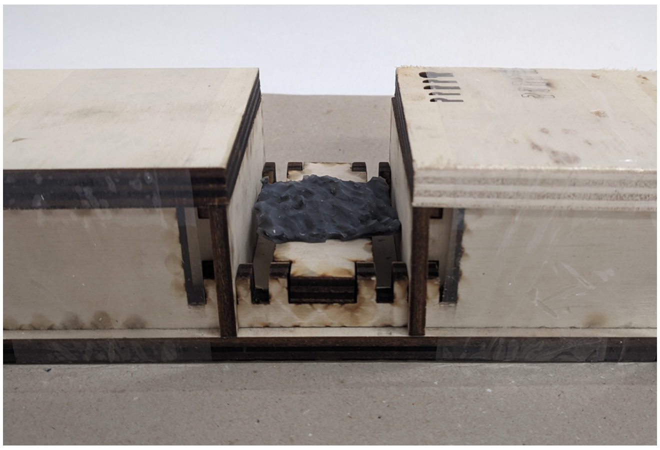


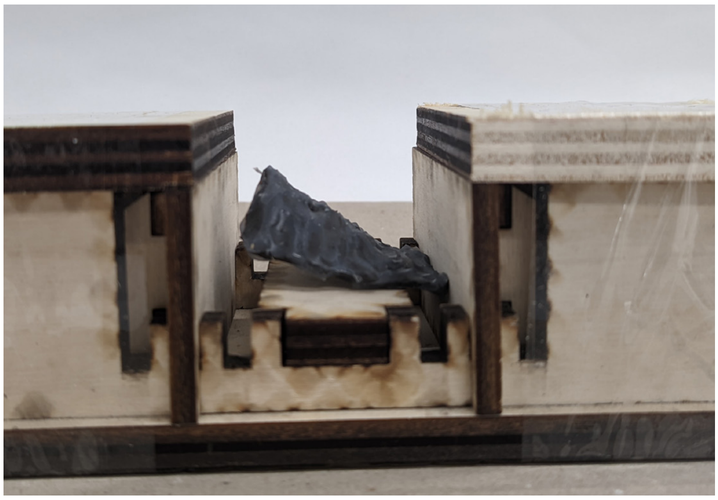


5.4.4. Flat Pipe Valve Demonstrator:

This demonstrator made following the geometry suggested by Kim et.al (2018) did not work as intended, after printing. The alternating direction of the lines caused the individual magnetization effects to be cancelled out. To possibly recify this, the print too was cast into resin, but it was soon observed that the resin made it too difficult for there to be any actuation. The resin was then attempted to be removed from the sample but there was a strong adhesion with the sample that made it difficult

A possible solution to this would be to have all the segments in every line be in the same direction.





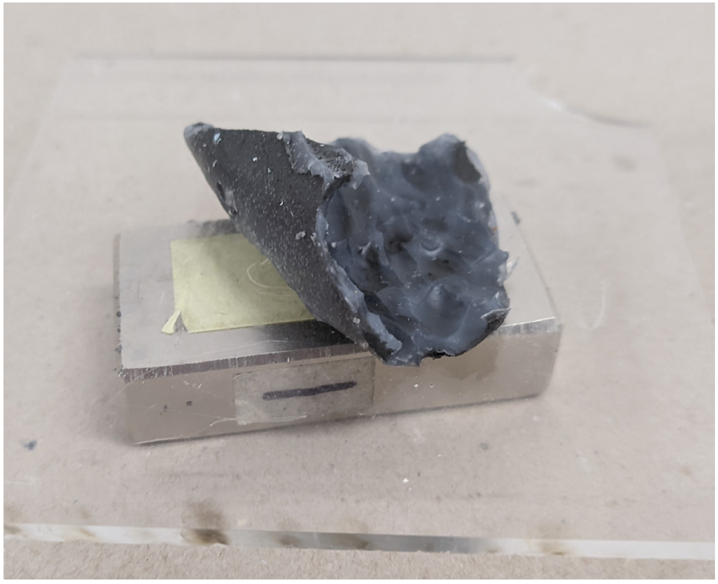


Figure 80. (Left) Pipe valve demonstrator coated in resin (Bottom left) Demonstrator when there is a magnet placed on its right (unseen). (top) Demonstrator between two attracting magnets, showing anomolous shape change. (Above) irregular deformation seen with magnet placed below the demonstrator

6. Conclusion

Soft magnetic memory materials hold considerable promise as a relatively recent innovation with extensive future potential. Their adaptability to various programmed shapes and the capacity to retain shape memory over prolonged periods opens up a wide array of possibilities for diverse applications.

Automating the manufacturing process is a critical step in realizing the full potential of these materials. The development of an automated extrusion system posed several challenges that needed resolution:

Ensuring sufficient force application to ensure reliable material flow through the printer.
Effective control over extrusion direction and rate for precise printing.
Reliable material mixing to achieve proper curing upon extrusion.

Observations highlighted the significance of neodymium microparticles (NdFeB) due to their ability to retain their magnetization for long durations of time, but due to their high cost, alternatives are also something that should be explored.

Maintaining lower viscosity (around 10,000 Pa.s) for reliable printing was found to be preferable, although higher viscosities might be considered with further testing. Notably, viscosity variations between batches indicate the need for testing of each ink to ensure prime printability.

The project's success was evident in demonstrating an initial iteration of a 4D printer capable of producing 2D shapes and the potential for 3D shapes. However, challenges still persist in maintaining consistent flow due to irregular pressures, necessitating manual intervention. Addressing material wastage during printing and refining the extrusion system are also areas for improvement.

Future research should focus on refining machine functionality, addressing challenges in material flow, and exploring applications for soft magnetic memory materials. While the current technology has limitations in exerting force, improving the strength of the base resin and enhancing material response to external magnetic fields could expand its applicability.

In conclusion, soft magnetic memory materials have unleashed a world of possibilities. As industrial design and engineering fields delve into further research, it will be intriguing to witness the diverse applications and innovations that arise from the potential of these materials.

6.1. Recommendation

Aside from the recommendations mentioned in the conclusion, there are several significant improvements that can be applied to enhance the usability of the printer:

6.1.1. Customized Motherboard for Greater Control:
Considering the use of a custom or modified motherboard, even within the Ender 3 platform, can offer distinct advantages. Individual control over the peristaltic pump motors would increase power delivery to the pumps, resulting in more reliable printing operations. Moreover, addressing the occasional pauses and starts during pump rotation, possibly a bug in the current setup, could be better managed by separately controlling the two motors, facilitated by a customized motherboard.

6.1.2. Electromagnet at Nozzle End:
An alternative to the permanent magnet at the nozzle's end is to employ an electromagnet. This approach would optimize printing, especially for lines that need to be printed in the same direction. An electromagnet would enable the shortest distance to be traversed, reducing the need to travel back and forth as with a permanent magnet. A polarity flip of the electromagnet would switch the deposited particle polarity, saving time. Alternatively, adding a third stepper motor controller to the current setup could boost motor power output and control.

6.1.3. Exploration of Different Resins:
Utilizing different resins for the mixing process could yield interesting outcomes. Combining diverse resins could enhance the printing quality and material behavior, expanding the printer's potential applications.

6.1.4. Dynamic Mixing Nozzle with Reduced Wastage:
Incorporating a dynamic mixing nozzle with a shorter length could significantly reduce the wastage of expensive ink materials. This modification would not only optimize material usage but also contribute to the financial viability of the printing system.

6.1.5. Smaller Diameter Nozzles for Finer Resolution:
Exploring smaller diameter nozzles presents an avenue for achieving finer extrusion resolution. However, this adjustment comes with challenges, as smaller holes necessitate higher pressures to maintain proper flow. Overhauling the nozzle system and implementing mechanisms to overcome these challenges could lead to improved printing results.

6.1.6. Pneumatic Control Over Piston Extrusion:
Consideration could be given to replacing the current piston-based extrusion mechanism with pneumatic control. This shift could offer more precise pressurization and better flow regulation, contributing to enhanced stoppage control and reliability, overcoming the limitations of the existing piston system.

6.1.7. Provision for having simultaneous extrusion of support material.

Particularly for the creation of 3D structures, it would be highly recommended to have another, cheaper and more structurally strong material with its own extruder that can be used to print supports and print in 3D without having excess usage of the magnetized ink.

In conclusion, these proposed enhancements, ranging from customized hardware to altered extrusion mechanisms, have the potential to substantially elevate the printer's functionality and usability. Exploring these avenues could contribute to overcoming current limitations and advancing the capabilities of the system, ultimately leading to more efficient and reliable 4D printing outcomes.

6.2. Reflection

When embarking on this project, I faced a blend of technical and design challenges, some within my comfort zone while others were uncharted territory. The technical aspects encompassed familiar ground, such as 3D printing, yet also delved into alien realms like electronics, coding, and 3D printer control. Learning on the fly became an intriguing challenge, requiring me to adapt rapidly. Several aspects were new terrain for me, particularly project planning and thorough research, which posed uphill battles. Nevertheless, I was able to meet my self-established timeline almost precisely.

Though certain segments occasionally exceeded expected timeframes, I managed to persevere through these stretches and maintain a productive pace. The absence of hard deadlines within the project proved both liberating and vexing. Striving to self-impose structure and urgency became paramount to maintain motivation and focus. This process of creating personal deadlines emerged as a valuable skill honed throughout the project.

Solitary work in this venture fostered a dichotomy of liberation and frustration. I found myself occasionally blindsided by unforeseen problems that required significant attention. This spurred heightened self-critique and organizational prowess in problem-solving. Striving to address issues holistically became a cornerstone, aligning individual solutions with the overarching project objectives.

The project's outset highlighted a miscalculation in timeline expectations. Initially assuming a two-month period for achieving reliable printer functionality, I encountered continuous design changes, particularly with the integration of the peristaltic pump. Finessing clearance and pump reliability entailed meticulous fine-tuning, consuming substantial time.

Transitioning to the ideation phase also brought its own set of hurdles. Broader exploration and ideation required careful consideration and extensive contemplation. Group ideation sessions underscored the significance of thorough preparation and clear explanation. Lacking complete elucidation of material implications led to the generation of numerous ideas that, while excellent, weren't always aligned with my intentions. Nonetheless, this process enriched my understanding across varied domains.

In retrospect, this journey encompassed an interplay of technical skill development, self-imposed discipline, and design evolution. Adapting to unforeseen challenges and acquiring new proficiencies underpinned the narrative of growth throughout this project.

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8. Appendices

8.1. Project brief

DESIGN FOR our future

TU Delft

IDE Master Graduation

Project team, Procedural checks and personal Project brief

This document contains the agreements made between student and supervisory team about the student's IDE Master Graduation Project. This document can also include the involvement of an external organisation, however, it does not cover any legal employment relationship that the student and the client (might) agree upon. Next to that, this document facilitates the required procedural checks. In this document:

- The student defines the team, what he/she is going to do/deliver and how that will come about.
- SSC E&SA (Shared Service Center, Education & Student Affairs) reports on the student's registration and study progress.
- IDE's Board of Examiners confirms if the student is allowed to start the Graduation Project.

