Self-Healing Soft Robotics:

Design & Prototyping of a Self-Healing Soft Gripper

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Academic year: 2019-2020

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Supervisors: Dr. Seppe Terryn, Ellen Roels

MANIPAL INSTITUTE OF TECHNOLOGY
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(A constituent institution of MAHE, Manipal)

Self-Healing Soft Robotics:
Design & Prototyping of a Self-Healing Soft Gripper

A Graduate Project Report submitted to Manipal Academy of Higher Education in partial fulfillment of the requirements for the award of the degree of

BACHELOR OF TECHNOLOGY

in

Mechanical Engineering

by

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under the guidance of

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May 22, 2020

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Manipal
May 22, 2020

CERTIFICATE

This is to certify that the project titled "**Self-Healing Soft Robotics: Design & Prototyping of a Self-Healing Soft Gripper"** is a record of the bonafide work done by **Siril Teja Dukkipati** (**160909048**) submitted in partial fulfillment of the requirements for the award of the degree of **BACHELOR OF TECHNOLOGY** in **MECHANICAL ENGINEERING** of Manipal Institute of Technology, Manipal, Karnataka (A constituent college of MAHE, Manipal) during the year 2019 - 2020.

Prof. Pramod Mallar
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Department of Mechanical and
Manufacturing Engineering.

Dr. Sathyashankara Sharma
Head of the Department,
Department of Mechanical and
Manufacturing Engineering.

BRUSSELS, 18/05/2020

TO WHOM IT MAY CONCERN

Dear Sir/Madam,

It's my absolute pleasure to recommend *Siril Teja Dukkipati*.

Siril worked a research assistant in my research group from the 15th of December 2019 till the 15th of May 2020, a total of 22 weeks.

Siril is a valuable asset to any team. He is honest, dependable, and hard-working. Beyond that, he is a true problem solver who addresses issues with strategy and confidence. He doesn't mind working some more hours than planned to solve a problem.

His knowledge in mechatronics and his programming skills were a huge advantage to our research group. He has successfully completed his project on 3D printing of Self-Healing materials and prototyping of a soft gripper. The work he delivered has speeded up the preliminary work that was necessary to do for the research of some of my PhD students.

Along with his undeniable talent, Siril is an absolute team player. During his internship, he worked partially together with another master thesis student and worked closely together with researchers of the team in which he integrated very quickly. Even after his internship, he is available for questions of our PhD students.

Without a doubt, I confidently recommend Siril to join a master's program at your university. As a dedicated and knowledgeable student and an all-round great person, I know that he will be a beneficial addition to your organization.

Please feel free to contact me at seterryn@vub.be should you like to discuss Siril's qualifications and experience further. I'd be happy to expand on my recommendation.

Best wishes,
Seppe Terryn
Postdoc at Robotics & Multibody Mechanics research group
Vrije Universiteit Brussel

i. Motivation

Robotics and 3D printing are the fast-evolving fields where innovation thrives. More specifically, soft robotics introduces a new bioinspired perspective within the field of robotics. Their inherent compliance gives rise to a wide range of novel applications. The soft material used provides safety for humans who come in contact or share the same environment with the robot. This safety aspect allows a closer connection between robots and humans. This is certainly interesting in the context of robotics.

Focusing on rapid prototyping, a soft robotic gripper could ensure safety, comfort and usability among other things. However, bringing soft material in such close contact with humans and the surrounding, makes the robot vulnerable to cuts, scratches, punctures, etc. A prominent solution to this problem is the use of self-healing material. When damage occurs, the material can be triggered to start the self-healing process in the form of a chemical reaction. Research on this material is been excessively done at the department of Physical Chemistry and Polymer Science (FYSC), University of Brussels.

This project aims to explore the additive manufacturing possibilities of self-healing material in the form of fused filament fabrication (FFF). While doing so, the idea is to work towards the manufacturing of a soft robotic gripper as a demonstrator. Such a robotic gripper will assist social robots and recreational robots where the robot is at a close proximity to human activity and probable damage causing agents like knives.

Additive manufacturing offers freedom of design, more complex designs can be manufactured compared to moulding and shaping by folding and self-healing. Moreover, 3D printing provides a high degree of customization. For example, when manufacturing such a soft robotic gripper, the payload size and shape can be taken into account. Another key element of this project is multi-material printing. Self-healing material can be tailored to have certain properties e.g. a certain stiffness. Combining these materials with different properties can augment the product performance and the users experience, e.g. incorporating more flexibility at the joints of a soft robotic grippers. Also, the stiffness of the joints can be varied for optimal functionality.

ii. Declaration

I, Siril Teja Dukkipati, declare that this work titled, "Self-Healing Soft Robotics : Design and prototyping of a self-healing soft gripper" and the work presented in it are my own and can be considered for the thesis project for the award of Bachelor's degree in Mechanical Engineering from Manipal Institute of Technology.

I confirm that:

1. This work was done in the context of the 8th Semester Project at Vrije Universiteit Brussel in Belgium, while completing B. Tech in Mechanical Engineering at the Manipal Institute of Technology, Manipal, India.
2. All the work done as a part of this study is my own and no part of this work has previously been submitted for review or any other qualification at this University or any other institution for the award of degree by myself for the truest of my knowledge.
3. I have acknowledged all main sources of help.

Siril Teja Dukkipati
Brussels, June 1, 2020.

iii. Acknowledgements

I would like to express my gratitude and warmest thanks, first and foremost, to my supervisors, Ellen Roles and Seppe Terryn for their friendly support and valuable guidance throughout the project.

I would like to thank Ikram Mohout for her friendly support and technical advices throughout the project.

I would like to express my gratitude to my guide Prof. Pramod Mallar for taking his time to review my work and giving valuable advices.

Finally, I would like to thank my family, without whom I would not be the person who I am, and where I am today.

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vii. List of Abbreviations

3D	*three-dimensional*
CNC	*computer numerical control*
DA	*Diels-Alder*
DPBM	*methylene diphenylene bismaleimide*
FEM	*finite element modelling*
FFF	*fused filament fabrication*
PLA	*polylactic acid*
PTFE	*polytetrafluoroethylene*
R	*maleimide-to-furan*
SH	*self-healing*
TPE	*thermoplastic elastomeric*
TPU	*thermoplastic polyurethane*

1. INTRODUCTION

This study aims to bridge the gap between soft robotics and polymer science by incorporating some specialized properties of the polymers in the use of designing soft gripping systems and robotic mechanisms.

1.1 Soft Robotics

Soft robotics is a sub field of Robotics and utilizes soft materials like rubbers and soft polymers for the mechanical modelling of robots. These robots are mainly used as social robots and human interaction robots as these are harmless and can provide confident human-machine interaction. These are also used in cases where there is a need of flexible interaction with the environment. For instance, to pick and place a fruit, a robot cannot use its rigid gripper fingers as there is a possibility that the robot may crush the fruit and damage it.

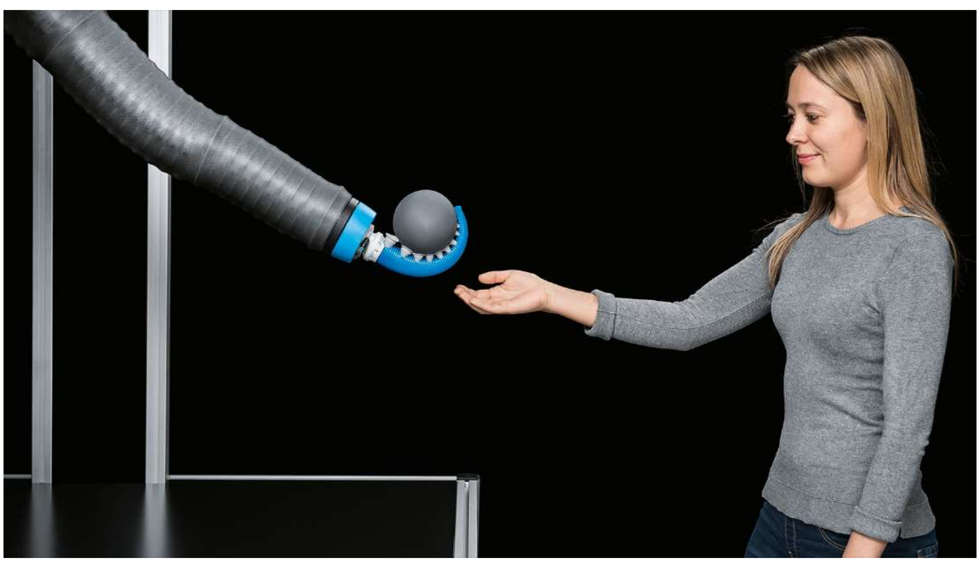

Fig.1.1 TentacleGripper inspired from Octopus, developed by Festo

1.2 Self-Healing Polymers

Most of the polymers used in the industry now a days don't possess the self-healing capabilities. If they experience any cuts and damages, the entire part or the sub assembly may be replaced which increases the maintenance costs. Many surveys have been conducted in the past so show that maintenance costs play a major part in the product management cycle and are factored in the project planning from the start.

This problem can be dealt with by the utilization of the self-healing polymers designed based on the Diels alder's reaction mechanisms [21]. These polymers have an ability to selfheal themselves without the addition of any external reagents. Based on the composition of the reactive sites in the polymer chain, these polymers are modified based on the use case.

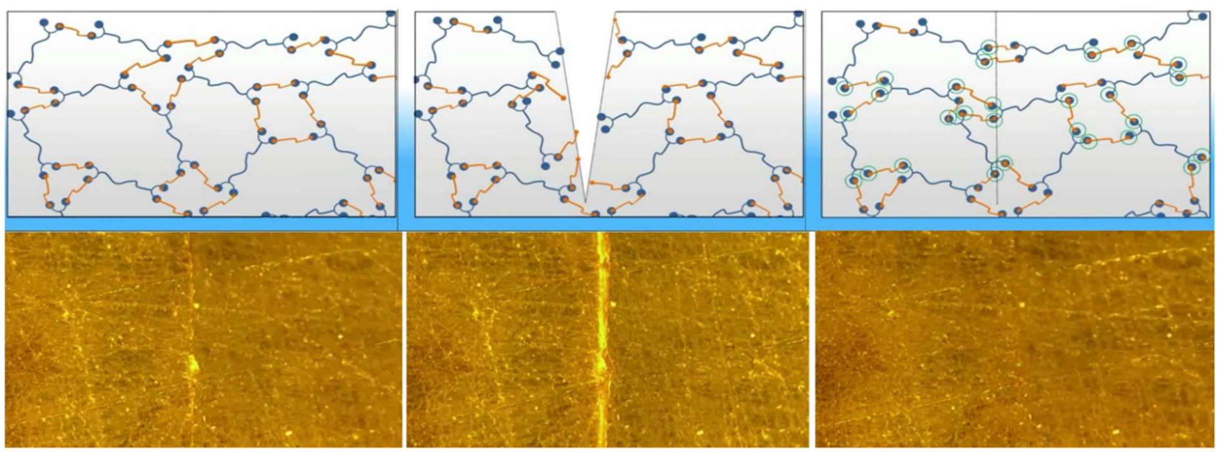

Fig.1.2 Reaction mechanism of the Self-Healing polymers. The second column indicates that a cut has been made in the sample with a knife. The Second row shows how the sample heals when subjected to a heat cycle. These external parameters depend on the reactivity of the polymer chains.

1.3 3D printing

With the recent developments in the field of 3d printing and rapid prototyping, it makes sense to develop an architecture for 3d printing of any new polymer material. There are also different types of 3D printing processes depending upon the use case and viability.

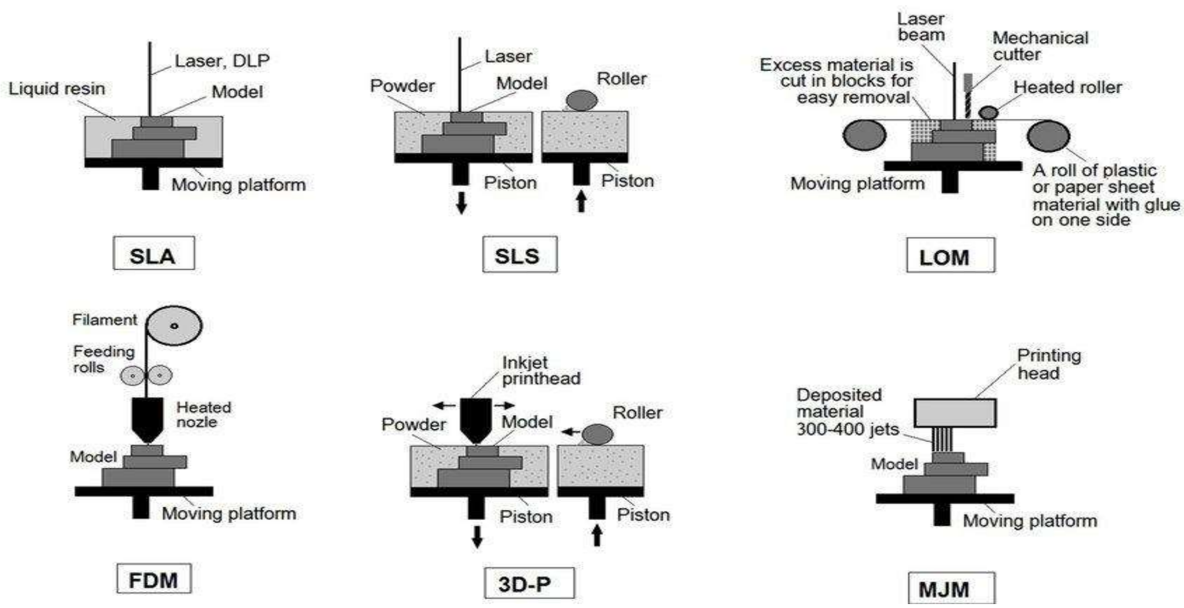

Fig.1.3 Different types of rapid prototyping methods described in [1]

FDM method is most common (Filament deposition method) out of all the processes as it is very easy to construct an FDM based 3d printer. Also, the self-healing material is soft and has temperature dependent properties which makes it susceptible for FDM type of 3d printing.