USE ADOBE ACROBAT READER TO OPEN, EDIT AND SAVE THIS DOCUMENT

Download again and reopen in case you tried other software, such as Preview (Mac) or a webbrowser.

STUDENT DATA & MASTER PROGRAMME

Save this form according the format "IDE Master Graduation Project Brief_familyname_firstname_studentnumber_dd-mm-yyyy".
Complete all blue parts of the form and include the approved Project Brief in your Graduation Report as Appendix 1 !

family name: Soni
initials: J. K. given name: Jayneel Kiran
student number: 5555728
street & no.:
zipcode & city:
country:
phone:
email:

Your master programme (only select the options that apply to you):

IDE master(s): ★ IPD / DfI / SPD
2nd non-IDE master:
individual programme: - - (give date of approval)
honours programme: Honours Programme Master
specialisation / annotation: Medisign / Tech. in Sustainable Design / Entrepeneurship

SUPERVISORY TEAM **

Fill in the required data for the supervisory team members. Please check the instructions on the right !

** chair: Dr. Sepideh Ghodart dept. / section: SDE/Emrging Materials
** mentor: Dr. Gijs Huisman dept. / section: HCD
2nd mentor:
organisation:
city: country:

comments (optional)

Chair should request the IDE Board of Examiners for approval of a non-IDE mentor, including a motivation letter and c.v..

Second mentor only applies in case the assignment is hosted by an external organisation.

Ensure a heterogeneous team. In case you wish to include two team members from the same section, please explain why.

APPROVAL PROJECT BRIEF

To be filled in by the chair of the supervisory team.

chair Dr. Sepideh Ghodart date 23 - 02 - 2023 signature Sepideh Ghodrat - IO Digitally signed by Sepideh Ghodrat - IO Date: 2023.02.23 11:35:49 +01'00'

CHECK STUDY PROGRESS

To be filled in by the SSC E&SA (Shared Service Center, Education & Student Affairs), after approval of the project brief by the Chair.
The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total: ____ EC

Of which, taking the conditional requirements into account, can be part of the exam programme ____ EC

List of electives obtained before the third semester without approval of the BoE

YES all 1st year master courses passed

NO missing 1st year master courses are:

name ____ date - - signature ____

FORMAL APPROVAL GRADUATION PROJECT

To be filled in by the Board of Examiners of IDE TU Delft. Please check the supervisory team and study the parts of the brief marked **.
Next, please assess, (dis)approve and sign this Project Brief, by using the criteria below.

- Does the project fit within the (MSc)-programme of the student (taking into account, if described, the activities done next to the obligatory MSc specific courses)?
- Is the level of the project challenging enough for a MSc IDE graduating student?
- Is the project expected to be doable within 100 working days/20 weeks ?
- Does the composition of the supervisory team comply with the regulations and fit the assignment ?

Content: APPROVED NOT APPROVED

Procedure: APPROVED NOT APPROVED

comments

name ____ date - - signature ____

Initials & Name J. K. Soni Student number 5555728

Title of Project 4D printed soft magnetic memory materials- exploration and design

4D printed soft magnetic memory materials- exploration and design

project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 23 - 02 - 2023

21 - 07 - 2023 end date

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

Shape Memory Materials (SMMs) have been around for many years, popularized by the discovery of Nitinol, a Nickel-Titanium alloy that was able to change shape in the presence of heat. This research has further been expanded towards the exploration of different types of shape morphing materials such as Shape Memory Polymers (SMPs) and Shape Memory Alloys (SMAs).

The main methods that shape morphing or shape memory materials can be activated by are humidity, temperature and magnetic fields. In the presence of such forces, which could be induced with methods such as resistive heating or electromagnets, various effects can take place depending on the nature of the material, for example, SMAs tend to undergo change in the crystalline structure of the metals (austenite to martensite or vice-versa) in the presence of heat and this causes a deformation in the overall structure of the object, this is a reversible deformation and once the heating is removed the process reverses and the material reverts to the original state.
In the case of polymers, most polymers tend to show shape morphing properties in the temperatures below either their glass transition temperature (Tg) or their melting temperature (Tmelt), this temperature and the nature of the deformation (permanent or temporary) also is dependent on the polymer.
There are many fields where the exploration of SMPs is being explored, these are application such as smart textiles, fabrics and clothing that are able to change geometry depending on the user and their environmental conditions, soft robotics, wherein SMPs are used in the actuation parts of the robot and can be design and controlled to perform specific and intricate motor function.

There also exist shape morphing materials that are influenced by magnetic fields, these can exist as SMAs, metal alloys which can deform in magnetic fields, also as epoxies wherein one part is made of a ferromagnetic material and after it has cured, it could be made to deform as long as the cured product is relatively soft and able to deform. These are the materials that are the main focus for this project as they are still a developing technology and so far have not been commercialized. These materials when created are sensitive to magnetism and are able to deform quickly in the presence of magnetic fields as the recipe can be modified to create soft materials (Kim, 2018). This is a desirable property for applications such as soft robotics (Ze et al., 2020) where the material can be controlled without having any physical connection to it such as a wire which is utilized for materials that deform with temperature.

This research also aims to serve as an initiation point for further study into possible applications of shape memory materials as this is a field sparsely explored due to the technical requirements. Shape memory materials have a huge potential for applications given the flexibility and customisability they offer, but with little research into this field, it is difficult to generate applications without the information on the capabilities of the material and this should be addressed.

Kim, Y., Yuk, H., Zhao, R., Chester, S. A., & Zhao, X. (2018). Printing ferromagnetic domains for untethered fast-transforming soft materials. Nature, 558(7709), 274–279. https://doi.org/10.1038/s41586-018-0185-0

Ze, Q., Kuang, X., Wu, S., Wong, J. Y. H., Montgomery, S., Zhang, R., Kovitz, J. M., Yang, F., Qi, H. R., & Zhao, R. (2020). Magnetic Shape Memory Polymers with Integrated Multifunctional Shape Manipulation. Advanced Materials, 32(4), 1906657. https://doi.org/10.1002/adma.201906657

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introduction (continued): space for images

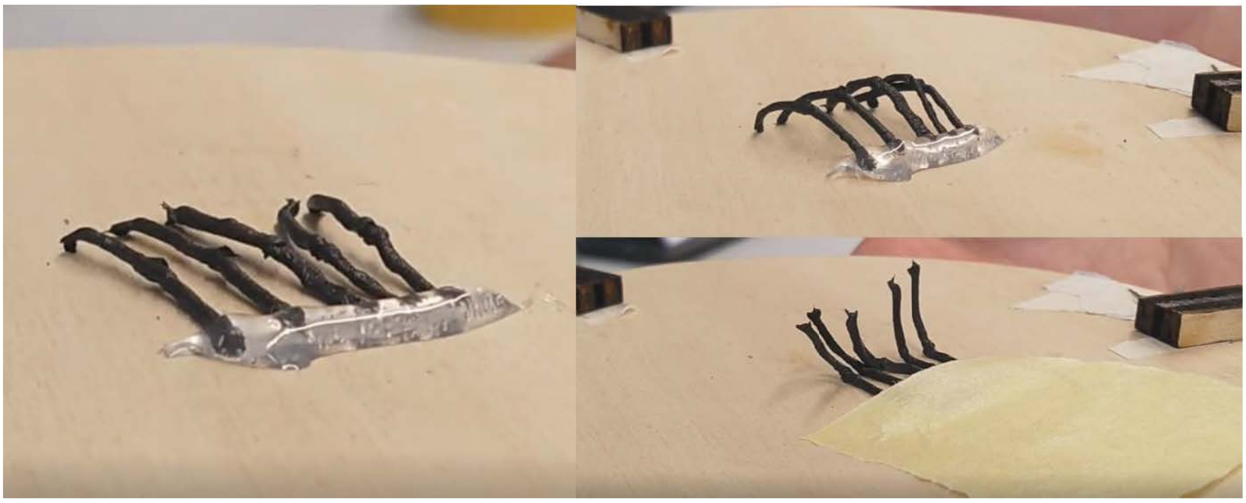


image / figure 1: Proof of concept of magnetic shape memory (Der Lans ,2022)

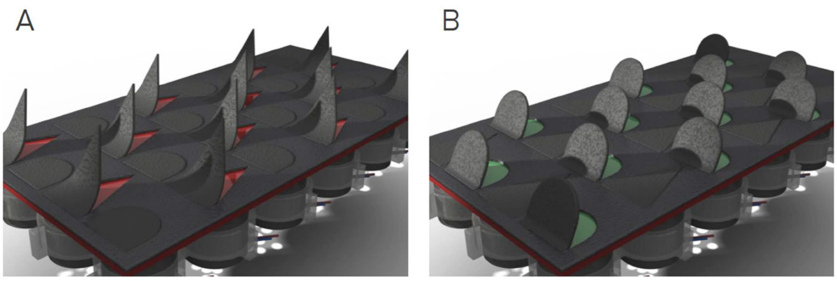


Figure 5.18: The spikey texture state exposes red colour underneath, emphasizing its state of danger (A). The more friendly texture state of rounded actuators show a green colour signalling all is good (B).

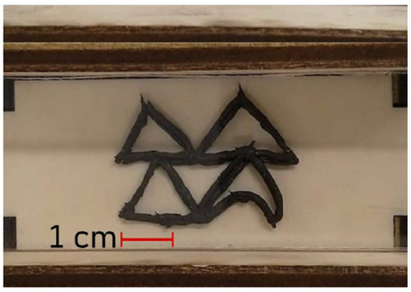


Figure 5.3: Maximum height and residual height after shape recovery of the analysed W-shape.

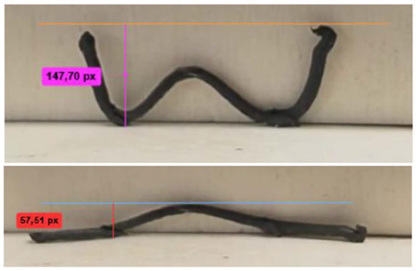


Figure 5.4: Maximum height and residual height after shape recovery of the analysed W-shape.

image / figure 2: Texture based application using SMMs (Der Lans, 2022)

Initials & Name J. K. Soni Student number 5555728

Title of Project 4D printed soft magnetic memory materials- exploration and design

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

The scope of this project is in two parts, the first is to create a functioning setup capable of 4D printing a 2 part epoxy which can be selectively magnetized to create the shape morphing effects required. Although this had been attempted previously in the graduation project of Kevin van der Lans, a completely working system was not established due to difficulties in material extrusion and magnetization. These two problems are to be fixed with a redesign of the system to create lesser flow resistance.

In the second part, the aim is to develop a product service system that incorporates these magnetic shape morphing materials, this is the uses/applications mentioned in the title. Given that this technology is still in a rather developing stage, the goal is to design applications that could show the potential that these materials have and the ease at which they can be further incorporated into the products that we see around us.

For this product service system, the primary field of development will be focusing on haptics based applications using the magnetic shape morphing materials. Haptics based applications include aspects like texture, touch, movement and similar sensation based functions. A concept of this had previously been developed in the work of Kevin van der Lans, 2022 but this will be revisited with a fresh approach to create a functional application incorporating both domains.

Der Lans, V. K. (2022). 4D Printing Magnetically Activated Shape Morphing Objects | TU Delft Repositories. https://repository.tudelft.nl/islandora/object/uuid:8465fe90-88f7-4132-a5d8-72832790589d

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

The goal is to create a prototype of a product/product service system made using magnetic shape morphing materials which demonstrates the usability of the materials and also the potential of the materials. This product-service system has to create a functional or experiential application by attempting to incorporate the domain of haptics based design. For this the setup for the printing of the shape morphing materials needs to be perfected as well.

The goal of this project is to end up with a usable prototype of a concept that is designed to incorporate shape morphing materials and their properties as the main functional parts of the design. This solution/product system is to incorporate the domain of haptics based design to create a useful sensory experience for the user. The final prototype is planned to have the shape morphing component be a 2D/3D shape made using the printing setup.

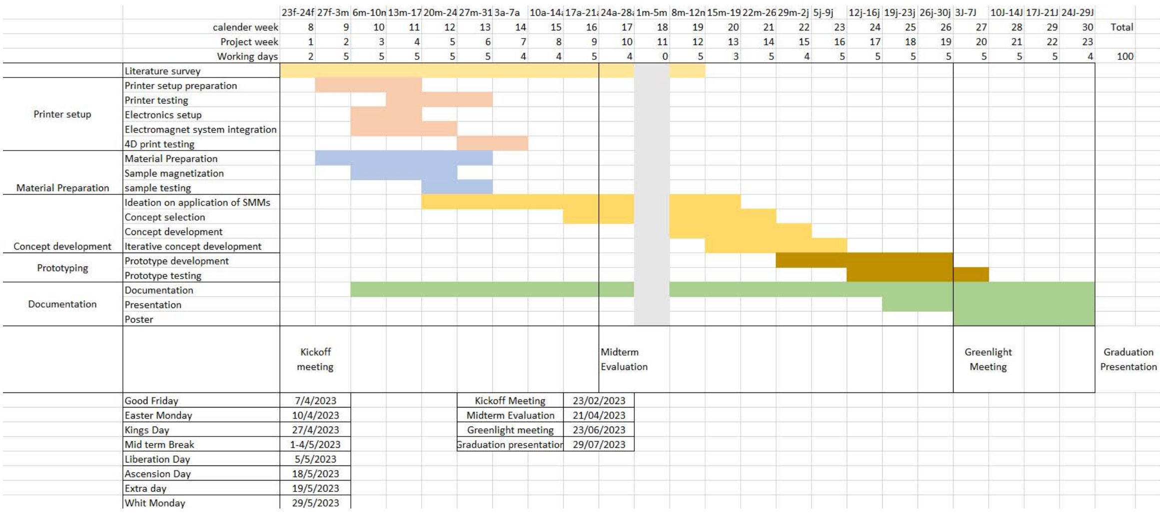
For making this prototype, the setup needs to be made which is able to print the shape morphing materials, in this case it is a 2 part resin with one part containing the magnetised NdFeB micro-particles. This setup is to be made with a 3D printer, modified to use an extrusion system similar to one previously used in the projects of Sanne van Listeren and Kevin van der Lans which consisted of motor driven syringes connected to a mixing nozzle which replaces the nozzle present on the 3D printer and uses the movement of the printer to create structures.
The progression to be followed is first, automatic extrusion of magnetic silicone elastomer, followed by designing the nature of deformation and finally create various 1D, 2D and 3D structures while validating their local magnetic deformation functionalities.

Vilsteren, V. S. (2021). Designing Magnetic Soft Materials for 4D Printing | TU Delft Repositories. https://repository.tudelft
Der Lans, V. K. (2022). 4D Printing Magnetically Activated Shape Morphing Objects | TU Delft Repositories. https://repository.tudelft.nl/islandora/object/uuid:8465fe90-88f7-4132-a5d8-72832790589d

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 23 - 2 - 2023 | 21 - 7 - 2023 end date



The planning follows 2 stages, the first part is the development of the printing setup, and the verification of its ability to print in multiple directions while ensuring that the magnetization of the ink during printing is successful and controllable.
Soon after the ideation for application using this shape morphing materials will commence with the goal of reaching the beginning of concept selection by the mid-term presentation. This will be continued till the greenlight meeting by which point the prototyping stage will have been entered and physical prototypes will be made as a proof of concept and as a prototype of the final product. All these will be presented along with the report during the greenlight meeting, after which the prototype will be finalized and the rest of the documentation work, along with creation of the poster and the presentation for the graduation will be made.
There is a one week break planned in the project after the midterm evaluation and before the beginning of the concept development phase.

Initials & Name J. K. Soni Student number 5555728

Title of Project 4D printed soft magnetic memory materials- exploration and design

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

Working with materials has always been of particular interest to me, my bachelors final project too had been in the domain of materials and material processing. Designing with materials also let me develop ideas that contain aspects of both traditional design as well as mechanical engineering, which is what my bachelors had been in.
My previous course of AED which also was very focused on prototyping was another inspiration for me to select this domain and this project for my graduation, it gave me the reinforcement towards working on something that is more technical and prototyping focused.
I also believe that shape morphing materials are going to be omni-present in the future and i would really like to be part of the process that brings them there.
I also have a lot of experience of 3D printing and printers and that led me to work on this project of creating a setup that allowed for adopting a 3D printer for 4D printing the shape morphing materials.

I also see this project as something that will be a good step towards my personal development as it incorporates aspects that are both within my comfort zone (3D printing, prototyping) and outside (experiential design, haptics, electronics) it, which will help me to have an enriching personal experience during this project.

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.

8.2. Iterations of peristaltic pump casing and rotors

Iteration	Open/closed wall	wall diameter	pipe arc angle (degrees)	Changes needed
1	open	100mm	180	smaller wall and closed to prevent pipe motion
2	closed	100mm	180	2 bearings used are having difficulty engaging and disengaging with pipe simultaneously
3	closed	100mm	210	transition between entry and exit hole of pipe and wall is not smooth, making engaging and disengaging of bearing difficult
4	closed	100mm	210	reduce overall diameter to increase torque at point of contact
5	closed	75mm	210	Further reduce diameter to increase torque to accommodate back pressure generated
6	closed	64.6mm	210	

No.	Radius (centre of rotor to centre of bearing)	motor attachment diameter	base geometry	remarks
1	34	5.25	circular rim	needs better contact
2	34.25	5.25	circular rim	needs better contact
3	34.5	5.25	circular rim	motor attachement too
4	34.5	5.35	circular rim	test smaller diameter
5	34.25	5.45	circular rim	too loose connection to
6	34.25	5.35	rim+spacers	spacer ineffective
7	34.25	5.35	slot for screws	
8	34.25	5.25	slot for screws	
9	34.25	5.2	slot for screws	irregular fitting of rotor observed due to minute changes in material and printer
10	34.25	5.15	slot for screws	
11	34	5.15	slot for screws	
12	34	5.05	slot for screws	
13	34.25	5.1	slot for screws	
14	34.25	5.18	slot for screws	Therefore multiple iterations of the same geometries were needed to confirm best fit
15	34.25	5.2	slot for screws	
16	34	5.18	slot for screws	
17	34	5.2	slot for screws	
18	34.25	5.2	slot for screws	
19	epicyclic gear 48.5mm	2.8mm high lobe		too much friction
20	22	5.4	flat	re-testing clearance to see if higher torque would allow for more compression of pipe during pumping
21	21.75	5.4	flat	
22	21.5	5.4	flat	
23	21.25	5.4	flat	
24	21.25	5.35	flat	geometry finalized, 1.2mm clearance between wall and rotor, 5.25mm hole for motor shaft, 2.15mm between hole centre and key of motor shaft
25	21.3	5.3	flat	
26	21.3	5.25	flat	
27	18.1	5.25	flat	
28	18.1	5.25	flat	

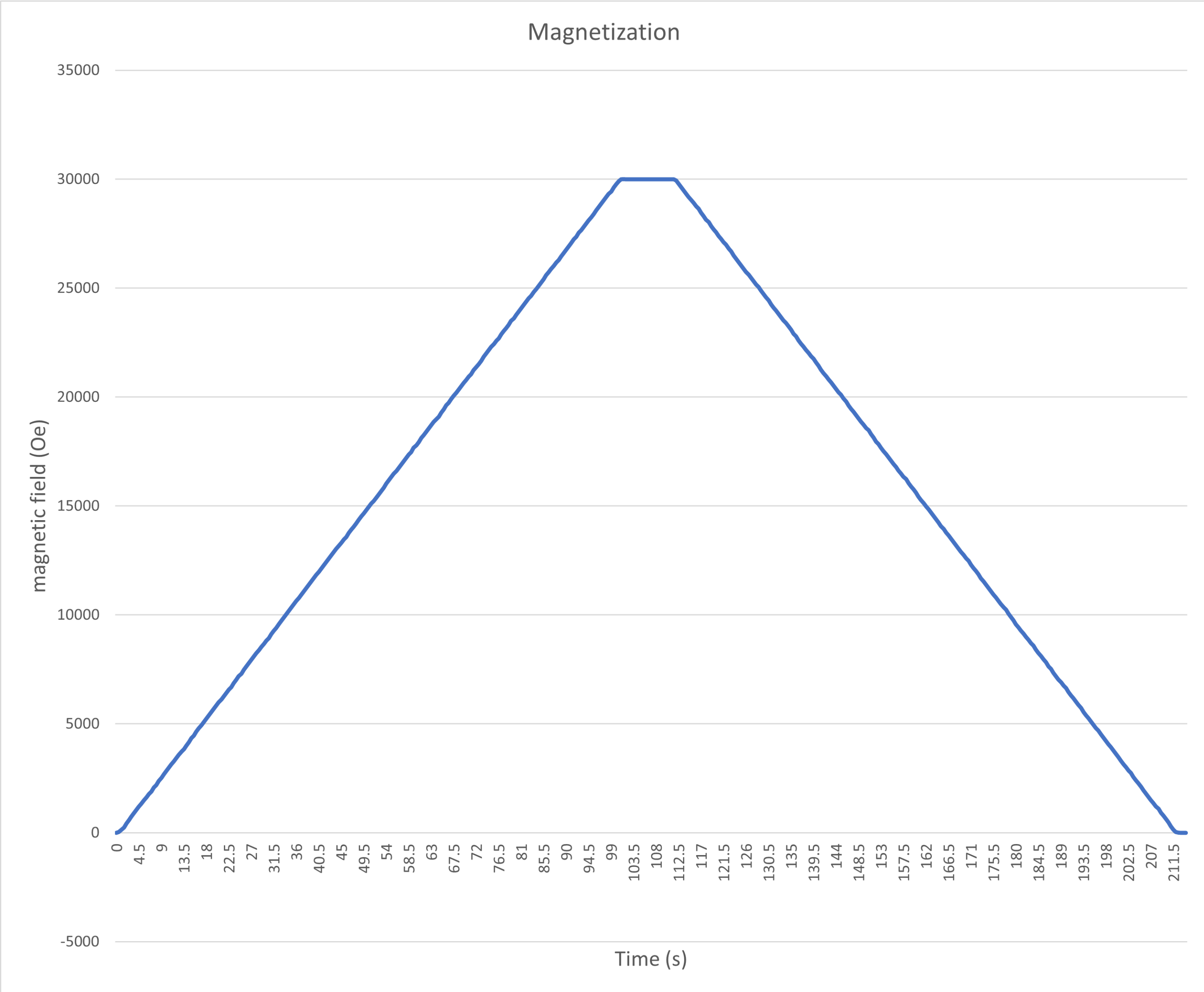
8.3. Ink preparations

Ink-No.	Ink Name	Part A	Part B	Micro-parti-	MP Part A	MP Part B	Fumed Silica Part A	Fumed Silica Part B
1	Practice Ink	10.23	10.23	Iron	17.47	17.47	1.125	1.125
2	First Test Ink	10.23	10.23	Iron	17.47	17.47	1.125	1.125
3	63% MP	5.542	7.507	Iron	9.9	11.865	0.61	0.825
4	50% MP	6.829	8.68	Iron	9.9	11.865	0.751	0.954
5	70-30% resin	7	3	Iron	8.611	8.611	0.77	0.33
6	30-70% resin	3	7	Iron	8.611	8.611	0.33	0.77
7	Magnetization Round 1	31.9	31.9	NdFeB	55	55	3.51	3.51
8	Magnetization Round 2	28.42	28.42	NdFeB	49	49	3.126	3.126
Adding Thinner								
	Adding thinner to round 1	Thinner added to each part						
	10%	3.19						
	20%	6.38						
	22%	7.02						
	25%	7.975						

Step 0: Wear PPE like lab coat, gloves and conduct all steps within a fume hood for safety, fine powders are being dealt with.