SH polymers are very sensitive to parameters like temperature, print speed, cooling etc. So, it is very important to keep in mind while dealing with 3d printing of these materials. The glass transition temperature if these self-healing materials has a very sharp band and below this band the material is not printable and above this band the material has very low viscosity and very high flowability which renders the printing ability.

Fig.1.4 3D printing of the Self-Healing material (Left); Filament extrusion process of the self-healing material (right)

2. IMPROTANCE OF THE PROPOSED WORK

This study has a paramount importance in the fields of Soft robotics and Product Life Cycle optimization as it has direct consequences in the maintenance costs of any product designed with the polymers having self-healing properties.

The main goal of this research was to incorporate an artificial healing mechanism in soft robotic components. If a damaging condition takes place, the robotic part may be damaged or even completely fail. However, using the healing ability, it can be healed back to its initial state, and this preferentially autonomously. Such a healing function can increase the lifetime of soft robotic components. In addition, with this ability, soft robots should not have to be dimensioned taking in account large safety factors, to be able to withstand damaging effects. Instead they experience damage but can subsequently heal. In this way, the integration of a healing mechanism leads to lighter components, which is eventually translated to more efficient designs.

"Self - healing technique combined with the soft robotics applications will be a very impactful study in the field of robotics."

3. LITERATURE REVIEW

3.1 Soft Grippers and their evolution

Traditional industrial robots are composed of rigid structures, they often carry out repetitive tasks and their capability to interact with their surroundings is limited. Crowded and unstructured environments are a challenge for conventional robots. Soft robotics, inspired by nature, attempts to overcome these issues, and tends to replace rigid structures by softer alternatives. The need for soft robotics can also be traced back to the idea of robots performing various tasks while sharing their work space with humans. These types of robots can create a safer environment for humans (compared to rigid traditional robots), giving the opportunity to bridge the physical gap between humans and robots as described by *D. Rus and M.T Tolley* in [3]

The image of soft robotics has evolved over time. From robots with rigid links and compliant joints that can be controlled or changed in stiffness the emphasis has shifted towards more bioinspired continuum robots that inherently embrace compliance and can display large strain during operation as described by *Ikram* in [20].

The definition of soft robots given by the *RoboSoft* community by *C. Laschi, et al.* in [4]:

> "*soft robots/devices that can actively interact with the environment and can undergo "large" deformations relying on inherent or structural compliance*."

A. D. Marchese et al. in [5] used Shape memory alloys to allow functionality to Soft robots. From a materials science point of view the involved materials are in general soft with a Young's modulus comparable to that of (soft) biological material. In contrast to traditional robots manufactured from metal or hard plastic (with Young's moduli in the range of 10^6-10^9 kPa), the novel soft materials mimic the mechanical properties of biological tissue such as muscle, skin and tendon with moduli between 10-10^6 kPa. In essence when distinguishing soft robots from traditional hard robots, the compliance of the involved materials can be used as a criterion of classification. Materials used in soft robots are often elastomers such as silicon and rubber. Also shape memory alloys (SMA) qualify as suitable material. Nitinol (a mixture of nickel and titanium) is a widely used SMA, that can alter its shape with respect to temperature changes.

Soft robots introduce skills that were not explored before, such as climbing, stretching, growing and squeezing.[4] They are resilient and are able to perform dexterous maneuvers.[5] This is in contrast with traditional rigid-bodied robots as they are more specialized for a specific task because of their limited adaptability.[3] Figure 3.1 (a) illustrates how traditional (or hard) and soft robots express dexterous mobility. The soft robot can reach practically any point in its workspace and has an infinite number of configurations. It can furthermore adapt its shape to objects, without damaging fragile objects as little resistance is generated. However, as shown in Figure 3.1 (b), position sensing is more difficult in soft robotics as well as controlling the shape of the robot.

Soft robots exist as a continuum structure, whereas with traditional robots, joint position can be precisely determined. Figure 3.1 depicts how conventional and soft robots make contact with objects and their surroundings. The traditional robot has an end effector that is in this case used to grab. The end effector is specific for a certain task, this is in contrast with the soft robot that adapts its structure to make contact with the object, creating friction that allows the object to be lifted. Interaction with loading is fundamentally different for soft and hard robots. Figure 5 (d) shows how only the position of the joints are affect in the traditional robot, the change of position can again be measured precisely. Soft robots on the other hand undergo continuous deformation due to an applied load or gravity. This could be difficult to control as described by *D. Trivedi et al.* in [2]

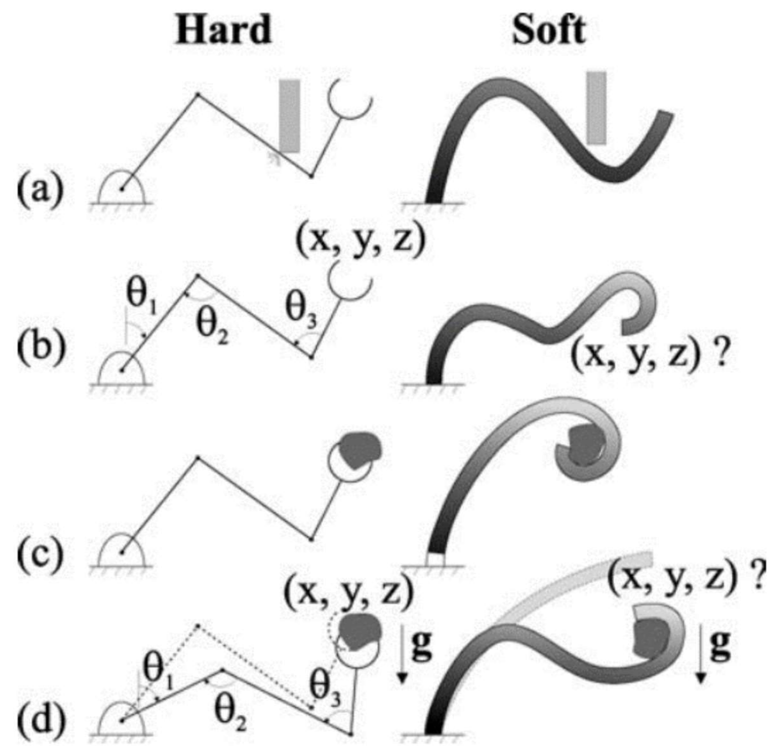

Fig.3.1 Abilities of hard and soft robots: (a) dexterity, (b) position sensing, (c) manipulation and (d) loading shown by *D.Trivedi et al.* in [2]

3.2 Self-Healing 3d Printing

In the previous chapter multiple advantages of soft robots were explained, however there is a significant disadvantage to soft robotics. Although soft robots are able to withstand mechanical impact by energy absorption, sharp objects that can cut, puncture or perforate the material are a real threat. Moreover repeated actuation of elastomeric material can lead to weakening due to cyclic fatigue as described by *S.Terryn et al.* in [6]

D.Y. Wu, *R. F. Shepherd et al.* in their studies [7], [8] showed a solution to this problem. One attempt to overcome these problems is by over-dimensioning the robot. Also compromising the design and material of soft robots leads to a better resistance to damage. *R. F. Shepherd et al.* developed actuators consisting of composite material, namely polyaramid fibers with an elastomeric matrix and used a folded (accordion-like) structure in order to increase the actuator's resistance to damage. However, a more prominent solution to overcome these problems, are materials that are able to self-heal.

The key challenge is to preserve the desired mechanical properties while expressing self-healing (SH) behavior. For soft robotics, SH polymers are relevant. Nevertheless, there has been research done on SH ceramics and metals among other materials, but this research is not as mature as that for SH polymers.[10] The focus of this project is on SH polymer material. Figure 4 shows an example of such an SH soft robot, namely a soft pneumatic gripper designed and manufactured by *S.Terryn et al*. [11]

Fig. 3.2 Self-Healing Soft pneumatic gripper developed in [11] by S.Terryn et al.

4. WORKING OF PRESENT SYSTEMS

4.1 Conventional 3d printing of polymers

Most of the 3d printing polymers are crystalline in nature. The most common choices for 3d printing with plastic polymers are Poly Lactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS), Thermoplastic polyurethane (TPU), Poly Vinyl Alcohol (PVA), Nylon etc. All these polymers exhibit excellent mechanical and thermal properties which makes them suitable for 3d printing and rapid prototyping. They are thermo plastic polymers which allows them to be recycled after use or a failed print. This is the best way to reduce the use of plastics and carbon footprint.

4.2 Bowden vs Direct extrusion

There are 2 types of extrusion systems being practiced in the industry in recent times. The direct extrusion system and the Bowden extrusion system. The main differences between these systems are weight of the print head, ability to print flexible filaments, retraction capabilities etc.

The Bowden setup has a very simple design and is spread across the printer. The extrusion motor pushes the filament into the heated nozzle and is responsible for the rate of filament deposition and retraction of the filament from the nozzle. This motor is located far away from the print head and is connected to the nozzle and the heat sink setup by a heat resistant tube made of Poly Tetra Fluro Ethane commonly known as PTFE. The weight of the print head is less as the motor is not a part of the print head and as a result this setup can achieve speeds up to 150 – 200 mm/s which is considered as highspeed printing.

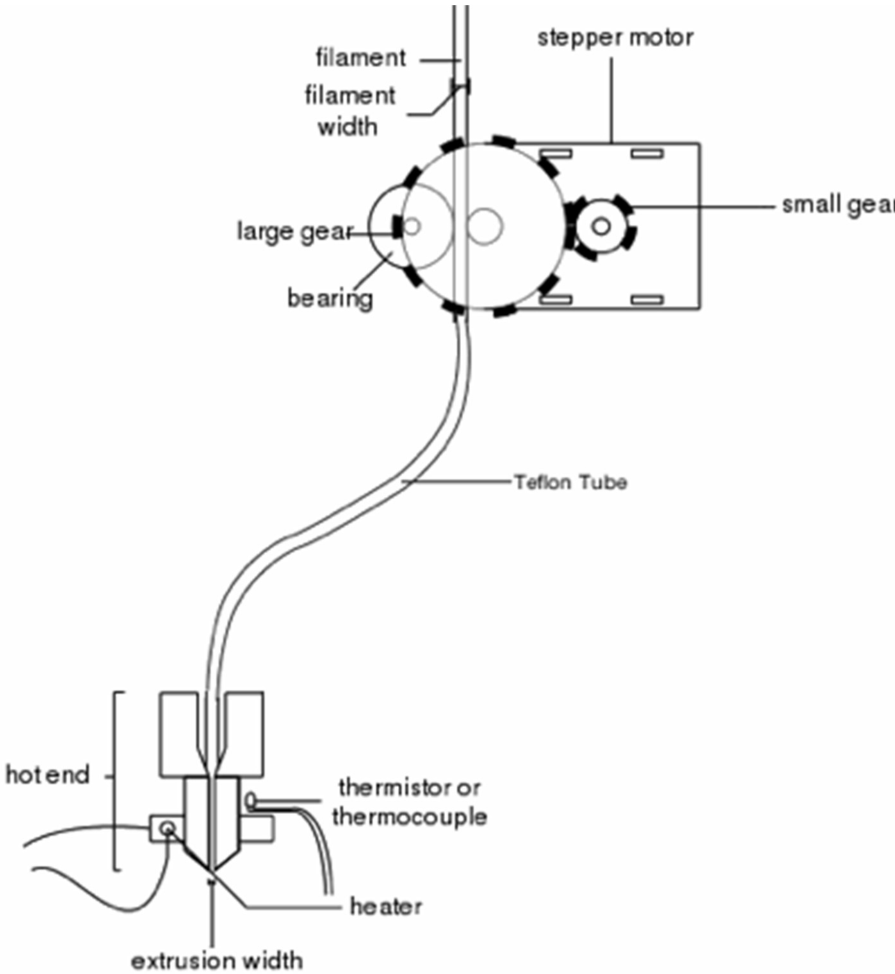

Fig. 4.1 Bowden Extruder setup [© Fargo3dprinting.com]

The direct setup is more compact and heavier. The motor is mounted on the print head itself in order to eliminate the use of any intermediate tubing. This allows the print head to print flexible filaments as there is less gap between the extrusion motor and the heated nozzle. The elimination of the PTFE tubing completely eliminates the friction between the filament and the tubing which accounts to lesser torque motors. Nevertheless, this setup is heavy compared to its counterpart. This wouldn't be an issue as flexible filaments cannot be printed at high speeds anyways. The direct extrusion system is considered superior to the Bowden setup as it can print almost all the commercially available filaments.

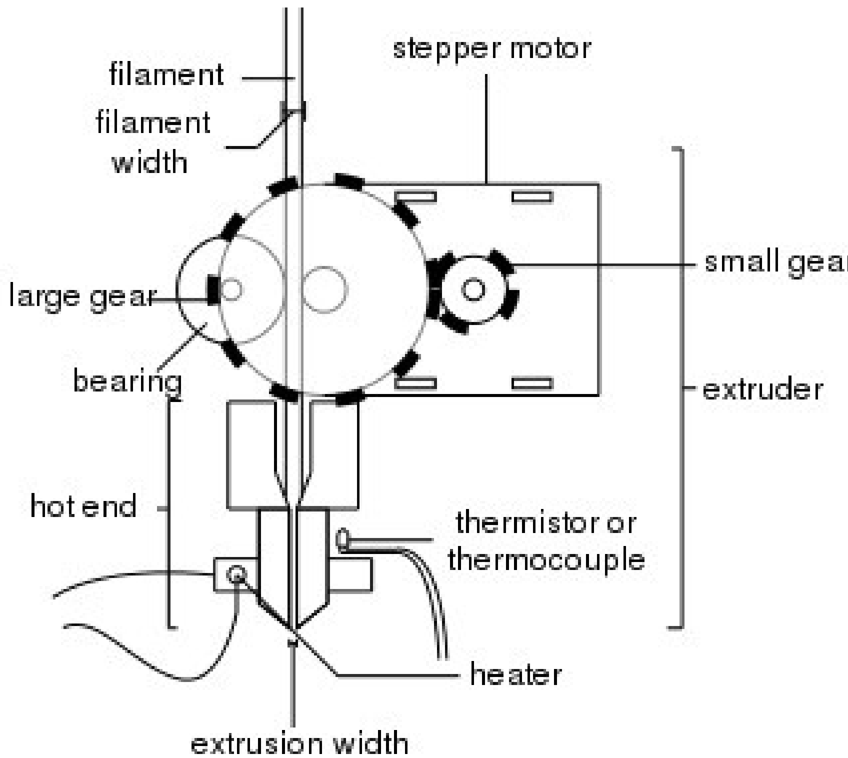

Fig. 4.2 Direct Extruder setup [© Fargo3dprinting.com]

4.3 Flexible filaments

There are some commercially available 3d printing polymers which are flexible and can be used for prototyping relatively flexible parts like vibration dampers, gripping pads set. Some of the materials include TPU, FilaFlex, NinjaFlex which are extremely flexible and can sustain strains of up to 1000%.