Step 1: Take an empty cup, tare it to measure values added on to it.
Step 2: Add required amount of Part A resin.
Step 3: Take a fresh cup, tare it and add required amount of microparticles proportional to part A.
Step 4: Take another fresh cup, tare it and add required amount of fumed silica to it.
Step 5: Add Microparticles to the resin cup and stir for 1 minute till they are reasonably well mixed.
Step 5: Add Fumed Silica and now stir well for another 3 minutes till the mixture becomes homogeneous.
Step 6: Repeat Step 1-5 for Part B
Step 7: Now these two parts can be either mixed and loaded into a syringe for manual deposition or individually loaded into separate containers for magnetization.
Step 8: Add thinner if necessary.

8.4. Magnetization

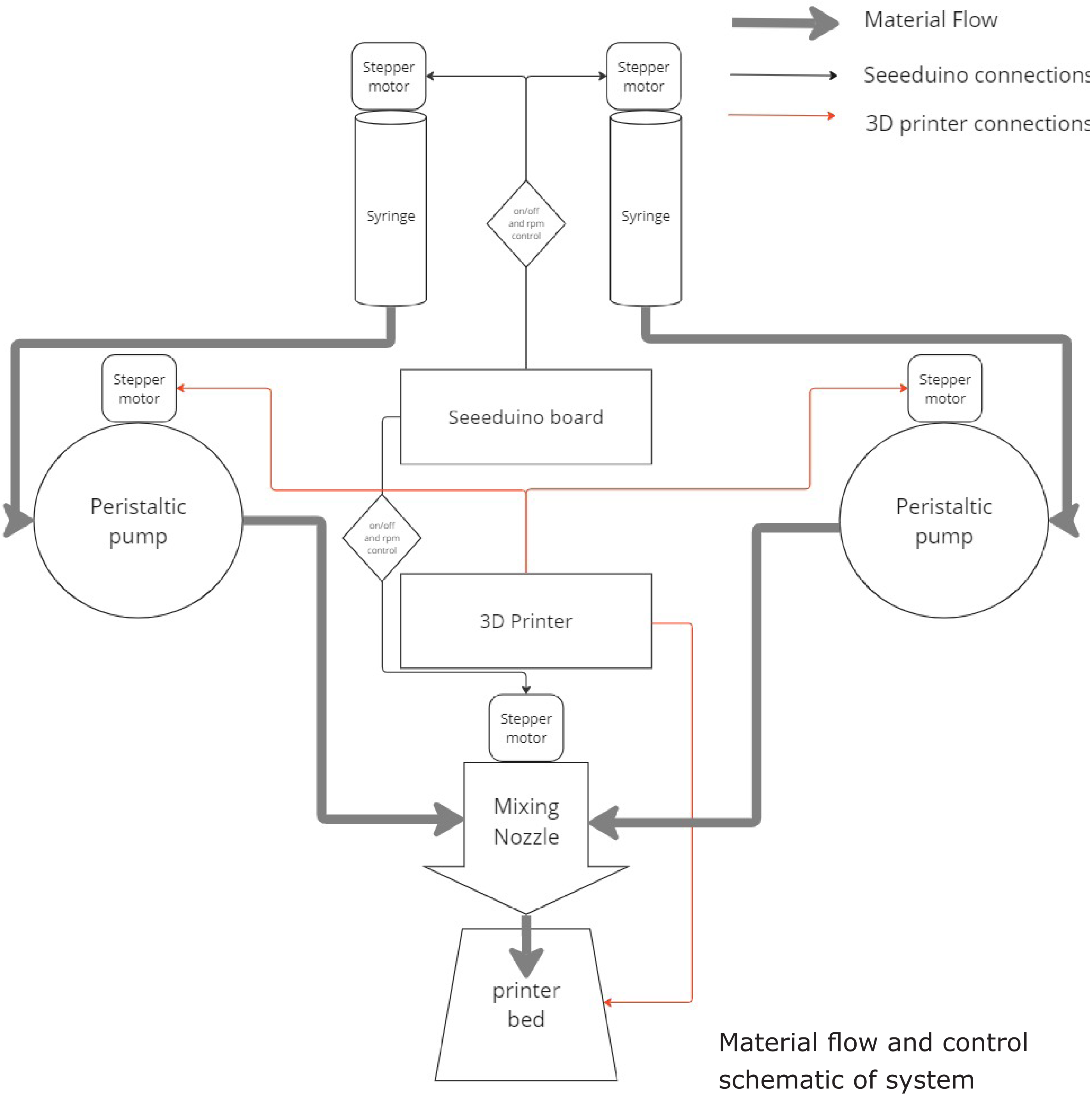


8.5. Control Electronics
Arduino code and schematic

pump_and_stirrer_control.ino

```
int LED1 = 12;
int switchStir = 2;
int spdStir = A0;
int switchPist = 3;
int spdPist = A2;
int delayy = 500;
int delaychng = 0;
bool a = HIGH;
bool setpulPist = LOW;
int driverPULpist = 4;
int driverDIRpist = 5;
bool setdirStir = LOW;
bool setpulStir = LOW;
int driverPULstir = 6;
int driverDIRstir = 7;
int pulsedelayStir = 300;
int pulsedelayPist = 400;
int reversePist = 8;

void StirMotorSwitch() {
  setpulStir = !setpulStir;
}

void PistmotorSwitch() {
  setpulPist = !setpulPist;
}

void Pistmotordirectio() {
  a = !a;
}
void pciSetup(byte pin) {
  *digitalPinToPCMSK(pin) |= bit(digitalPinToPCMSKbit(pin));  // enable pin
  PCIFR |= bit(digitalPinToPCICRbit(pin));                     // clear any outstanding interrupt
  PCICR |= bit(digitalPinToPCICRbit(pin));                     // enable interrupt for the group
}

ISR(PCINT0_vect)  // handle pin change interrupt for D8 to D13 here
{
  //    digitalWrite(13,digitalRead(8));

  if (digitalRead(8)) {
    a = !a;
    Serial.println("reverse");
  }
}
void setup() {
  Serial.begin(115200);  // put your setup code here, to run once:
  pinMode(driverPULstir, OUTPUT);
  pinMode(driverDIRstir, OUTPUT);
  pinMode(driverPULpist, OUTPUT);
  pinMode(driverDIRpist, OUTPUT);
  attachInterrupt(digitalPinToInterrupt(switchStir), StirMotorSwitch, FALLING);
  attachInterrupt(digitalPinToInterrupt(switchPist), PistmotorSwitch, FALLING);

  pciSetup(8);
}
```

```
void loop() {
  //delaychng = map((analogRead(spd)),0,1023,2000,50);
  pulsedelayStir = map((analogRead(spdStir)), 0, 1023, 300, 50);
  digitalWrite(driverPULstir, setpulStir);
  //digitalWrite(driverPULstir, HIGH);
  delayMicroseconds(pulsedelayStir);
  digitalWrite(driverPULstir, LOW);
  delayMicroseconds(pulsedelayStir);

  digitalWrite(driverDIRpist, a);
  pulsedelayPist = map((analogRead(spdPist)), 0, 1023, 3000, 2000);
  digitalWrite(driverPULpist, setpulPist);
  delayMicroseconds(pulsedelayPist);
  digitalWrite(driverPULpist, LOW);
  delayMicroseconds(pulsedelayPist);
}
```