The flexibility of these materials makes the printing process more complex and the probability of print failure is high. These can be printed only with a direct extrusion setup as there is less friction and there is less probability for the filament buckling in the system. Bowden setup has a long PTFE tube which is not ideal for these materials.

Fig.4.3 A 3d printed shoe sole using Polyurethane material [© Snowtree Group Co.]

4.4 Soft grippers

Soft robots are also compliant robots and often inspired by biology. They typically consist of soft materials, rather than metals or hard plastics [2][12]. The elasticity modulus of these materials is often close to the ones found in living organisms (104-109 Pa) [11]. This opens the possibility for safe interaction with natural environments (such as human interaction) [3]. Moreover, by using soft materials, they can deform around obstacles, which makes them very useful for soft grasping applications. They are already finding their way into commercial applications, as described by Bogue [13]. For example, the companies Festo (Fig. 10) and Empire Robotics have soft gripper designs available on the market [21].

More general, soft actuators can be split into different categories based on actuation modes [14]. Bending actuators are ideal for making grippers, while expanding and contracting actuators are more often used as artificial muscles [15][16][17]. These actuators can either be actuated by tendons connected to a motor [15][16] or pneumatically as described by Gorissen et al. [14].

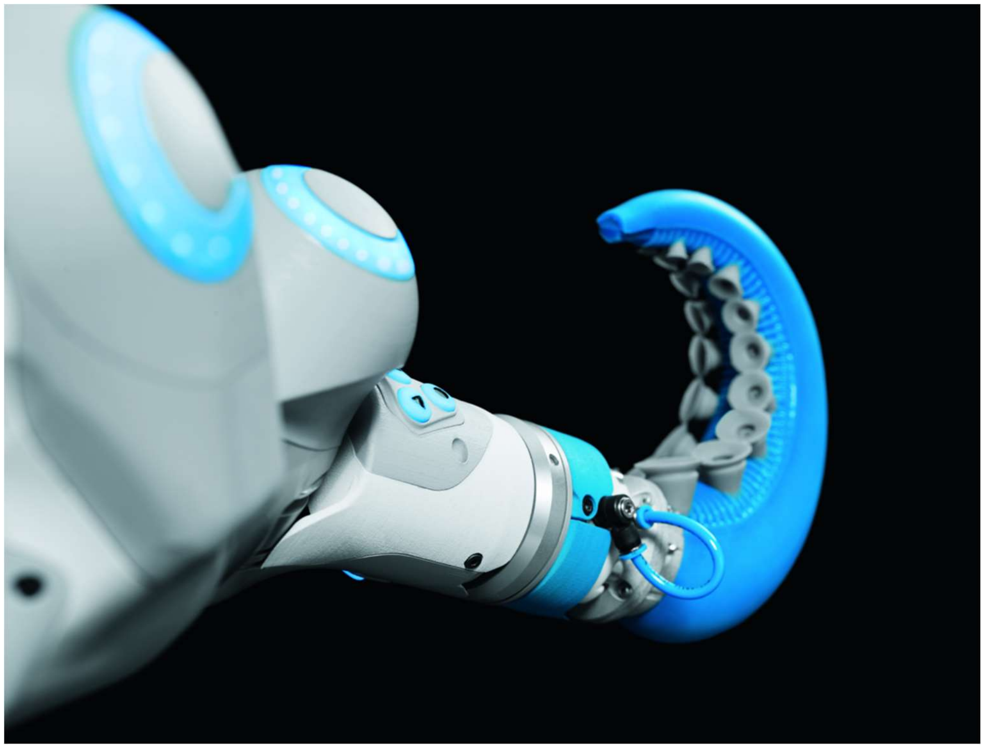

Fig.4.4 A bioinspired soft gripper by FESTO, inspired by the tentacles of octopus.

The flexibility and softness of these robotic parts also have several drawbacks. As the used materials are soft and have a low modulus of elasticity, they are more prone to tearing, piercing and other forms of damage, besides the usual wear. This can happen when handling sharp objects or working in an environment with sharp objects or edges. In pneumatically actuated parts, a leak can, for example, happen by applying overpressure in the actuator. When a leak is present in the actuator, it can still work given that the leak is small. However, this will make the actuator less energy efficient and it can apply less force. Because of this behavior, the trend is to over-dimension (soft) robots, which makes them heavier and more expensive [9].

Moreover, a thicker layer of flexible material will reduce the flexibility. The amount of over dimensioning needed, is preferably as low as possible. Furthermore, permanent deformations can also occur in soft actuators, which are induced by creep [21]. This creep is due to the high stresses acting on the material when creating high pressures inside the actuator [18].

5. PROBLEM STATEMENT

This study enables us to evaluate the possibilities of integrating 3d printing self-healing polymers with soft robotics. If the result of this study turns out positive, it would be a very impactful contribution in the field of soft robotics.

The aim of the project is to develop a 3D printable self-healing Soft Gripper. This gripper can later be equipped with sensors for different measurements like force of gripping, COM detection etc.

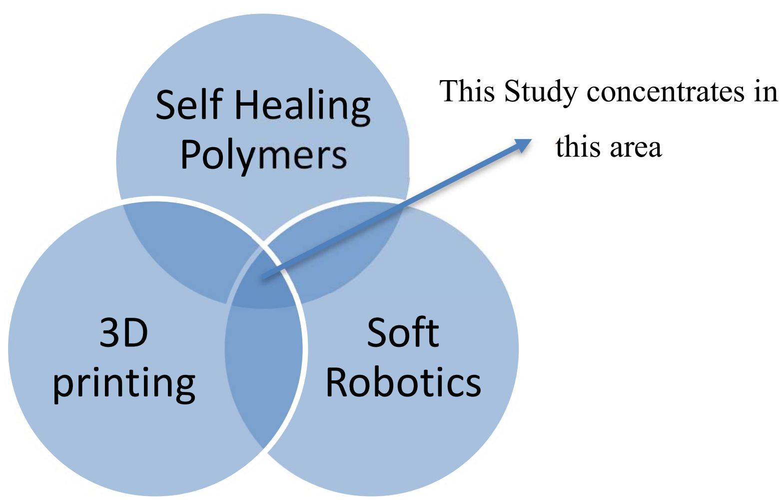

Fig. 5.1 Representation of various aspects of this study

6. OBJECTIVES

All the objectives of this study are described below in the table form.

To Design	To prototype	To study
A direct drive system capable of printing SH material ⇨	Direct drive system ⇨	Performance of the Direct drive system
Tool docking adapter to fit the designed direct drive on the printer ⇨	Tool docking adapter	
Soft gripper ⇨	Soft gripper ⇨	Performance of the gripper
	SH Filament for printing ⇨	Print quality of SH material

Table 6.1 Objectives of this study.

6.1 To design:

6.1.1 Direct drive system

With the recent developments in the field of 3d printing and rapid prototyping, it makes sense to develop an architecture for 3d printing of any new polymer material. SH polymers are very sensitive to parameters like temperature, print speed, cooling etc. So, it is very important to keep in mind while dealing with 3d printing of these materials.

As the SH material is very flexible, traditional Bowden extruders will not work. So, a direct extrusion method will be incorporated. A completely custom extrusion mechanism will be designed especially for self-healing materials which incorporates multiple tool heads for multi-material printing in the later stages.

6.1.2 Tool Docking adapter

To incorporate the custom direct drive extruder on the tool changer 3D printer, a tool docking adapter is to be designed. This adapter will allow the custom print head to be mounted on the tool changer 3d printer without any space and cooling issues.

6.1.3 Soft Gripper

An underactuated gripper is designed keeping in mind that it will be made of flexible materials. A rigid link gripper is modified in design to incorporate manufacturing with flexible materials. This design of the gripper will have two modes of grasp, A power grasp and a precision grasp. These grasp modes allow the gripper to encompass a variety of payloads of diameters ranging from 5mm to 60mm such as nails to hammers.

6.2 To prototype:

6.2.1 Direct drive system

The designed direct drive system will be manufactured in this step. Aluminium is chosen for this prototype as it is a very good conductor of heat and can dissipate the heat from the heatsink quickly. This allows the SH material to not clog inside the extruder as the SH material has very narrow glass transition temperature band and is highly sensitive to temperature.

6.2.2 Tool Docking adapter

The docking adapter will be made from Aluminium as it is light yet rigid. A permanent magnet is glued in the cavity of the adapter to incorporate the locking mechanism of the tool.

6.2.3 Soft Gripper

Soft materials such as Vytaflex, Econ80, EcoFlex etc will be first used for the manufacturing the preliminary design. Molding technique will be incorporated as these materials are not 3d printable.

6.2.4 SH filament extrusion

Before printing, the SH material is to be extruded into filaments of diameter 2.2 mm. For this, a heated filament extruder is used. While doing this step, it must be kept in mind that the band heating nozzle of the extruder must be kept at a constant optimum temperature. If it is not maintained, then extrusion artifacts like shark skin effect, brittleness etc can occur.

6.3 To study:

6.3.1 Performance of the Direct drive system

The designed direct drive extruder is then tested with SH filament. Test prints will be collected and inspected for any unusual artifacts like layer delamination, under extrusion, over extrusion, nozzle rubbing, surface finish etc.

6.3.2 Performance of the Soft Gripper

The soft gripper prototype will be tested with different objects of diameters ranging from 5mm till 60mm like nails, wine glass, hammer etc. Based on the performance, suggestions will be made to improve the grip quality of the design and functionality.

6.3.3 Printing with SH material

The printer will be calibrated for printing with SH material. Various test prints will be made in this step to ensure accuracy and repeatability of the print. After ensuring that the printer can print SH material with reasonable accuracy and print quality, we move to the multi material printing with the SH material, i.e. printing simultaneously with two different SH materials. Then the two SH materials will fuse together as a single print. This will have numerous applications in terms of prototyping with SH materials.

Multi-material 3D printing of the gripper with self-healing materials ideally will be a proof of concept for the idea of 3d printing with self-healing materials.

*Multi-material printing with self-healing materials is a very complex process. So, this step is optional and have not been accomplished in this study because of lack of time. These can be accomplished in the future developments of this project.

7. METHODOLOGY & EXPERIMENTAL SETUP

7.1 Design of the Custom Extruder

A completely custom extruder mechanism is designed to aid the process of 3d printing with self-healing materials. The design process went into various steps of design modifications and validations.

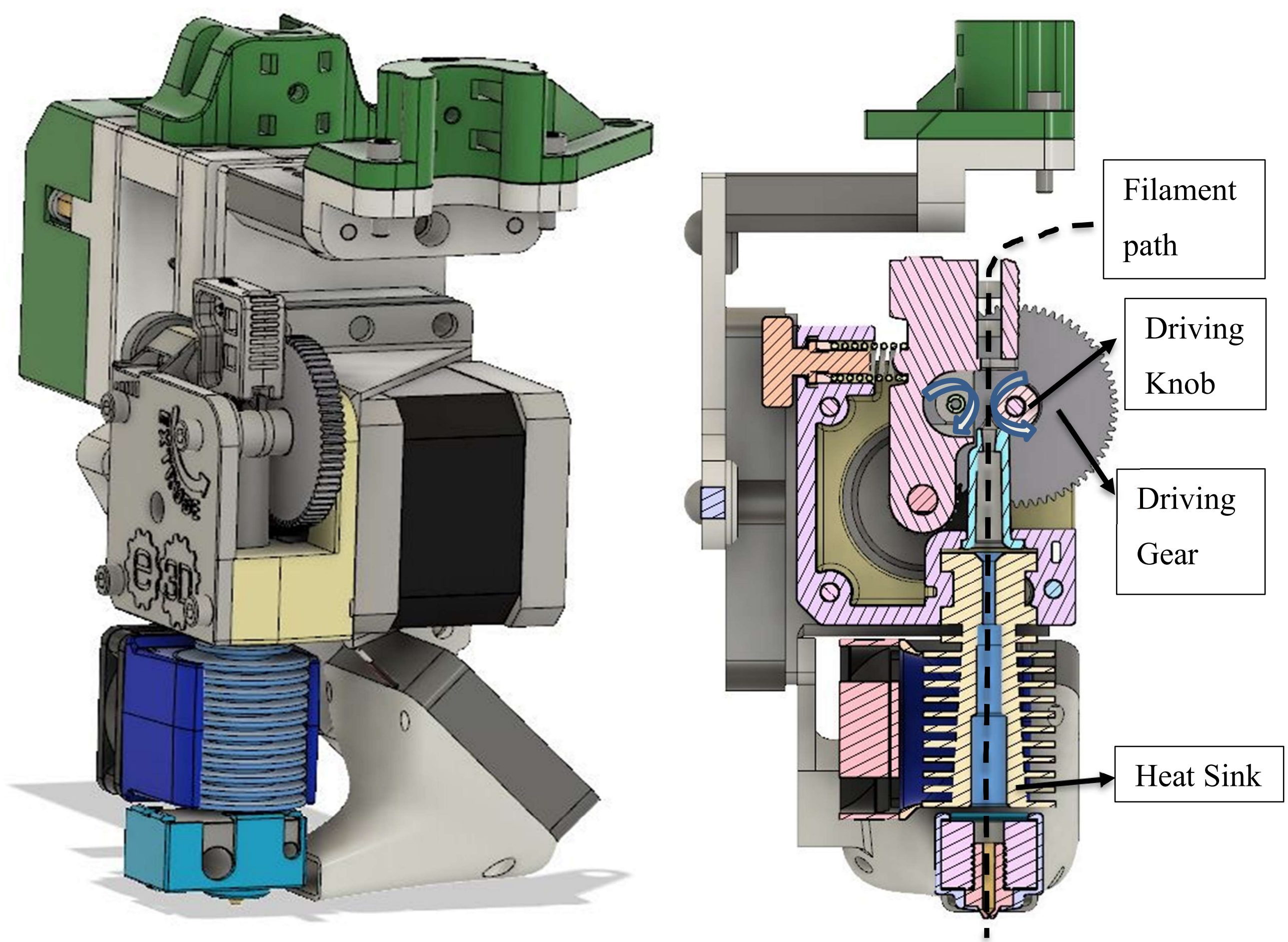

Fig. 7.1 Design Iteration 1 – Custom Extruder Design

Off the shelf parts are used in the 1st iteration of the design to minimize the machining time and to test the proof of concept of the idea. All the print heads are developed for the tool changing mechanism by E3D keeping in mind the long-term goal of the project i.e. multi-material self-healing printing. A custom mount is designed to fit the direct extrusion system offered by E3D to incorporate into the design.

The design is then assembled, and test prints were done. Even though this system is designed to work with most of the flexible filaments, it performed poorly with the self-healing material. The heat sink is too long, and the filament is often struck in the heatsink because of buckling. Also, the self-healing filament is too fragile, and the extruder's force is too much for the SH material. As a result, it kept on shearing and breaking. As these are design inherited issues and there no direct solution or modification, it is decided that the extruder mechanism is to be completely redesigned especially for the self-healing material.

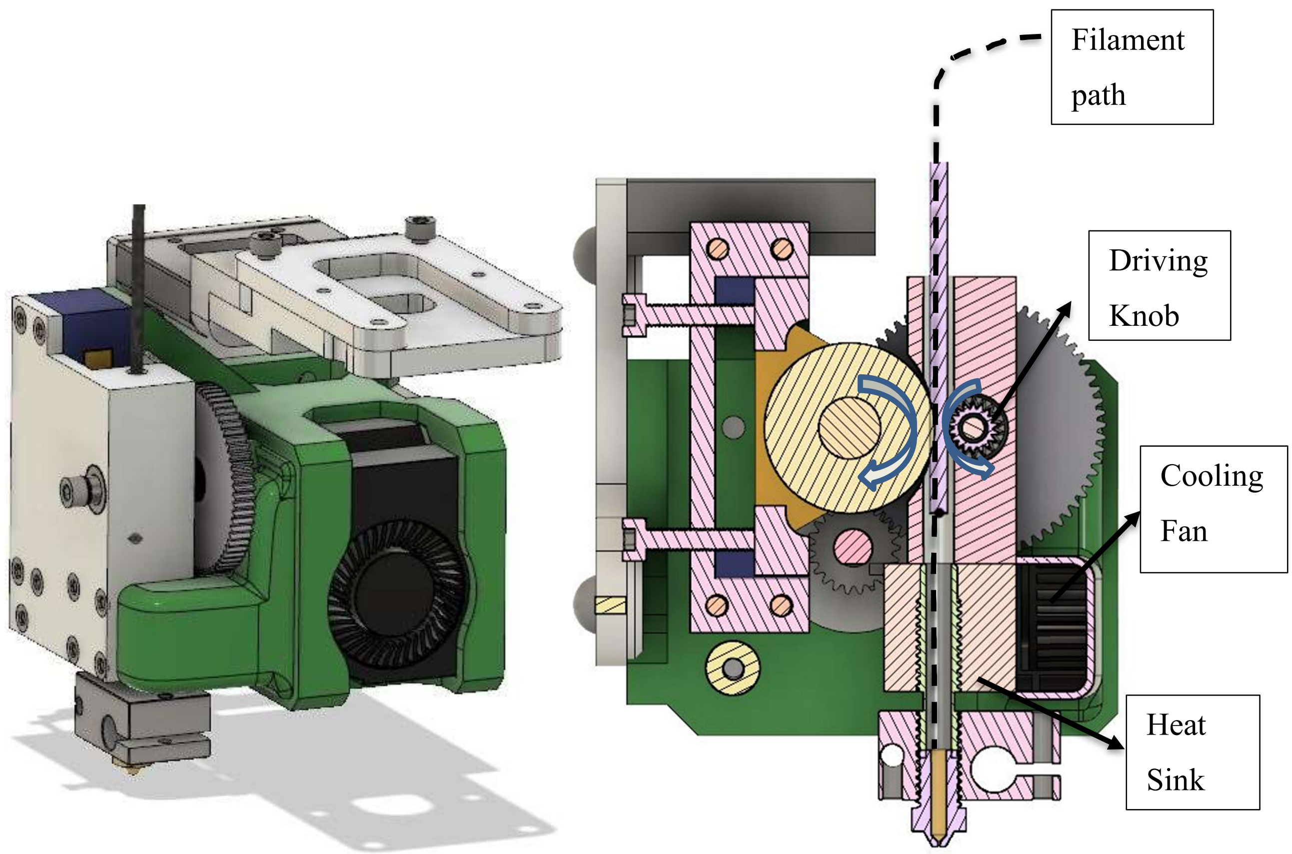

Fig. 7.2 Design Iteration 2 – Custom Extruder Design

The shortcomings of the Design Iteration 1 are thoroughly noted and solved in the second design iteration. The Fig.13 shows a much better design and a robust build quality as all the parts are custom made especially for filaments which are very flexible.

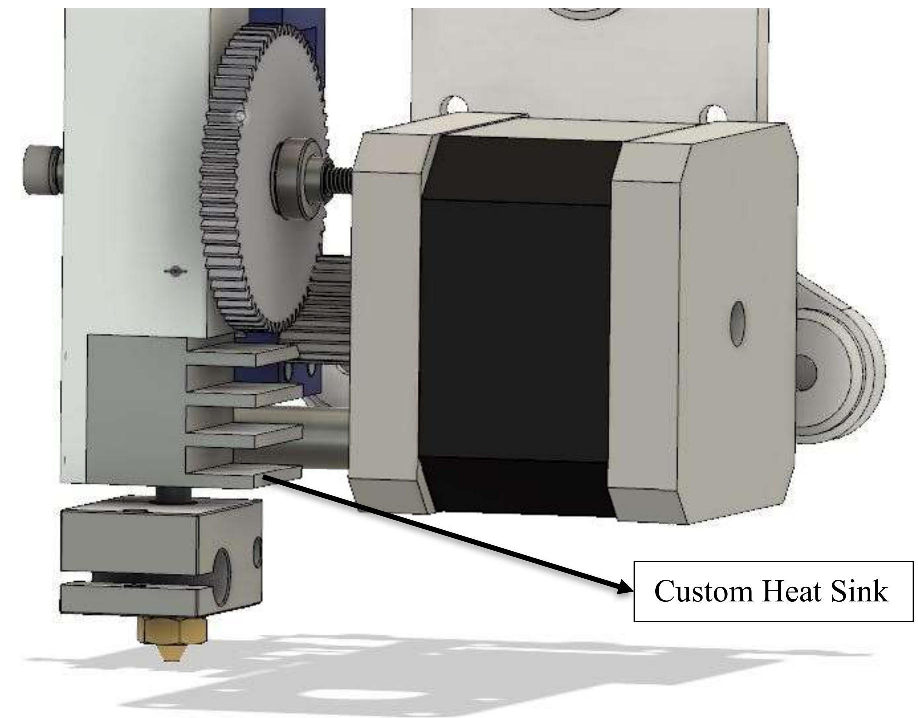

Fig. 7.3 Design Iteration 2 – Custom Heat Sink

The heat sink is redesigned and is decreased in length to prevent nozzle blockage and buckling of the material in the heat break. As a result of decreasing the length, the heat dissipating capability of the heat sink decreases as there is less surface area. This is compensated by forced cooling of the heat sink. A blower is directly mounted across the fins to keep the heat sink cooled throughout the print.

Several test prints are made, and this design is proven to be capable of successfully printing the self-healing material with a much better quality than the previous design iteration.

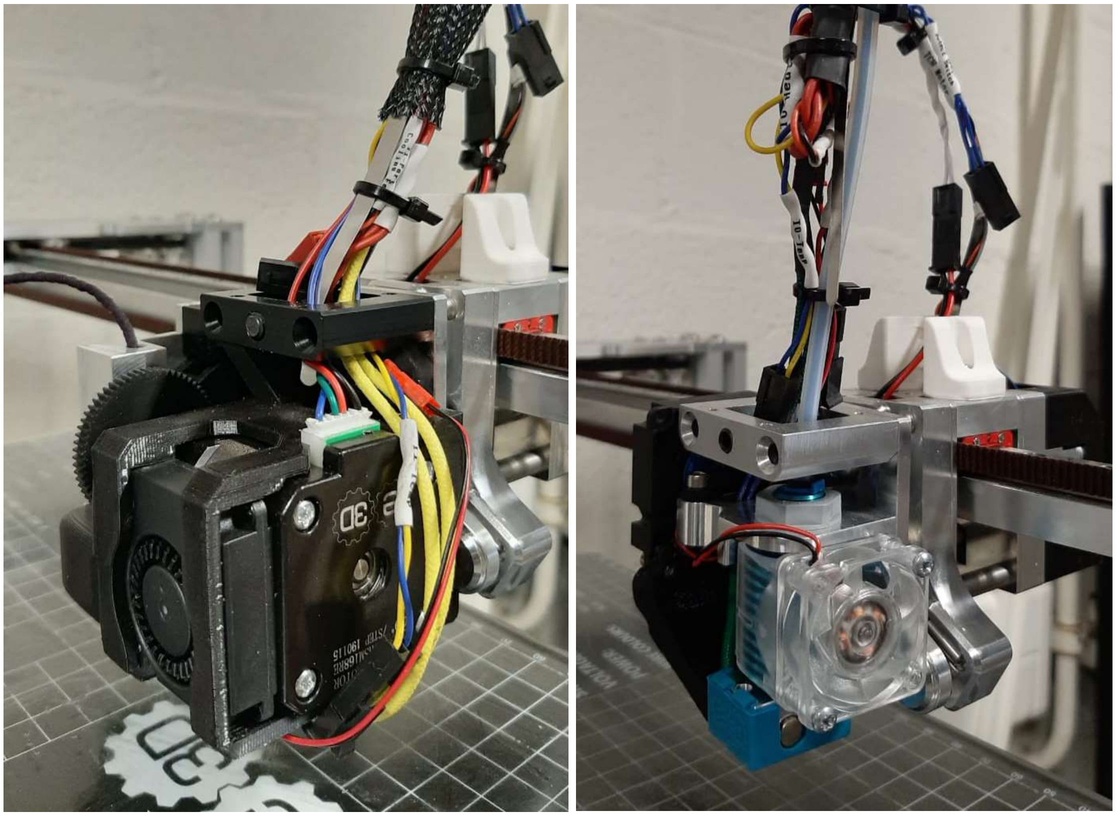

Fig. 7.4 Developed Direct drive system (left) vs Commercially available Bowden system (right)

The above figure illustrates the fundamental differences between the commercially available Bowden setups and the custom designed extruder setup. It can be seen that the filament must travel a much lesser distance in the custom designed extruder compared to the commercially available designs.

7.2 Tool changing system and docking mechanism

The tool changing mechanism is incorporated to facilitate the development of different types of tool heads for different materials, instead of changing the materials in the extruders which is time consuming. In this system, there is one dedicated extruder for every material. This will result in much cleaner transition of material change in the print while dealing with multi material prints.

As there are 4 tools, a cocking mechanism must be incorporated to pick up the tool and drop the tool when necessary. This is achieved by using a separate clamping mechanism and magnets for docking.

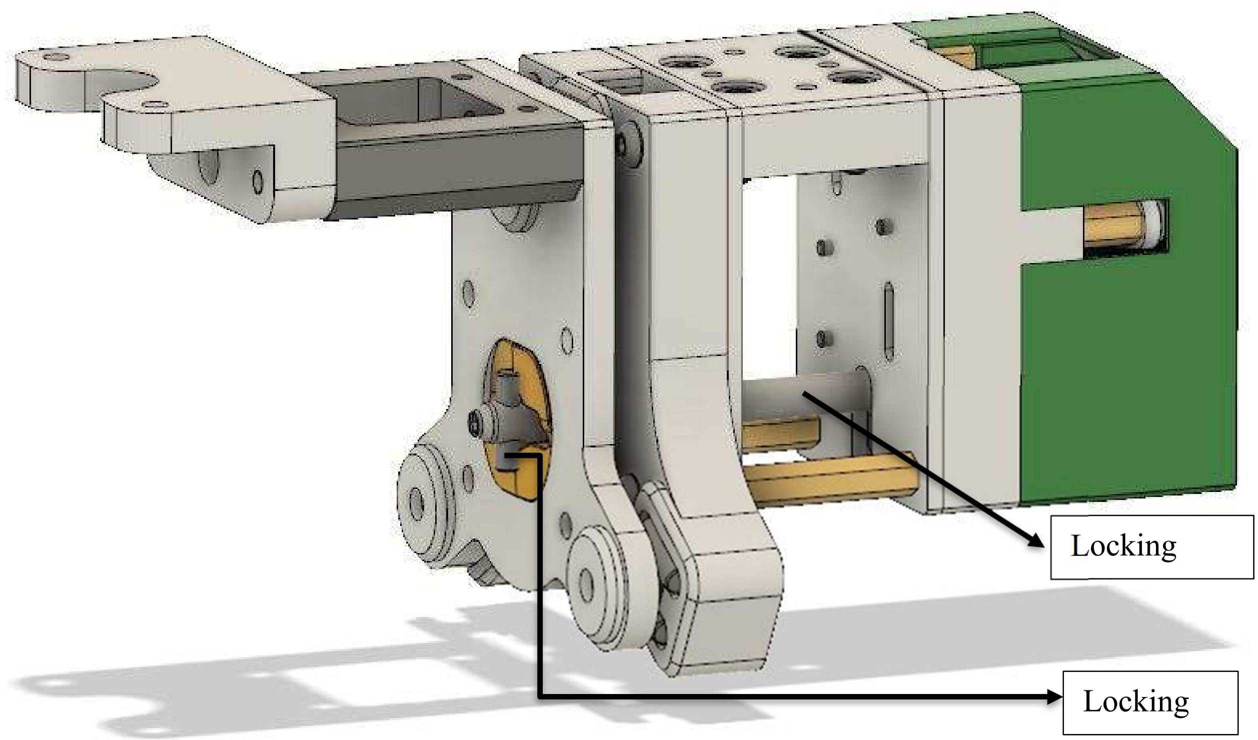

Fig.7.5 Tool Docking mechanism

The tool head is held in place in the docking station by 2 guide pins and a magnet. When the tool is required, the mechanism is moved into the position of the docking station and with the help of the guides and the locking motor, the tool is firmly held on to the print head. This way, we can achieve the tool changing and multi material printing.