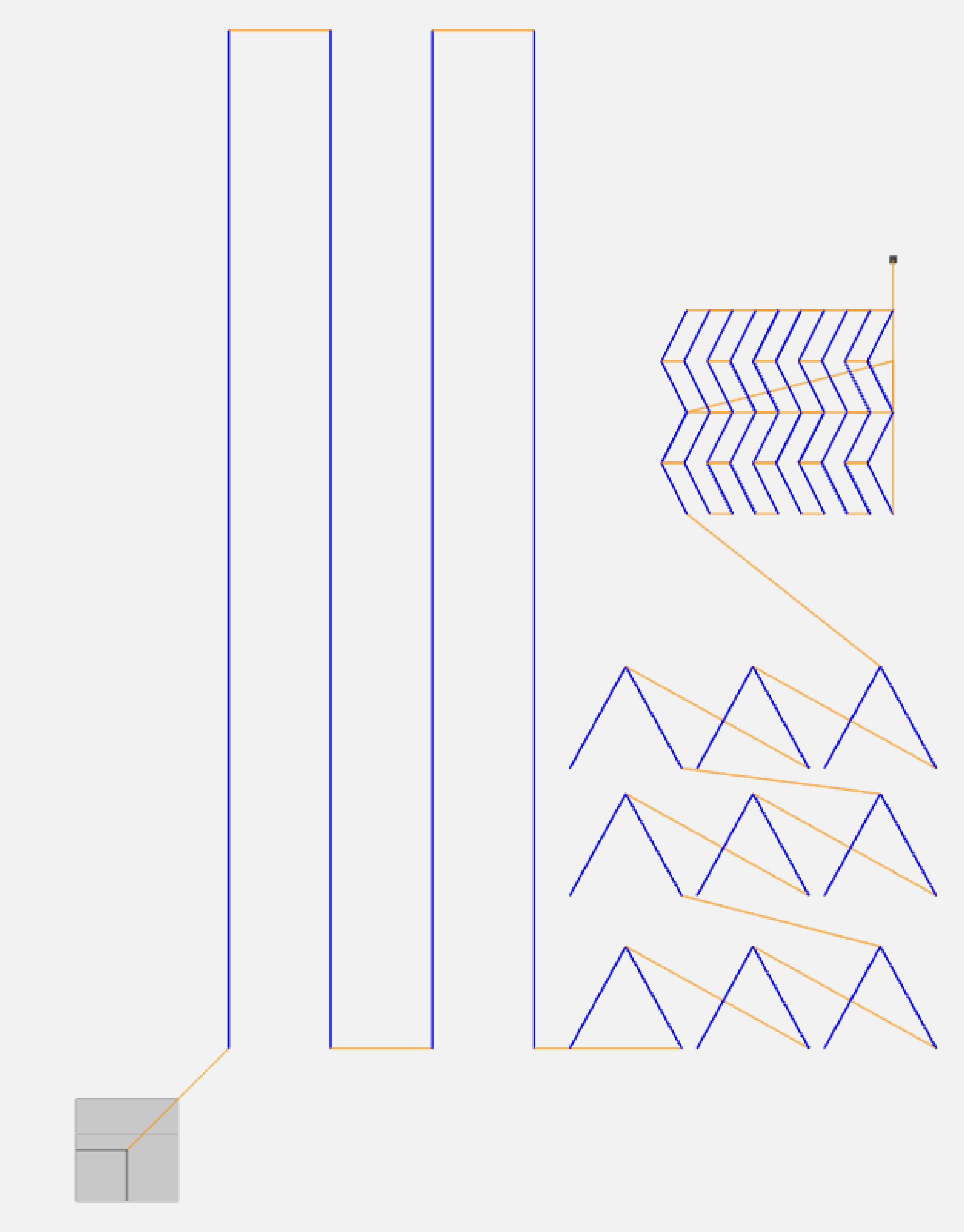


Material flow and control schematic of system

8.6. Gcodes and codes for writing Gcodes

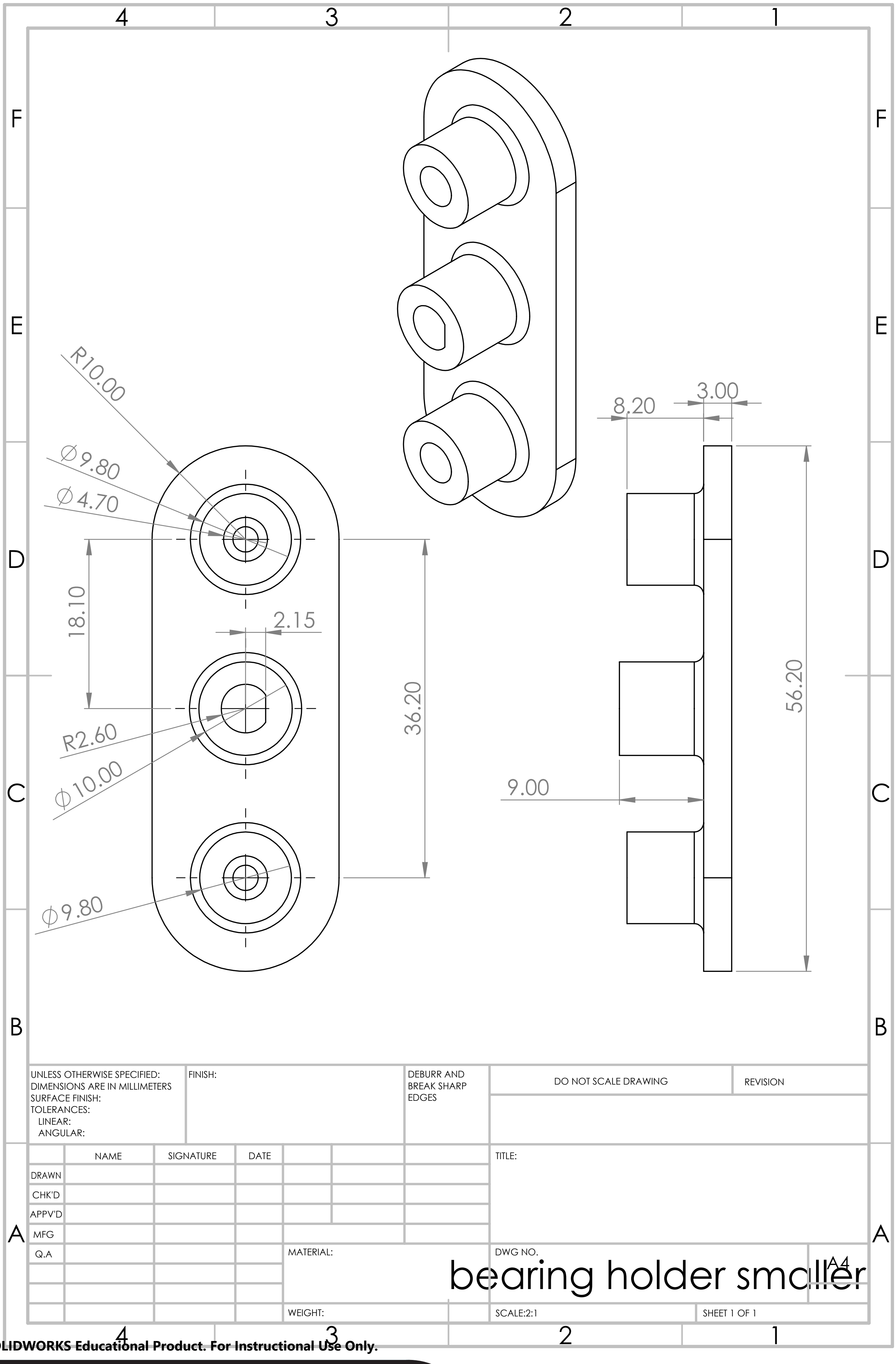
```
#include <stdio.h>
int spikes ();
int lines ();
int pipelock ();
int
main ()
{
  float xdist = 45;
  float ydist = 20;
  int i = 1;
  int j = 1;
  int k = 1;
  printf ("M104 S190\n M105\n M109 S190\n G28;HOME\n G90\n G92 E0\n");  //setup co
  printf ("F200\n");        //print feed rate
  printf ("G0 Z1.2\n");
  lines ();
  spikes ();
  pipelock ();
}
int
spikes ()
{
  float xdist = 110;
  float ydist = 20;
  int i = 1;
  int j = 1;
  int k = 36;
  for (i = 1; i <= 3; i++)
    {
      for (j = 1; j <= 3; j++)
    {
      //a=extrusion*i;
      printf ("G0 F1200 X%f Y%f\n", xdist - 1, ydist);
      printf ("G1 F60 X%f Y%f E%f\n", (xdist - 12), (ydist + 20),
          (45.5 * k));
      k = k + 1;
      printf ("G0 F1200 X%f Y%f\n", (xdist - 23), ydist);
      printf ("G1 F60 X%f Y%f E%f\n", (xdist - 12), (ydist + 20),
          (45.5 * k));
      k = k + 1;
      xdist = xdist + 25;
    }
      ydist = 25 * (i + 1);
      xdist = 110;
    }
}
```

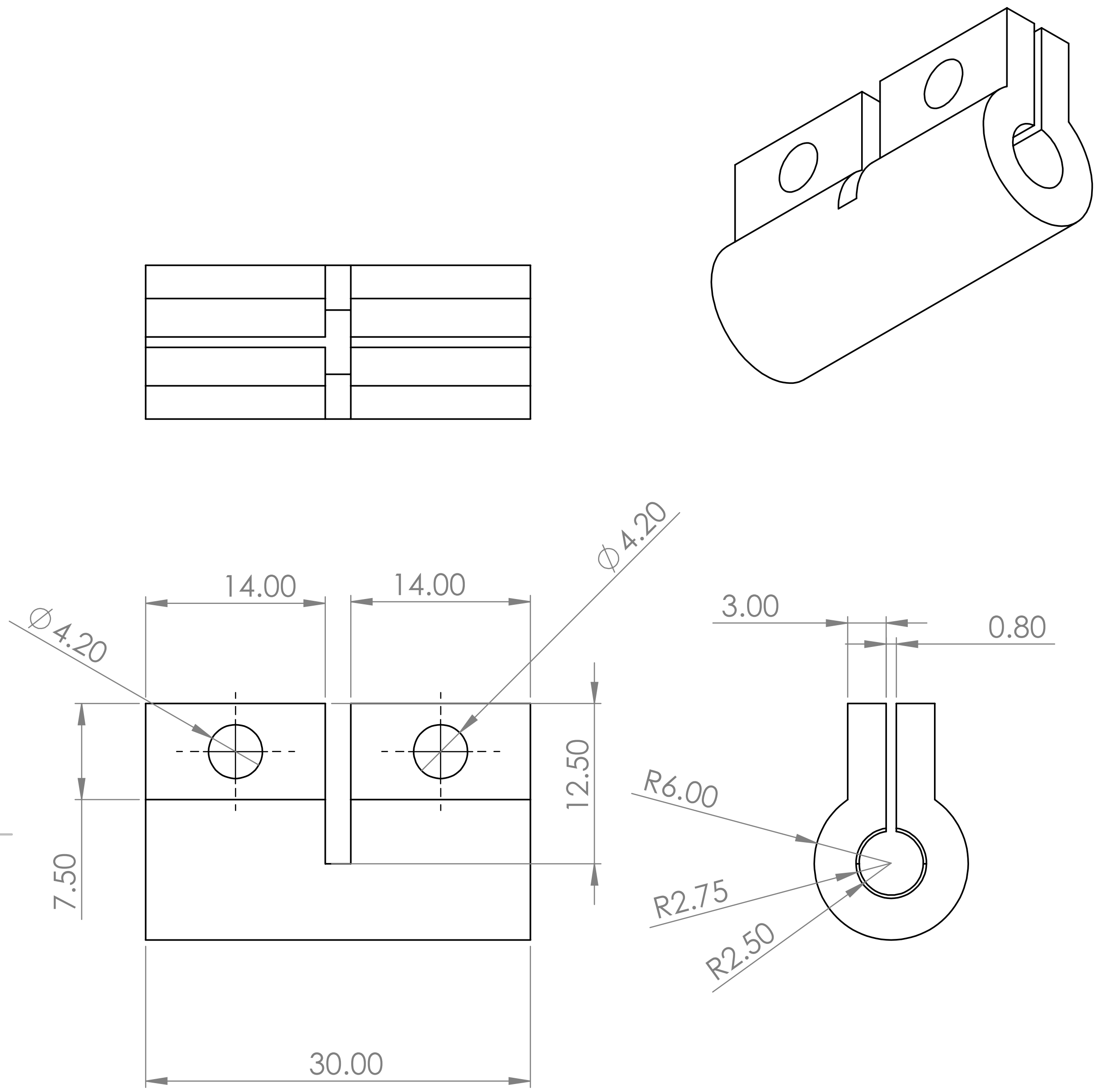
```c
int
lines ()
{
  float xdist = 20;
  float ydist = 20;
  int i = 1;
  int j = 1;
  int k = 1;
  for (i = 1; i <= 2; i++)
    {
      //a=extrusion*i;
      printf ("G0 F1200 X%f Y%f\n", xdist, ydist);
      printf ("G1 F60 X%f Y%f E%d\n", xdist, (ydist + 200), (400 * k));
      k = k + 1;
      printf ("G0 F1200 X%f Y%f\n", (xdist + 20), (ydist + 200));
      printf ("G1 F60 X%f Y%f E%d\n", (xdist + 20), (ydist), (400 * k));
      k = k + 1;
      xdist = xdist + 40;
    }
int pipelock ()
{
  float xdist = 110;
  float ydist = 125;
  int i = 1;
  int j = 1;
  float k = 173;
  int l = 1;
  for (i = 1; i <= 2; i++)
    {
      for (j = 1; j <= 5; j++)
    {
      printf ("G0 F1200 X%f Y%f\n", xdist, ydist);
      printf ("G1 F60 X%f Y%f E%f\n", (xdist - 5), (ydist + 10),(14 * k));
      k = k + 1;
      printf ("G0 F1200 X%f Y%f\n", (xdist - 0.5), (ydist + 10));
      printf ("G1 F60 X%f Y%f E%f\n", (xdist + 4.5), (ydist), (14 * k));
      k = k + 1;
      xdist = xdist + 9;
    }
      ydist = ydist + 10;
      xdist = 110;
      printf ("G0 F1200 Y%f\n", (ydist + 10));
      for (l = 1; l <= 5; l++)
    {
      printf ("G0 F1200 X%f Y%f\n", xdist, ydist + 10);
      printf ("G1 F60 X%f Y%f E%f\n", (xdist - 5), (ydist), (14 * k));
      k = k + 1;
      printf ("G0 F1200 X%f Y%f\n", (xdist - 0.5), (ydist));
      printf ("G1 F60 X%f Y%f E%f\n", (xdist + 4.5), (ydist + 10),(14 * k));
      k = k + 1;
      xdist = xdist + 9;
    }
      ydist = ydist + 10;
      xdist = 110;
      printf ("G0 F1200 Y%f\n", (ydist + 10));
    }
}
```