7.3 Polymer extrusion into filaments

Any polymer, before 3d printing, is converted into filaments of diameter of 1.75mm or 2.85mm (industry standards) depending of the requirements. The self-healing polymer has also to be converted into filament form for 3d printing. For this, a filament extruder is used [20].

DPBM-FGE-FT5000 material (***referred as the self-healing material in this document***) is grinded prior to extrusion (Figure 18), this allows for a smooth transition from funnel to extruder and improves filament quality. The material is submerged in liquid nitrogen during this process, allowing the material to drop beneath its glass temperature, making it brittle and thus easier to grind.

Fig. 7.6 Grinded DPBM-FGE-FT5000 material

The Noztek touch single screw extruder is shown in Figure 18. Optimal extrusion parameters are found through trial and error. The temperature of the pre-heater and heater were both initially set at 107 °C, results improved when gradually changing the temperatures up to 119 °C. The rotation speed of the screw on the other hand was gradually decreased beneath the threshold of 10 rpm. A die with a diameter of 2 mm was used. when measuring the diameter of the filament with a caliper after extrusion, the average diameter was about 2.40 mm due to die swell.

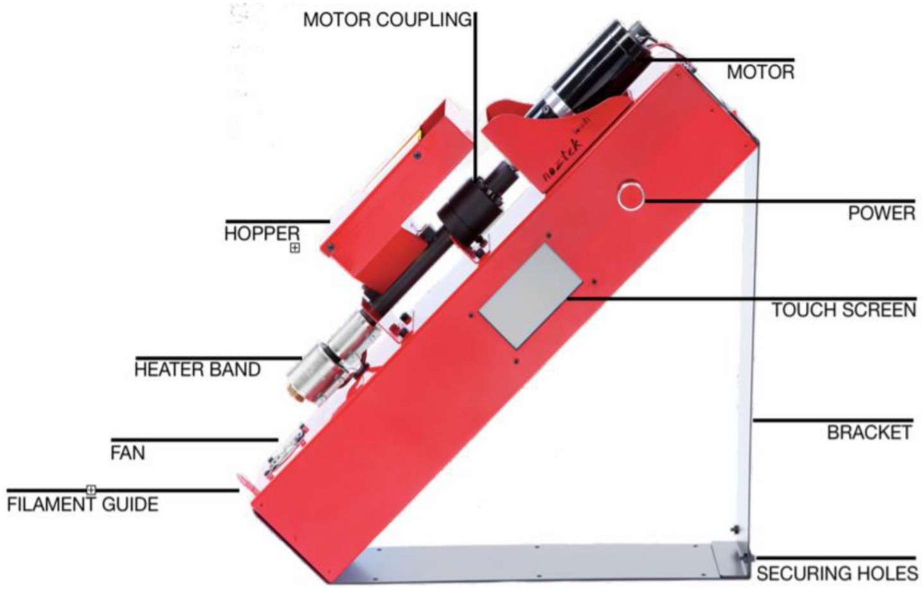

Fig. 7.7 The Noztek touch single screw extruder © Noztek.com 2018

The extruded filament is depicted in Figure 20, the first couple of windings on the spool are not of the desired quality. The rough surface of the filament indicates sharkskin, possibly because of material slippage at the wall of the die as a result from a lack of adhesion. Another explanation is the presence of flow instability because of increased visco-elastic stresses.[18], [26]

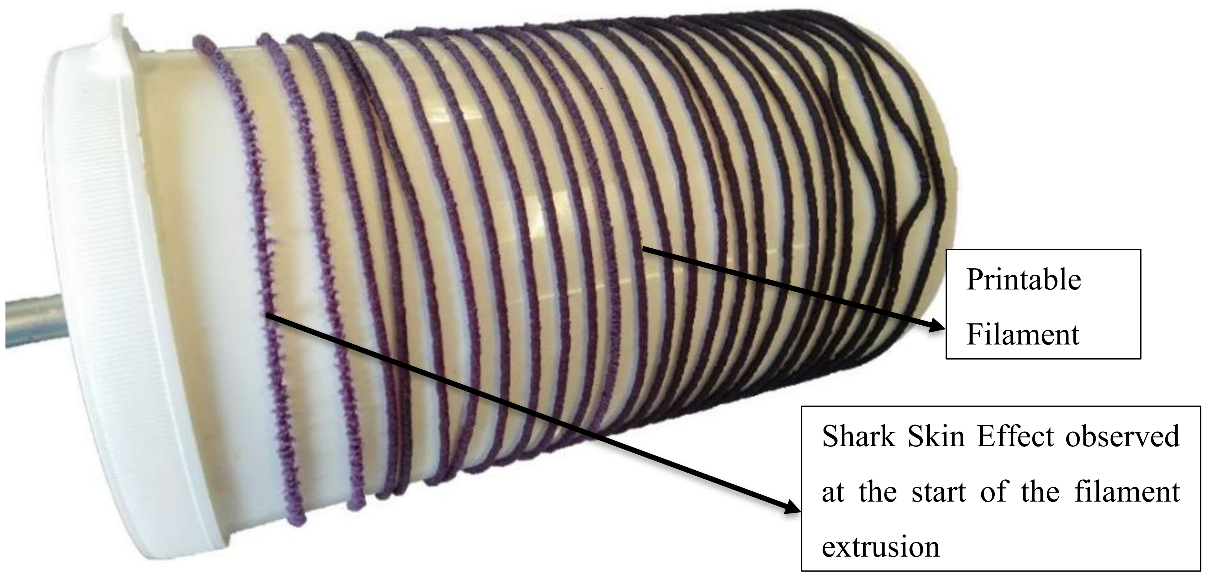

Fig. 7.8 Extruded DPBM-FGE-FT5000 filament on spool

7.4 Extrusion and Print parameters

There are multiple critical parameters to be considered when printing. The most import being the nozzle temperature, print speed, build plate temperature and extrusion speed. Through trial and error, the objective is to find suitable printing parameters (evaluation is done based on the quality of the print). This is done within feasible boundaries. An example of such a boundary is the nozzle temperature, irreversible changes can be detected within the self-healing material above 120 °C as well as a certain viscosity is required for the material to be printable.[11] Moreover the printing speed is significantly slower than commercially available material as time is needed for the material to form a network and gel.

During printing the nozzle temperature was varied between 116 °C and 118 °C and the print bed temperature was varied between 60 °C and 90 °C. Lowering the printing temperature and increasing the temperature of the heated bed will decrease the gelation time.

An issue that occurred with multiple prints was that there was not enough gelation time between the layers, causing the structure to lose its shape. The situation could possibly be improved by decreasing the printing speed or lowering the nozzle temperature which would rise to a higher viscosity. As mentioned before the range of the nozzle temperature is very limited, so one way to counter this problem is by altering the input diameter of the filament as this would changes the flow rate. The relationship between the input filament diameter and the speed of extrusion can be expressed in terms of the mass conservation law, which states that the volume of filament pushed down by the motor of the extruder should equal the volume of the extruded filament.

The formula is the following [19]:

$$\frac{V_x}{V_a} = \left(\frac{D}{d}\right)^2$$

With: V_x: printing speed (mm/s); V_a: extrusion speed (mm/s); D: diameter of the filament (mm) ; d: diameter of the nozzle (mm).

Not only are the filament diameter and the extrusion speed inversely proportional, the diameter is also squared. A minor alteration of the input diameter could have a significant impact on the extrusion speed. An additional remark is that the wall speed is intrinsically set at a lower value by the software, this is not necessarily a problem as it is important to have firm walls where the infill can attach to.

7.5 Test setup for printing

Fig 20 shows the standard setup for printing test samples with the designed extruder. Various parameters described in Table 1 are varied in different iterations of the print and checked for print quality. At this point of the project, the prints are only inspected, and no tensile tests are conducted because of lack of time.

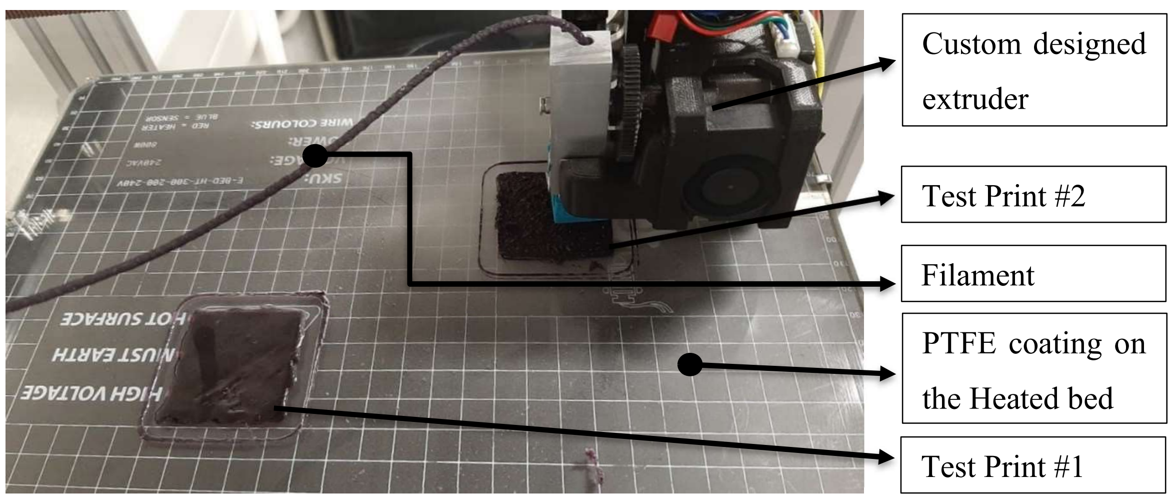

Fig. 7.9 Test Setup for printing samples

7.6 Mechanism of the gripper

The underactuated gripper mechanism published in [22] is used as a basis and is redesigned for prototyping with soft materials and self-healing materials.

This paper presents an underactuated gripper with slip prevention strategy for an unstructured human environment. In such environment the objects are of wide range in terms of size, shape and varying deformable properties. For the gripper to be able to grasp such objects an underactuated mechanism is. Using appropriately placed sensors the mathematical model of the gripper is used developed and is used to lift objects with minimal amount of force without damaging them. The results show that the proposed gripper is suitable for unstructured human environments.

Finger design in this study is restricted to only 1 extra degree of freedom to minimize functional failures due to singularities in mechanism. The object principal diameter and the velocity of approach of the finger towards the object can be found out from this study. Proceeding in the same lines as in 2.1, with a local origin setup at O, the coordinates of points A, B, F, E can be easily found out. The coordinate of point D can be derived as follows, considering the link lengths OA=30mm, AF=75mm, CD=25mm, OF=15mm, FE=ED=DB=30mm. [22]

$$x_D = (-15\cos\phi - 15) + (60 - 30\sin\phi)\sqrt{(\frac{30}{d})^2 - 0.25}$$

$$y_D = (15\cos\phi + 45) - (-30 + 30\cos\phi)\sqrt{(\frac{30}{d})^2 - 0.25}$$

Where, $d = \sqrt{(30 - 30\cos\phi)^2 + (60 - 30\sin\phi)^2}$

which is the distance between the points E and B. Now, ψ can be found out easily by calculating the slope of the line ED.

$$\psi = \mathrm{atan}\left(\frac{y_D - 15 - 30\sin\phi}{x_D + 30\cos\phi}\right)$$

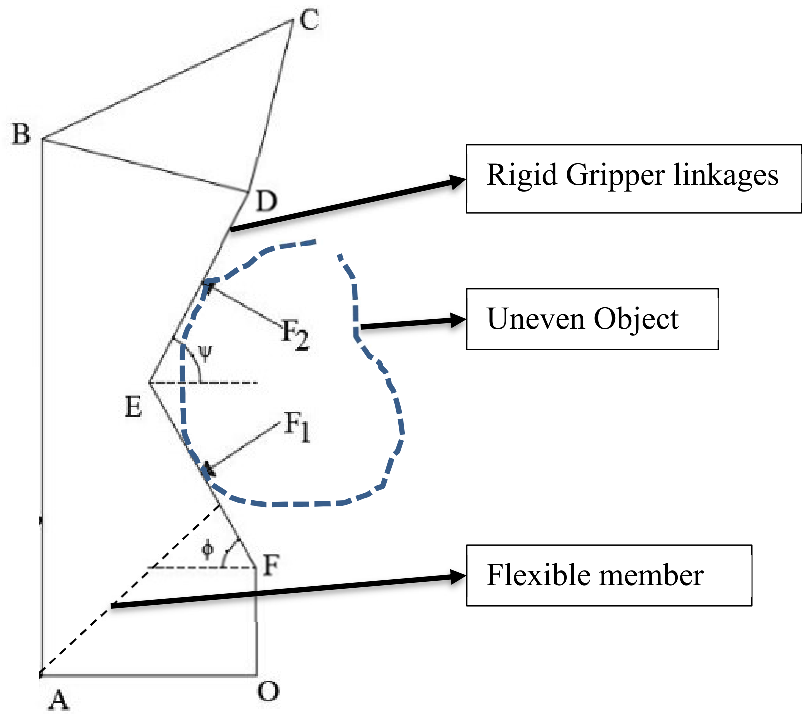

Fig. 7.10 Schematic of the soft gripper mechanism

7.7 Design of the gripper

It is kept in mind that the gripper will be made up of soft polymers. So, the design approach is inclined towards the manufacturing of the soft gripper. Various iterations are made to check the manufacturability and feasibility of the design. Molding or casting of the gripper is done first with commercially available materials such as Vytaflex, EcoFlex etc to check for proof of concept of the mechanism. Efforts will be made to 3d print the design once it is finalized.

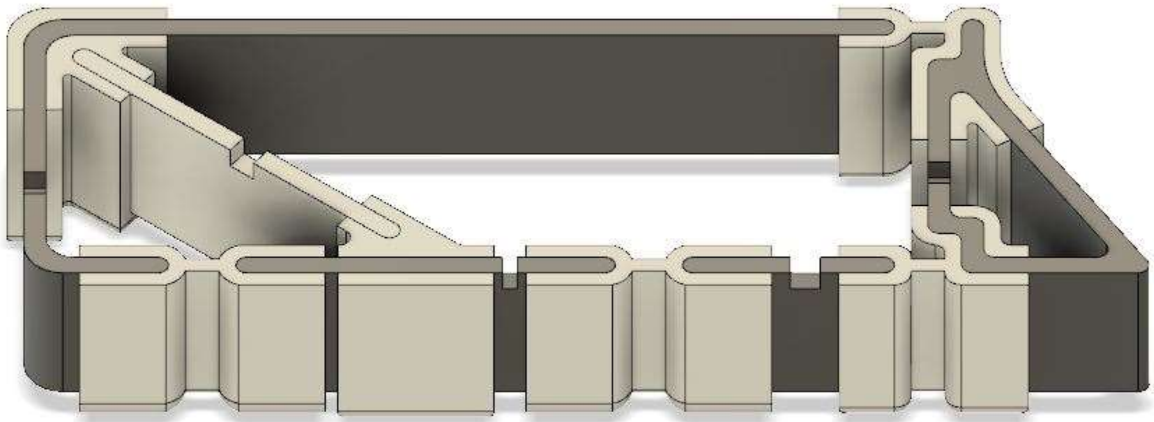

Fig.7.11 Design Iteration 1 – Soft gripper CAD

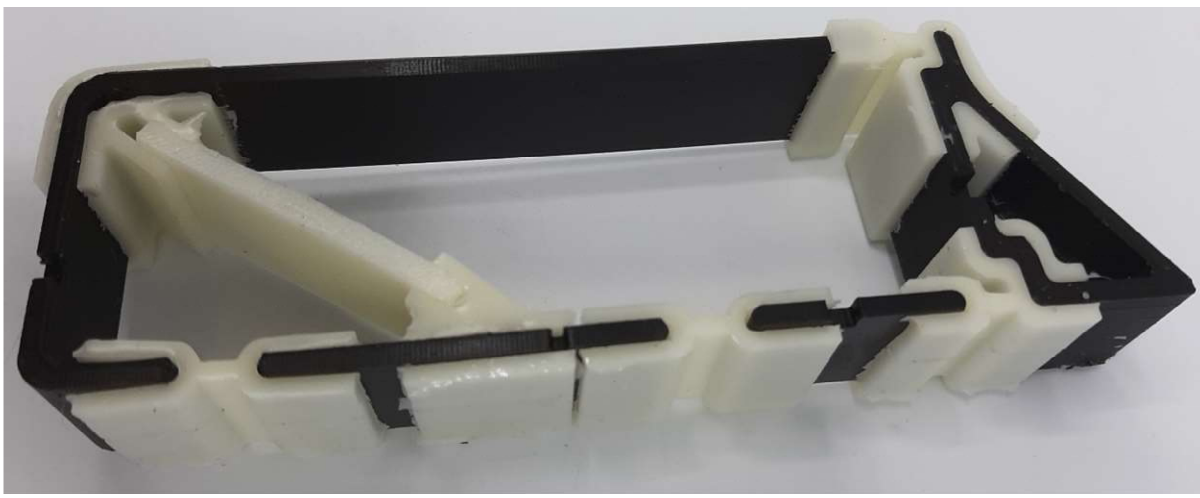

Fig. 7.12 Design Iteration 1 – Prototype of Soft gripper design

The above design has a lot of individual parts and will require a mould for each individual part and will not be feasible. Also, the parts had to be glued together in order to make the gripper work. Gluing the parts in place will not be a good idea as the ultimate idea of the gripper is to make is self-healing.

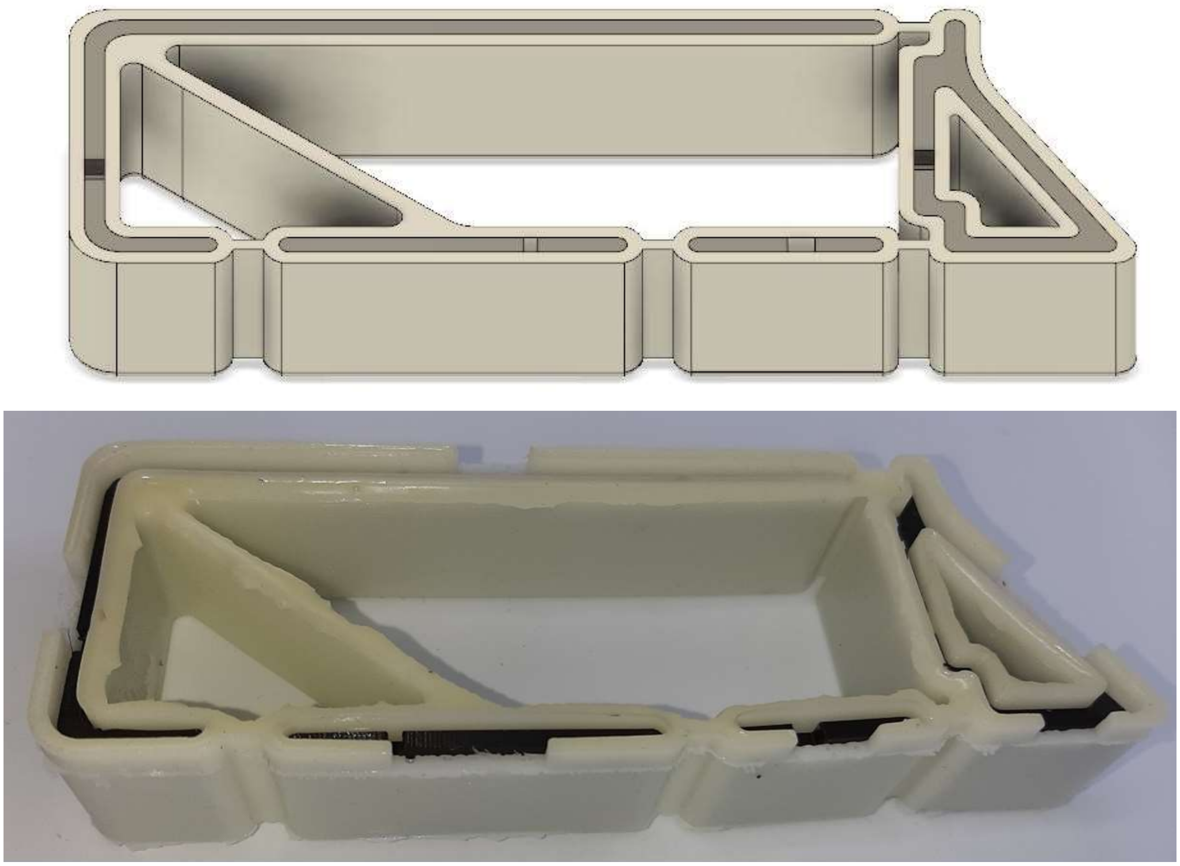

Fig. 7.13 Design Iteration 2 – CAD and Prototype of Soft gripper design

In this iteration, the rigid links of the gripper are made with PLA by 3d printing. These individual rigid links are then covered with soft skin made up of polymer material. This design is better than its previous iteration as it is a single cast of material and if it is decided to 3d print the design, it will be easy to print one singe part instead of printing multiple times. The design is casted with Vytaflex polymer and is tested with different objects ranging a wide variety of diameters. The design looks promising and efforts will be made to 3d print this design.

7.8 Design of the mould

Moulds are designed and 3d printed using PLA. Split mould pattern system and core material is incorporated keeping in mind the complexity of the print. The mould consists of 3 individual parts that can be screwed together. Guide pins are incorporated for the alignment of the 3 parts of the mould. If this gripper is to be made with self-healing material, then the mould is to be put into oven and heated up to 130 degrees. In that scenario, the mould will be redesigned and manufactured out of Aluminium as it can withstand that heat.

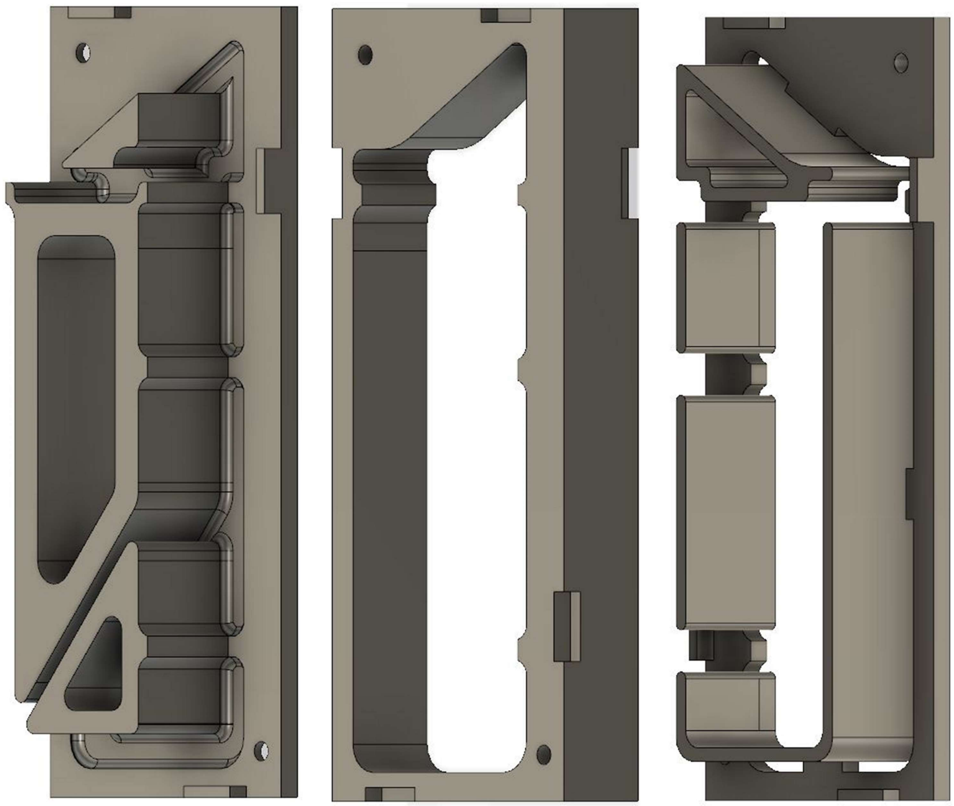

Fig. 7.14 Mould CAD

Fig. 7.15 Mould 3D Printed out of PLA

8. RESULTS

8.1 Extrusion system

The custom designed extrusion system delivered much better print qualities that the commercially available extrusion systems. Figure 27 shows the sample that currently depicts the best overall quality, the printing parameters are shown in the table. A remark is that the tracks of the nozzle are visible in some area and in other areas more flowing was present. The printing speed was increased as well as the layer height, this was done to suppress printing time. The printing was done under an hour. Printing larger objects with a low printing speed would lead to extended printing times, providing a larger window of opportunity for errors to occur during printing.

Print and Parameters:

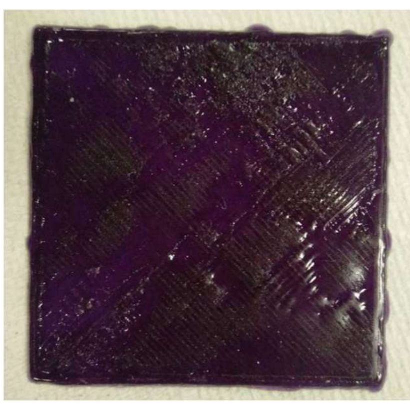

Fig. 8.1 Sample of 50x50x1 mm printed at 118°C

Nozzle temp	**(°C)**	118
Print bed temp	**(°C)**	80
Layer height	**(mm)**	0.2
Filament diameter	**(mm)**	2.2
Print speed	**(mm/s)**	8
Line width	**(mm)**	0.8
Z-axis offset	**(mm)**	-1.3

Table 8.1 Printing parameters of sample shown in Figure 27

Trials are conducted to further increase the printing quality.

8.2 Self-Healing Gripper

The design shows promising results as this design has been verified by using Vytaflex, a commercially available polymer which has the same hardness as the self-healing materials.

The design has been checked against different materials using computer simulations and real-life objects like wine glass, hammer, nails, screws etc. The passive spring member also shows promising results in terms of long-time functionality as Vytaflex is flexible yet tough.

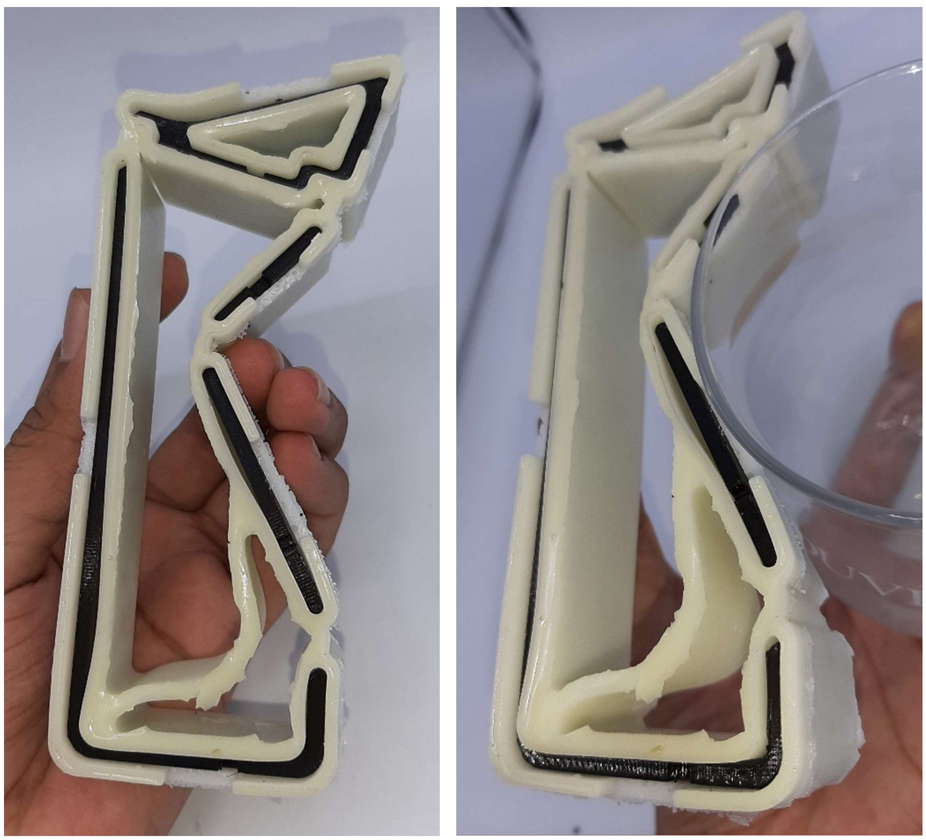

Fig. 8.2 Gripper Prototype tested against a wine glass(left)

PLA structural members are used in this prototype to represent the rigid members in the mechanism. The Vytaflex membrane acts as a skin around the PLA rigid members.