Resultant Gcode

8.7. Drawings of printer components





UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

DWG NO.

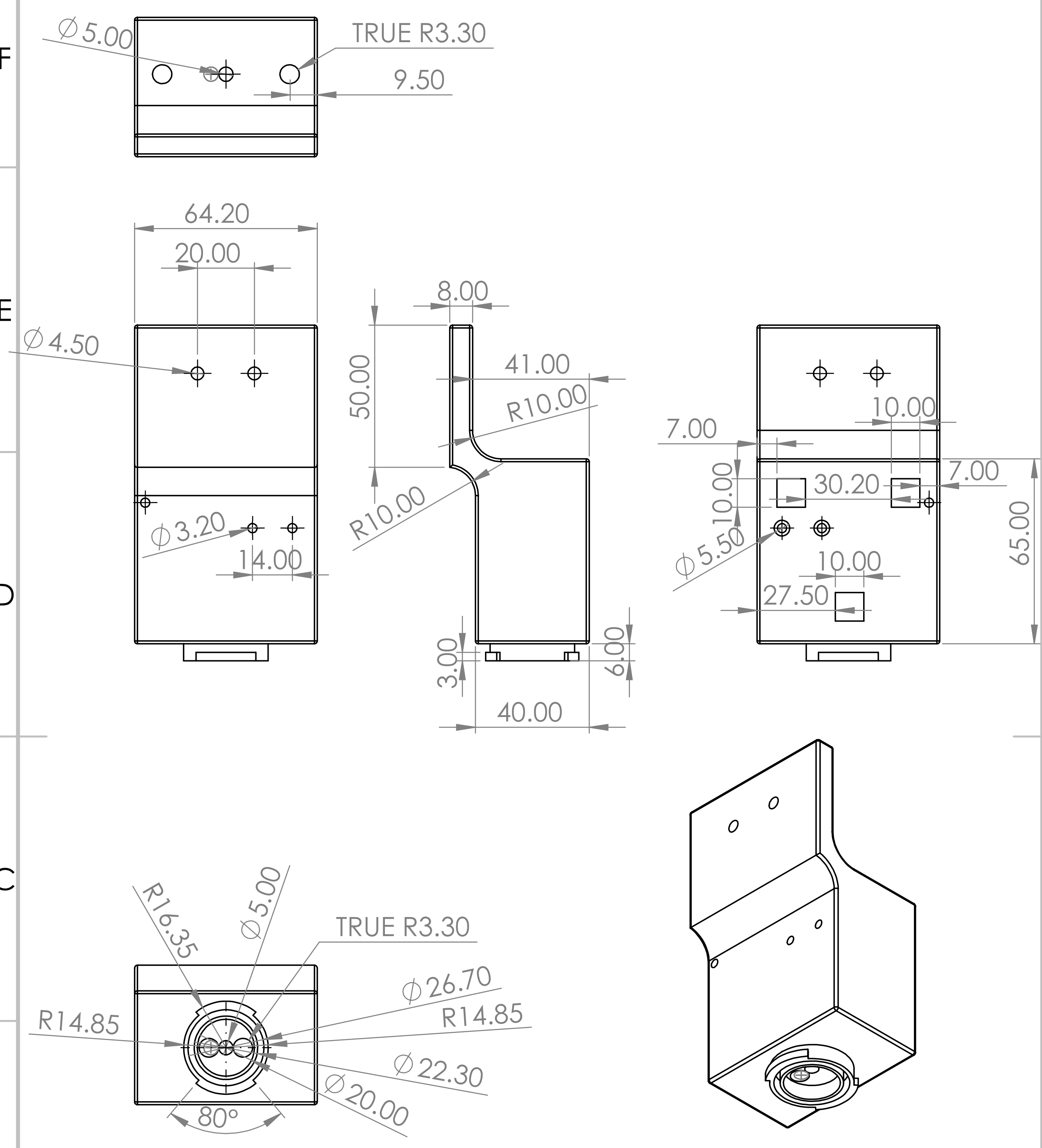
collet

A4

WEIGHT:

SCALE:2:1

SHEET 1 OF 1



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DIMENSIONS ARE IN MILLIMETERS
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DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE		
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A					

TITLE:

MATERIAL:

DWG NO.

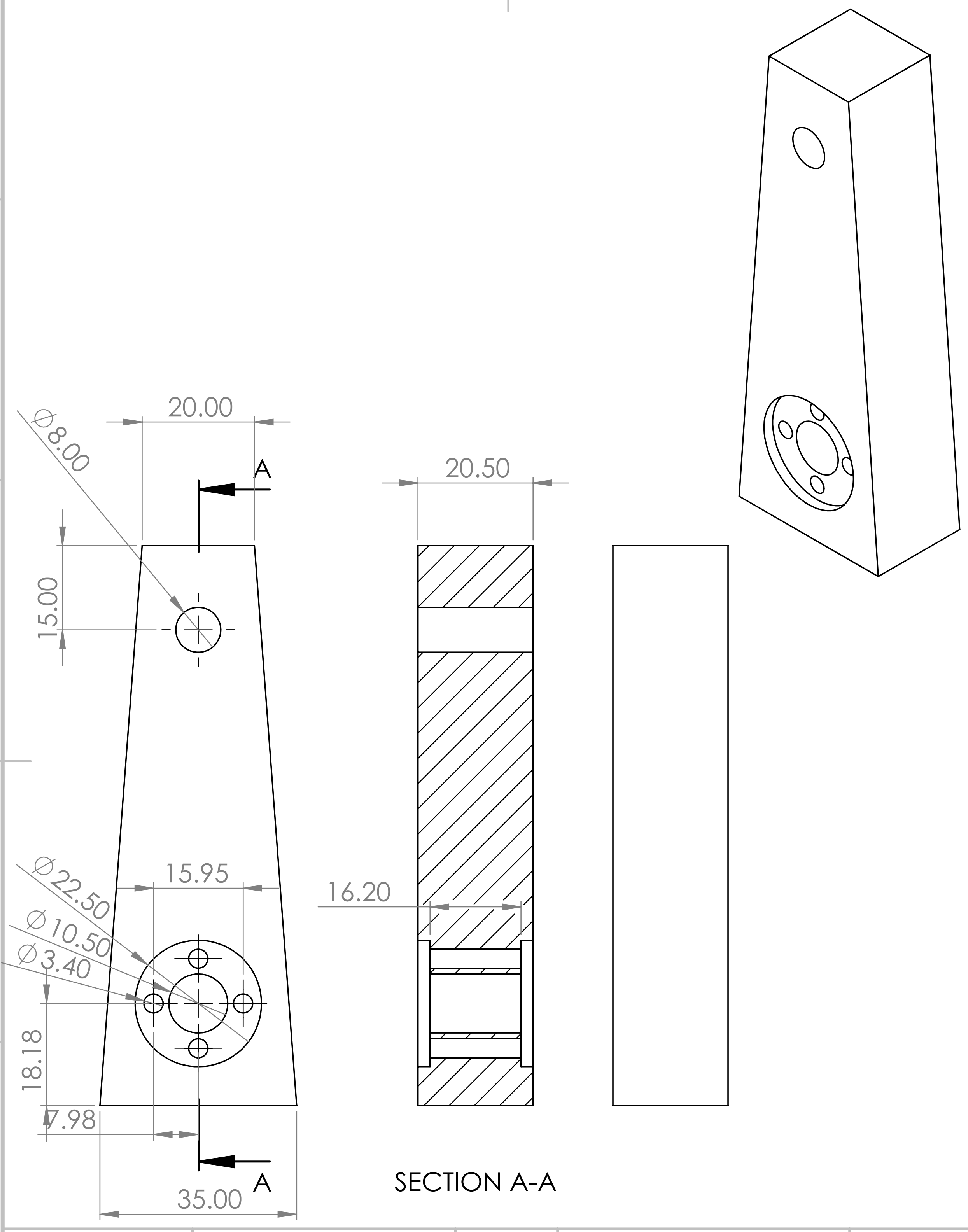
connection block

A4

WEIGHT:

SCALE:1:2

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
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DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
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TITLE:

MATERIAL:

WEIGHT:

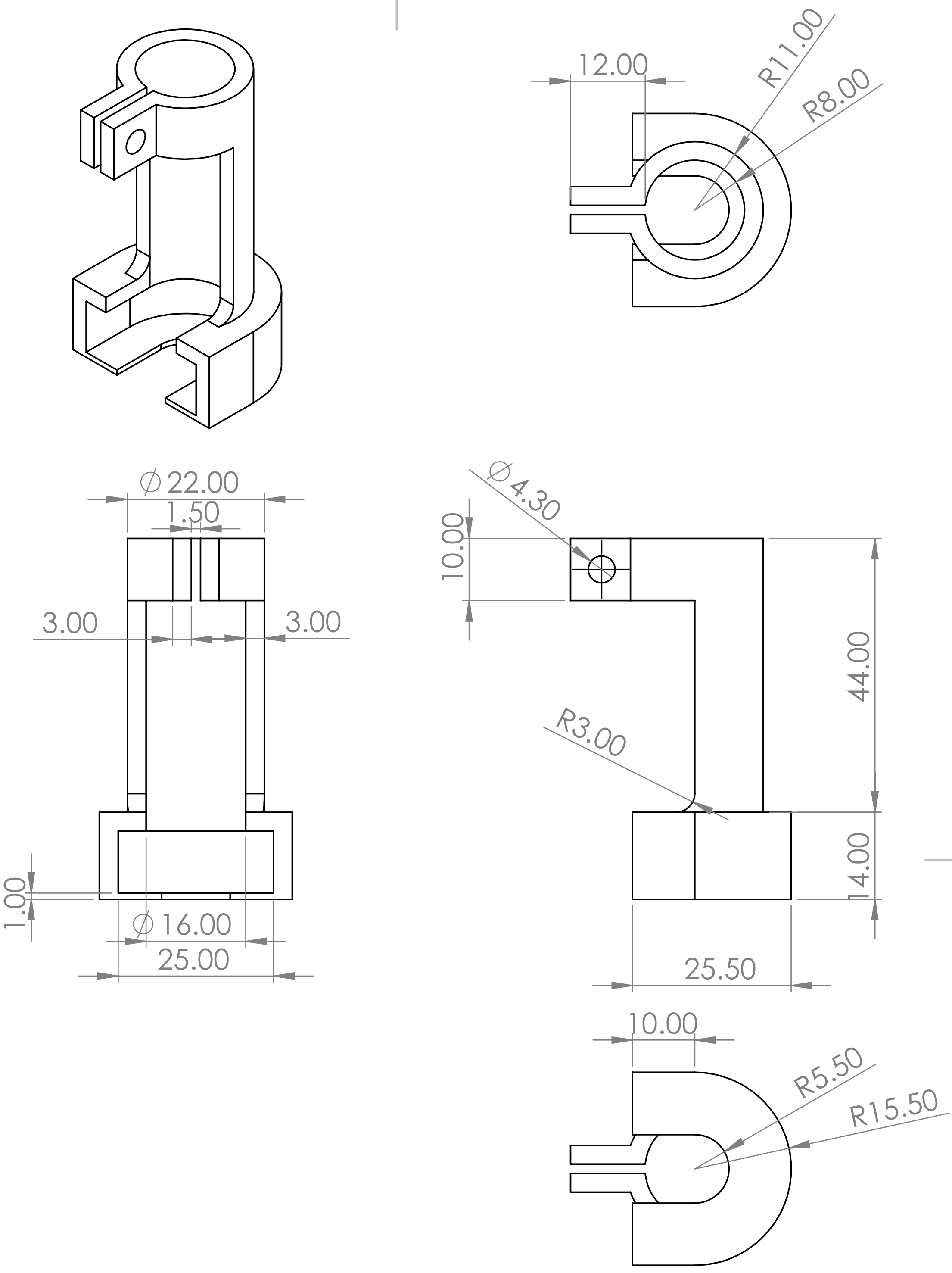
DWG NO.

connector

A4

SCALE:1:1

SHEET 1 OF 1



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DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

WEIGHT:

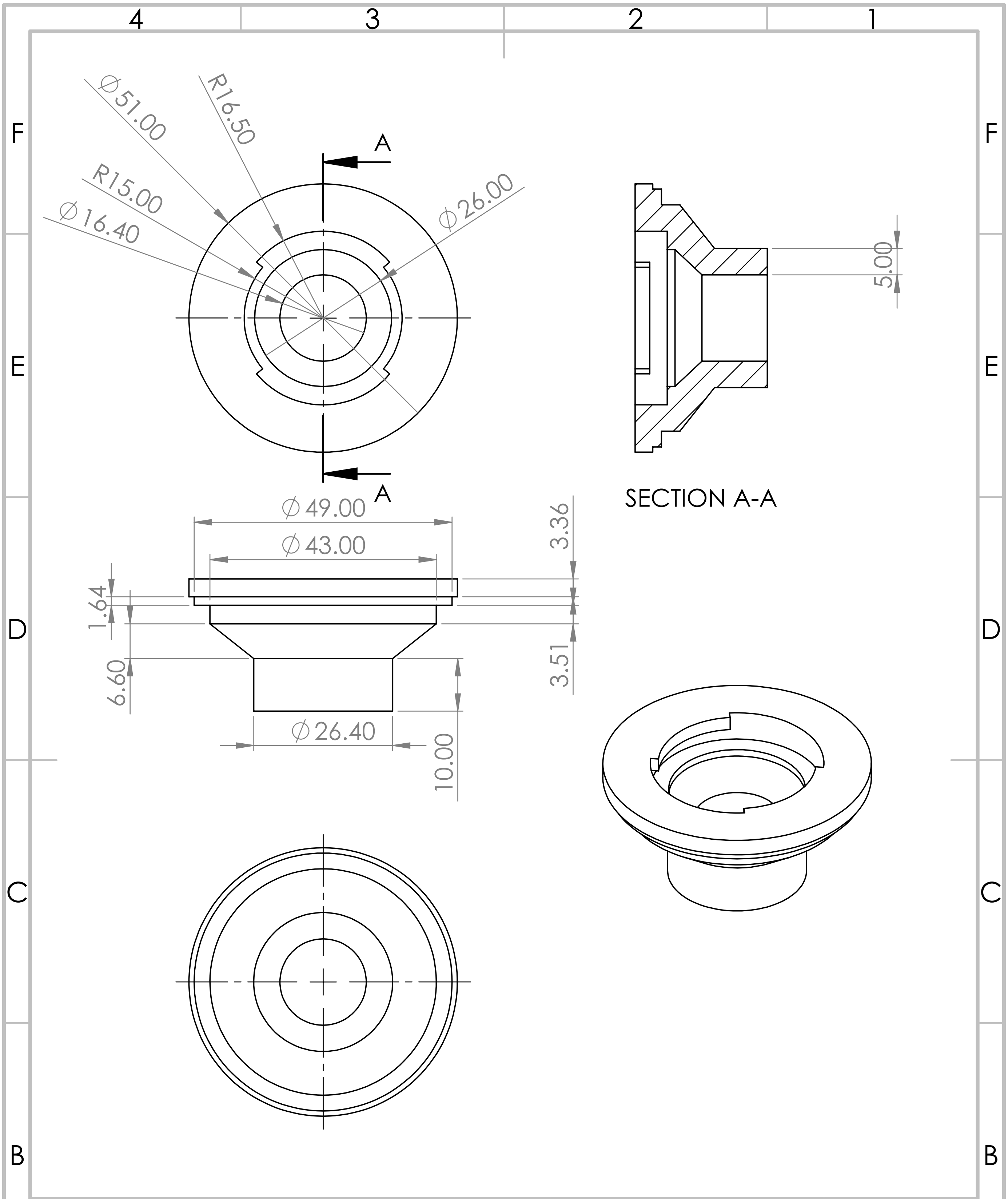
DWG NO.

magnet holder

A4

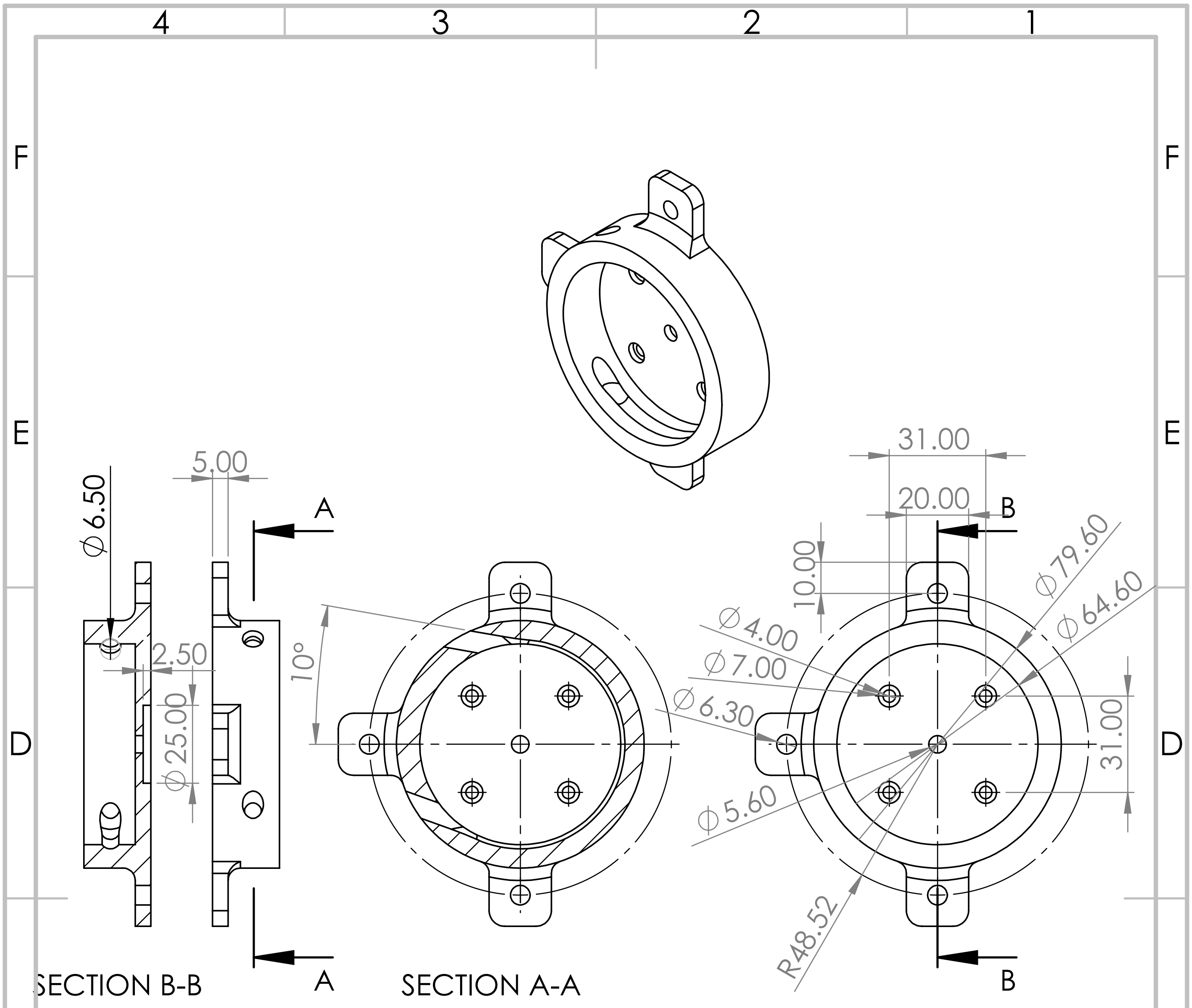
SCALE:1:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION

	NAME	SIGNATURE	DATE		TITLE:
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A				MATERIAL:	DWG NO. nozzle clamper — A4
				WEIGHT:	SCALE:1:1 — SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
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FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

DWG NO.