In case of any damage to this skin, if made out of SH material, the skin should self-heal itself without any human intervention in due course of time.

8.2.1 Self-healing property

The self-healing property of this particular prototype has not been tested as the manufacturing of the design with the self-healing polymer was not completed due to time constraints.

But, it is almost certain that this healing technique works as there is a lot of testing done especially involving the self-healing property, bond strength after healing, healing of two different classes of polymers, etc and the literature strongly suggests that this technique works.

8.2.2 Finite Element Analysis

Before prototyping the soft gripper, an FEA analysis is carried out to estimate the deformation levels and the level of stiffness of the gripper passive spring mechanism. The analysis results correlate with the physical behavior of the gripper. In the simulation, the gripper is pressed against a cylinder of diameter 60mm, approximately the size of the wine glass.

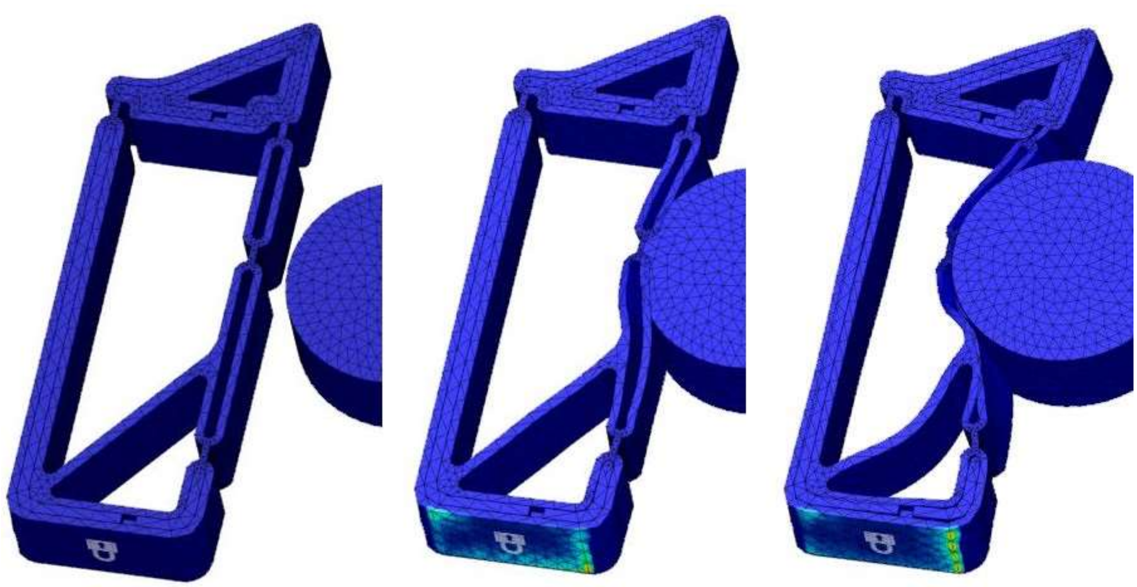

Fig.8.3 FEA of the gripper prototype. The figures show the different stages of the event – "Gripper interacting with the wine glass" from left to right.

This section shows the FEA analysis of a Fold based soft pneumatic gripper described in [23]. The gripper fingers are pressurized with air at 35KPa. The gripper bends at inwards, gripping the object in the middle. This analysis proves that FEA analysis can in fact be used to approximate the behavior of the soft materials, given that the material properties are correctly assigned.

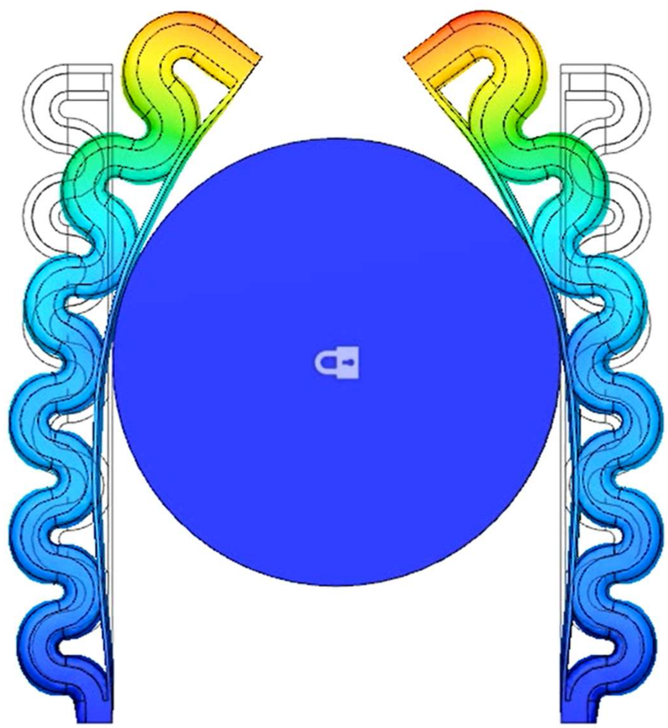

Fig. 8.4 Finite element analysis of Fold-Based Soft finger [23].

The material properties assigned to the above analysis is according to the properties of DPBM-F5000 Series, R=1. R is the malimide to furan ratio in the polymer. It is also a measure of the self-healing nature of the polymer. The material properties of the different variants of the DPBM-Fx family polymers are described below.

Method	Property	Symbol	Unit	Diamine based Networks					Triamine based Networks								
Furan functionalized Jeffamine		Jx		F4000	F2000-F4000 2	F2000-F4000 1	F2000	F400	F5000				F3000-F5000	F3000			
	Moleculair weigtht / Furan funct	M*	g/mol	1297	1105	829	657	269	1102	1102	1102	1102	880	647	647	647	647
	Malimide-to-furan ratio	R		1	1	1	1	1	3/6	4/6	5/6	1	1	3/6	4/6	5/6	1
Differential Scannic Calorimetry		DSC															
	Glass Transition Temperature	Tg	°C	-65,1	-63,8	-63,8	-54,7	69,5	-64,2	-64,8	-64,1	-64,3	-63,6	-50,4	-50,9	-50,9	-50,6
Dynamic Mechanical Analysis (DMA)		DMA															
	Glass Transition Temperature	Tg	°C	-57,8	-56,3	-56,3	-46,3	72,1	-57,0	-56,7	-56,6	-56,7	-55,3	-43,6	-43,4	-43,2	-43,1
	Storage Modulus at 25°C	E'	MPa	6,11	11,5	44,1	104,3	3576	0,46	1,67	3,98	16,7	89,2	3,17	8,94	68	202,4
	Loss Modulus at 25°C	E"	MPa	0,76	2,03	7,3	23,4	163,8	0,08	0,26	0,58	2,15	11,6	0,58	2,08	14,6	23,4
	Loss Angle at 25 °C	δ		7,1	10,0	9,4	12,6	2,6	9,9	8,7	8,2	8,3	7,4	10,2	13,1	12,1	6,6
Stress Strain Tensile testing																	
	Young's Modulus	E	MPa	4,57 ± 0,28	7,41 ± 0,11	22,7 ± 1,8	49,3 ± 1,5	1901 ± 194	0,120 ± 0,006	0,72 ± 0,05	2,40 ± 0,22	8,21 ± 0,67	46,0 ± 2,3	2,67 ± 0,09	8,00 ± 0,18	48,8 ± 2,6	139,0 ± 5,1
	Strain at Fracture	εmax	%	220 ± 12	229 ± 10	231 ± 12	228 ± 14	1,59 ± 0,07	365 ± 44	333 ± 20	223 ± 8	214 ± 9	166 ± 19	126 ± 7	123 ± 10	142 ± 19	160 ± 11
	Stress at Fracture	σmax	MPa	1,46 ± 0,05	2,07 ± 0,07	3,21 ± 0,12	5,33 ± 0,23	21,6 ± 1,6	0,11 ± 0,01	0,58 ± 0,05	1,12 ± 0,04	2,02 ± 0,07	3,84 ± 0,14	1,05 ± 0,04	2,12 ± 0,11	5,19 ± 0,32	7,94 ± 0,23
Rheology		Rheo															
	Gel Temperature	Tgel	°C	93	98	102	110	120	90	102	106	110	112	111	120	126	128
Thermogravimetric analysis		TGA															
	Degradation temperature	Tmax	°C	220 ± 10				200 ± 10	220 ± 10								
Density																	
	Density	ρ	g/ml	1,05	1,06	1,10	1,13	1,19	1,02	1,02	1,04	1,06	1,08	1,04	1,06	1,09	1,11

Table 8.2 Material properties of self-healing material family

9. CONCLUSION

To conclude this study, an overview of the accomplishments has been provided below as a bird's eye view. Furthermore, comments on improvements and design suggestions are made in the following section.

To Design ✓	To prototype ✓	To study ✓
A direct drive system capable of printing SH material ⇨	Direct drive system ⇨	Performance of the Direct drive system
Tool docking adapter to fit the designed direct drive on the printer ⇨	Tool docking adapter	
Soft gripper ⇨	Soft gripper ⇨	Performance of the gripper
	SH Filament for printing ⇨	Print quality of SH material

✓: All the objectives in that column are completed.

Table 9.1 Achievement table

In this study the goal was to develop a self-healing soft gripper and to check the proof of concept for that allows the Fused Filament Fabrication (FFF) or so-called 3D-printing of self-healing (SH) Diels-Alder (DA) polymer networks. To do this, the problem is divided into three subtasks, being the design, prototyping and testing.

- **To design:**
  - A Direct drive extrusion system capable of printing SH materials has been designed.
  - Tool Docking adapter for the custom direct drive has been designed.
  - Soft Gripper capable of encompassing a wine glass has been designed.
- **To prototype:**
  - Custom designed direct drive system has been manufactured and assembled.

- Tool Docking adapter has been manufactured and assembled.
- Soft Gripper had been manufactured.
- SH filament extrusion had been done for printing process.

- **To study:**
  - *Performance of the Direct drive system*

    The results of the 3D-printing depend largely on the quality of the filament. If it is too thick, it will not fit, and if it is too thin, the filament will buckle and be damaged easily. When the filament is of good quality, the 3D-printing works, and even multiple materials could be printed. The overall performance of the system is satisfactory as this system can print with SH material with minimum artifacts.

  - *Performance of the soft gripper*

    The soft gripper grasps with considerable amount of force which varies from object to object as this is a passive mechanism. This gripper can encompass a broad range of objects with its precision and power grasp modes. Overall performance of the gripper is satisfactory.

  - *Printing performance with SH material*

    Even though printing with SH materials is a challenge due to the temperature sensitive nature of the material, the test prints are satisfactory and show no artifacts like rough top layer, under extrusion, inconsistent bead diameter etc. It must be noted that this result is achieved after a lot of fine tuning of parameters.

    The printing height of the shapes that are currently feasible is limited. By adding a heated chamber around the printer, this problem will most likely be solved. Also printing overhang is currently not possible due to the low viscosity of the DA material when exiting the nozzle.

In conclusion, this study justifies the use of self-healing materials in robotic applications and presents ways to achieve this feat by 3D printing process. This can be considered as a proof of concept for the idea of "***3D printing of self-healing soft robots***".

10. FUTURE WORK

This study allows us to understand the possibility of extending the 3d printing technology to non-conventional materials like the Self-healing polymer discussed in the above sections. Some of the problems faced during this study are:

- Consistency of the diameter of the filament during the extrusion process
- Shark skin effect of the filament during extrusion
- Consistency in the surface finish of the print
- Swelling of the material when printed

These problems will be solved by improving the extrusion methods and different nozzles can be tried to determine the optimal filament diameter for the printing process. Lubricants like PTFE spray, release agents can be used while extruding the filament.

Sensor integration is an interesting area to probe into. Printing the sensors directly into the gripper will be revolutionary. For this, a conducting self-healing material is being developed and the possibilities of printing this material is being worked upon. Carbon black is mixed in the self-healing material which increases the conductivity of the material.

Appendix A: Instructions for Printing and Precautions to be taken

A.1 Connecting to the ToolChanger

1. Power up the machine
2. The Duet Wi-Fi board now should go into access point mode automatically.
3. Check your computer for available networks. You should find following the network.
    - SSID = toolchanger
    - Password = toolchanger
4. After connecting to the network, open http://duettest.local/ or with the IP address.

A.2 Pre-Printing Checks

1. Tool should not be attached to the tool head while homing
2. The tool can be manually detached by simply homing C axis.
3. Printer must be homed and the calibrated through "Home all" and "Auto bed compensation" in the Dashboard menu in that order.
4. Tools should be in the respective docks

A.3 Tool offset calculation

If a new tool is to be adapted in the toolchanger, the printer needs to know the tool position with respect to the printer origin.

This is done by storing the tool offsets in the config.g file. The tool offsets are always with respect to the Z end-stop switch that is on the tool head. The following figure shows the axis alignment of the tool head with respect to the nozzle of the tool. In case, if the nozzle has to be swapped, the Z axis offset of the nozzle has to be noted down before unscrewing the nozzle and cleaning. The Z-offset has to be kept constant while refitting the nozzle. This is because the printer homes the Z axis with the limit switch on the tool head and not with the nozzle.