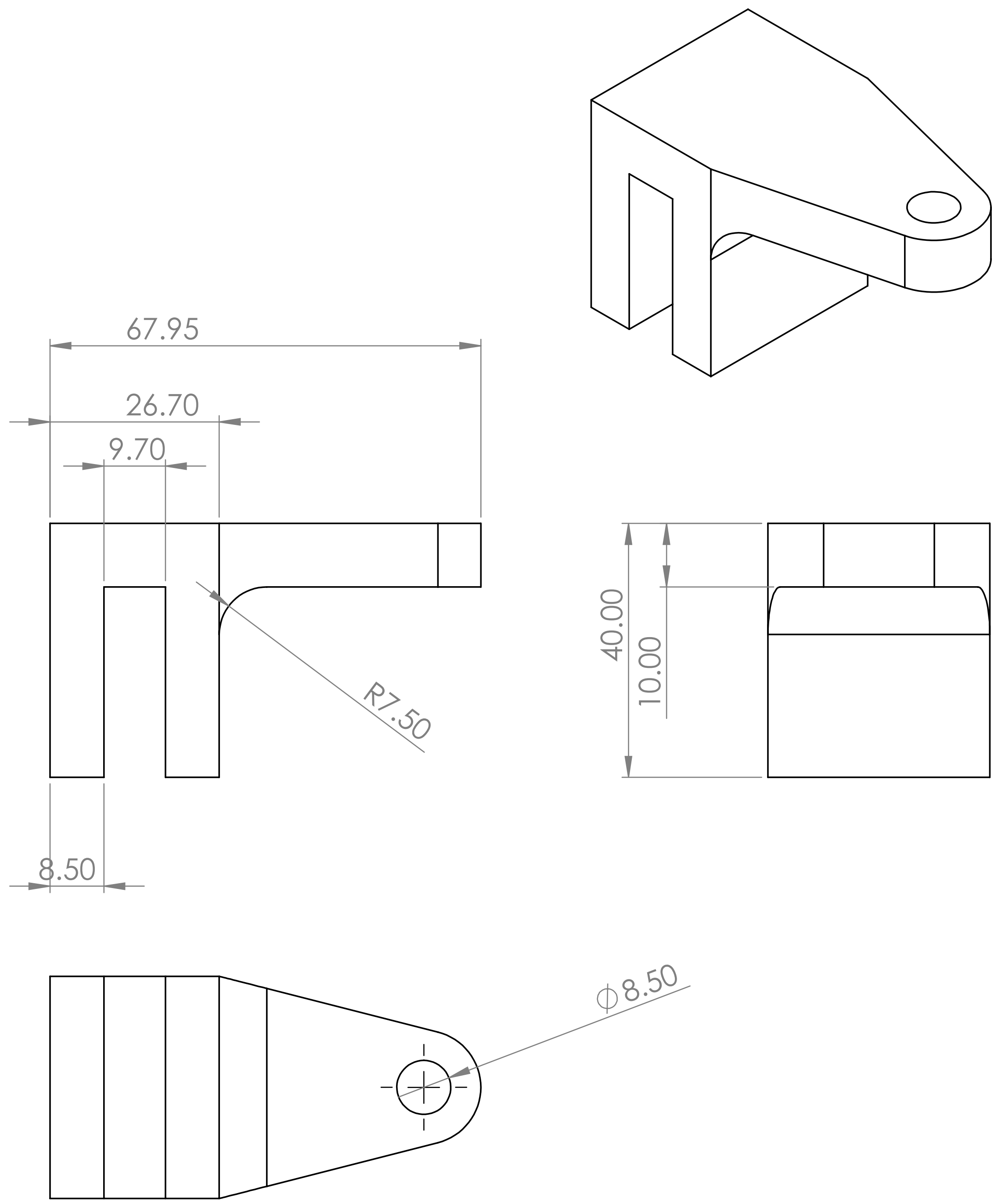
peristaltic pump small

A4

WEIGHT:

SCALE:1:2

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
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FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

DWG NO.

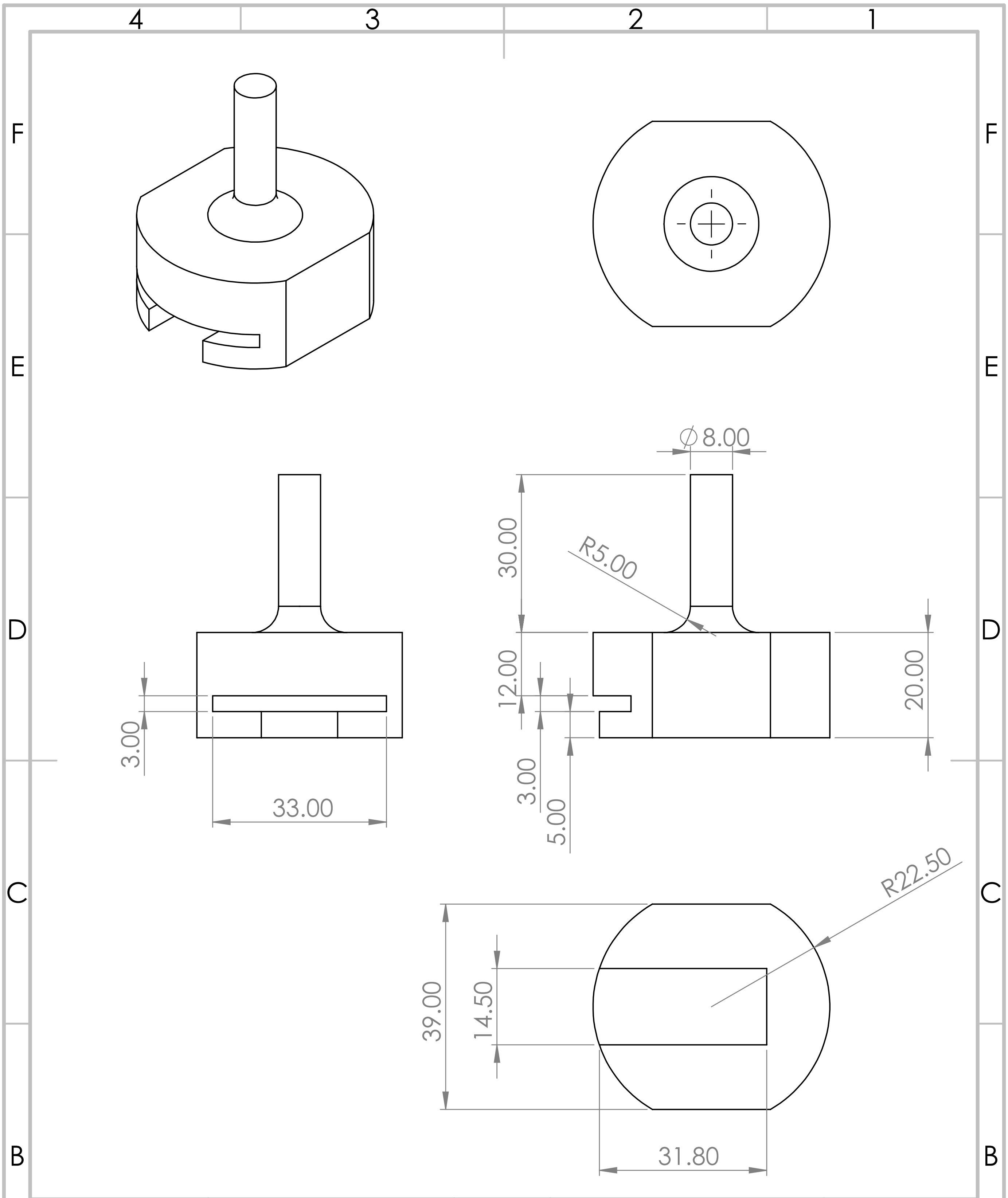
piston rod support

A4

WEIGHT:

SCALE:1:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

DWG NO.

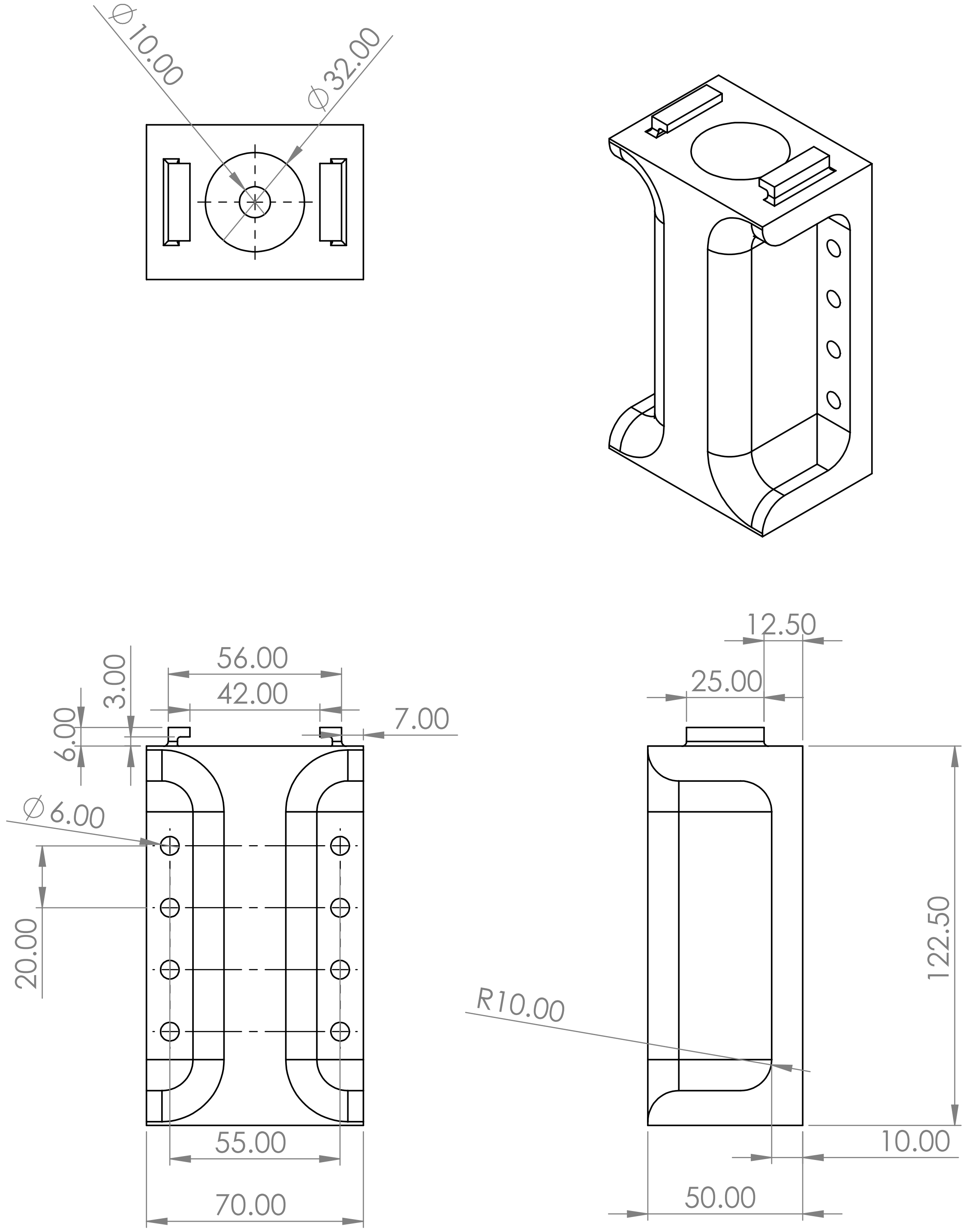
piston

A4

WEIGHT:

SCALE:1:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING / REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

DWG NO.

syringe holder new

A4

WEIGHT:

SCALE:1:2

SHEET 1 OF 1