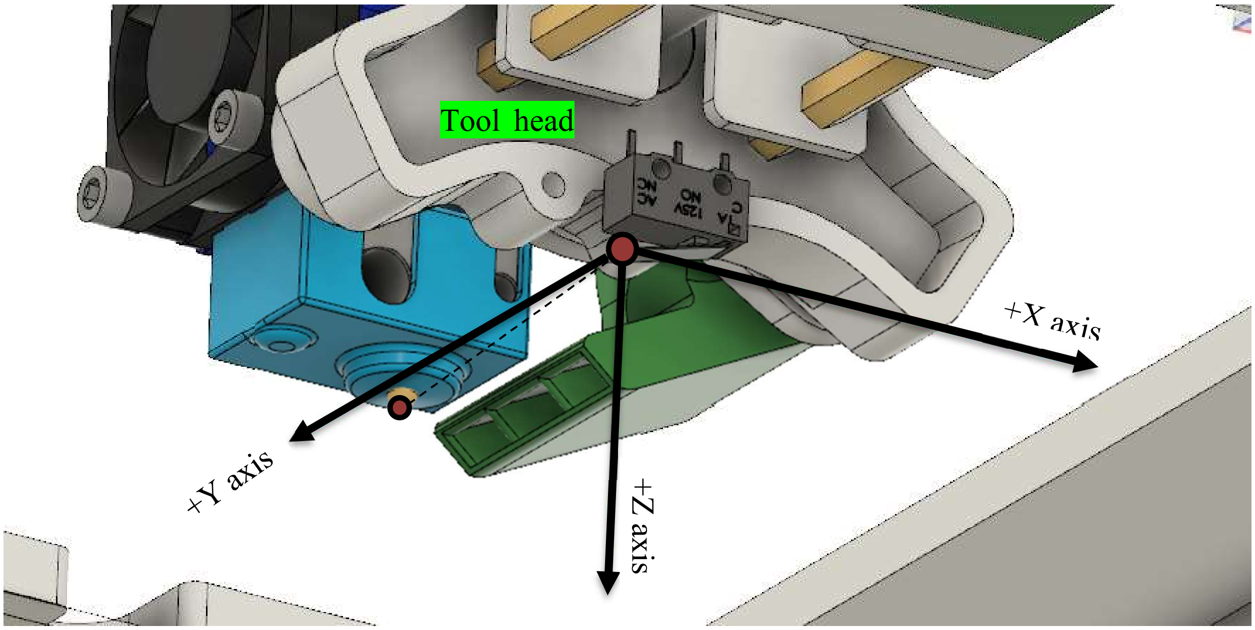

Fig. 11.1 Tool Offsets

A.4 Changes to commit to system files while using new tools

These highlighted changes are to be committed to the **config.g** file in the System editor if a new tool has to be incorporated for the printing process.

Heaters

M305 S"BED" P0 T100000 B4138 C0 ; Set thermistor

M143 H0 S225 ; Set temperature limit for heater 0 to 225C

M305 S"T0" P1 R4700 T100000 B4388 ; Set thermistor

M143 H1 ***S130*** ; Set temperature limit for heater 1 to ***130C***

; ***As a safety precaution***

```
M305 S"T1" P2 R4700 T100000 B4388                 ; Set thermistor
M143 H2 S130                              ; Set temperature limit for heater 2 to 130C

M305 S"T2" P3 R4700 T100000 B4388                 ; Set thermistor
M143 H3 S300                              ; Set temperature limit for heater 3 to 300C

M305 S"T3" P4 R4700 T100000 B4388                 ; Set thermistor
M143 H4 S300                              ; Set temperature limit for heater 4 to 300C
```

Tool offsets

```
G10 P0 X-9 Y39 Z-5                        ; T0 (Bowden setup)
G10 P1 X10 Y50 Z-58.45                    ; T1 (Custom design of the Direct drive tool)
G10 P2 X-9 Y39 Z-5                        ; T2
G10 P3 X-9 Y39 Z-5                        ; T3
```

Note that subsequent changes have to be made in **tpre.g** and **tpost.g** files as well. This is because the existing custom design has been adapted by extending the tool post forward, effectively decreasing the Y- axis travel by 25 mm.

A.5 Temp limit override

Because the maximum temperature limit of the heaters 1,2 are limited to 130 degrees, the printer should be enabled to cold extrude. This is because of the safety precaution that is included in the RepRap firmware which does not allow the printer to extrude below certain temperature.

M302: Allow cold extrudes

Parameters:

- This command can be used without any additional parameters.
- Pnnn Cold extrude allow state (RepRapFirmware)
- Snnn Minimum extrusion temperature (RepRapFirmware 2.02 and later)
- Rnnn Minimum retraction temperature (RepRapFirmware 2.02 and later)

Examples:

M302: Report current state

M302 P1: Allow cold extrusion

M302 S120 R110: Allow extrusion starting from 120°C and retractions already from 110°C

This tells the printer to only allow movement of the extruder motor above a certain temperature, or if disabled, to allow extruder movement when the hotend is below a safe printing temperature.

The minimum temperatures for extrusion can be set using the Snnn parameter with a default value of 160°C if unset. A minimum retraction temperature can be set with the Rnnn parameter. The default for this is 90°C.

M302 with no parameters it will report the current cold extrusion state.

Note:

One limitation of M302 is that it requires a thermistor to be present for the temperature to be monitored. If your system does not have a thermistor or heater to be monitored, you can define your tool in M563 without a heater to disable cold extrusion protection on that tool. ex: M563 P0 S"Pump" D0 F0 Note the lack of H parameter.

A.6 Useful G and M codes

- G28: Home
- M82: Set extruder to absolute mode
- M83: Set extruder to relative mode
- M106: Fan On
    - P0 = tool 0 hotend fan
    - P1 = tool 0 part cooling fan
    - P2 = tool 1 hotend fan
    - P3 = tool 1 part cooling fan
- M107: Fan Off
- M589: Configure access point parameters
- T: Select Tool

A.7 Ideal print settings for SH Filament

- Layer height = 0.2 mm
- Infill 100%
- Speed 5mm/s
- First layer speed 30%
- Filament diameter 2.2 mm
- Extruder temp 120 deg
- Bed temp 60 deg
- Part cooling fan off
- Slicer : PrusaSlicer (preferred)

a. https://forum.e3d-online.com/threads/the-prusaslicer-thread.3378/
b. https://github.com/StevenCregan/Slicer-Profiles
c. https://github.com/siril-teja/PrusaSlicer-Config-Bundle-for-SH-Materials-on-TC

A.8 Fan fuse issue

The 1 Amp fuse on the Duet wifi PCB has been replaced. The original ***mini blade fuses*** are not readily available in the market so a normal sized blade fuse has been modified to fit in the fuse seat on the PCB.

"*It is advised not to test the PCB Fan circuit by using the multimeter needles in case of any confusion regarding wiring. The connector pins are very closely seated and are prone to shortage and can cause fuse blow out or Mosfet burnout. The former can be repaired but the later is not. This can also be caused by using cheap cooling fans with non-standard circuitry in them.* ***Precaution is highly advised***."

A.9 Misc Advices

1. Do not poke around the Duet board with the multimeter prongs.
2. Always ensure that the tool is not attached before "Home All"
3. Use caution while docking and undocking the tool. If there is any kind of resistance while doing so, the numbers can be fine-tuned in the ***tpre.g*** and ***tpost.g*** files
4. Always run mech compensation before printing. This will help counter the inherent uneven bed.
5. Serial communication with the board can be done with the provided USB port and "YAT"
6. When using the Custom direct drive design, it is advised to always run the hot-end fan because the heatsink is small. It is also advised to keep the temperatures below 150 deg.

Appendix B: Bibliography

[1] Minev, Roussi & Minev, Ekaterin. (2016). TECHNOLOGIES FOR RAPID PROTOTYPING (RP) - BASIC CONCEPTS, QUALITY ISSUES AND MODERN TRENDS. 10.13140/RG.2.1.4917.4002.

[2] D. Trivedi, C. D. Rahn, W. M. Kier, and I. D. Walker, "Soft robotics: Biological inspiration, state of the art, and future research," Appl. Bionics Biomech., vol. 5, no. 3, pp. 99–117, 2008.

[3] D. Rus and M. T. Tolley, "Design, fabrication and control of soft robots," *Nature*, vol. 521, no. 7553. Nature Publishing Group, pp. 467–475, 27-May-2015.

[4] C. Laschi, B. Mazzolai, and M. Cianchetti, "Soft robotics: Technologies and systems pushing the boundaries of robot abilities," *Science Robotics*, vol. 1, no. 1. 2016.

[5] A. D. Marchese, R. K. Katzschmann, and D. Rus, "A recipe for soft fluidic elastomer robots," *Soft Robot.*, vol. 2, no. 1, pp. 7–25, Mar. 2015.

[6] S. Terryn, G. Mathijssen, J. Brancart, D. Lefeber, G. Van Assche, and B. Vanderborght, "Development of a self-healing soft pneumatic actuator: A first concept," *Bioinspiration and Biomimetics*, vol. 10, no. 4, Aug. 2015.

[7] R. F. Shepherd, A. A. Stokes, R. M. D. Nunes, and G. M. Whitesides, "Soft machines that are resistant to puncture and that self-seal," *Adv. Mater.*, vol. 25, no. 46, pp. 6709–6713, Dec. 2013.

[8] D. Y. Wu, S. Meure, and D. Solomon, "Self-healing polymeric materials: A review of recent developments," *Progress in Polymer Science (Oxford)*, vol. 33, no. 5. pp. 479–522, May-2008.

[9] S. Terryn, G. Mathijssen, J. Brancart, T. Verstraten, G. Van Assche, and B. Vanderborght, "Toward Self-Healing Actuators: A Preliminary Concept," *IEEE Trans. Robot.*, vol. 32, no. 3, pp. 736–743, Jun. 2016.

[10] B. Blaiszik *et al.*, “Self-Healing Polymers and Composites Second Sandia Fracture Challenge View Project Shock Wave Energy Dissipation by Mechanochemically-active Materials View project Self-Healing Polymers and Composites,” *Annu. Rev. Mater. Res*, vol. 40, pp. 179–211, 2010.

[11] S. Terryn, J. Brancart, D. Lefeber, G. Van Assche, and B. Vanderborght, “Self-healing soft pneumatic robots,” 2017.

[12] S. Kim, C. Laschi, and B. Trimmer, “Soft robotics: a bioinspired evolution in robotics, Trends in Biotechnology”, vol. 31, no. 5, pp. 287 - 294, 2013.

[13] R. Bogue, “Flexible and soft robotic grippers: the key to new markets?" Industrial Robot: An International Journal, vol. 43, no. 3, pp. 258 - 263, 2016.

[14] B. Gorissen, D. Reynaerts, S. Konishi, K. Yoshida, J.-W. Kim, and M. De Volder, “Elastic inflatable actuators for soft robotic applications," Advanced Materials, pp. 1 604 977- 2017.

[15] M. E. Giannaccini, I. Georgilas, I. Horseld, B. Peiris, A. Lenz, A. G. Pipe, and S. Dogramadzi, “A variable compliance, soft gripper," Autonomous Robots, vol. 36, no. 1-2, pp. 93-107, 2013.

[16] M. Manti, T. Hassan, G. Passetti, N. D'Elia, C. Laschi, and M. Cianchetti, “A bioinspired soft robotic gripper for adaptable and effective grasping," Soft Robotics, vol. 2, no. 3, pp.107-116, 2015.

[17] D. Villegas, M. V. Damme, B. Vanderborght, P. Beyl, and D. Lefeber, “Third-generation pleated pneumatic artificial muscles for robotic applications: Development and comparison with mckibben muscle," Advanced Robotics, vol. 26, no. 11-12, pp. 1205-1227, 2012.

[18] C. Blanes, M. Mellado, and P. Beltran, “Novel additive manufacturing pneumatic actuators and mechanisms for food handling grippers," in Actuators, vol. 3, no. 3. Multidisciplinary Digital Publishing Institute, 2014, pp. 205-225.

[19] P. Geng et al., “Effects of extrusion speed and printing speed on the 3D printing stability of extruded PEEK filament,” J. Manuf. Process., vol. 37, pp. 266–273, Jan. 2019.

[20] Ikram Mohout, “Multi-material 3D printing of self-healing soft robots”, Master’s thesis, Vrije Universiteit Brussel, 2019-2020.

[21] Ellen Roles, “Additive manufacturing of self-healing polymers for soft robotics applications”, Master thesis submitted under the supervision of prof. dr. ir. Bram Vanderborght, prof. dr. ir. Guy Van Assche, 2017-2018

[22] Siril Teja Dukkipati, M Sulaiman, KS Dhankar, “Design and analysis of underactuated gripper using chebyshev's lambda mechanism with slip preventive strategy for fragile objects”, Second International Conference on Advancements in Automation, Robotics and Sensing, Dec 2018.

[23] Benjamin Ang Wee Keong, Raye Yeow Chen Hua, “A Novel Fold-Based Design Approach toward Printable Soft Robotics Using Flexible 3D Printing Materials” DOI: 10.1002/admt.201700172, © 2017 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, Adv. Mater. Technol. 2017, 1700172.

[24] https://github.com/siril-teja/PrusaSlicer-Config-Bundle-for-SH-Materials-on-TC

[25] https://github.com/dc42/RepRapFirmware

[26] https://duet3d.dozuki.com/Wiki/Firmware_Overview#Section_Where_to_get_firmware_software_and_drivers

[27] https://duet3d.dozuki.com/Wiki/Gcode

[28] https://forum.duet3d.com/

Appendix C: Cost estimation

The table below shows the cost of products involved in this study. The cost of the self-healing material is approximate. All the other expenses like manpower, electricity are not included.

S.no	Product	Description	Quantity	Unit Price	Tax	Subtotal
1	MS-TC-FULL-110-WIFI	E3D ToolChanger & Motion System Bundle	1	1990	398	2388
2	TITAN-EXT-ST-+MTR-+BA175	Titan Extruder - 1.75mm Bowden with Motor	2	60.5	24.2	145.2
3	TC-TOOL-V6	ToolChanger V6 Bowden Tool (1.75mm)	2	100	40	240
4	TC-TOOL-PLATE-DOCK-BLANK	ToolChanger Blank Tool Plate & Dock Kit	2	57	22.8	136.8
5	V6-300-D-FUN	V6 All-Metal HotEnd-3mm-Direct Drive-12V-Nozzle Fun Pack (Range of Brass Nozzles)	2	68	27.2	163.2
6	V6-300-B-FUN	V6 All-Metal HotEnd	2	73	29.2	175.2
7	TITAN-EXT-ST-+BR-+MTR-+BA300	Titan Extruder	2	68.5	27.4	164.4
8	F-SW-PLA-ORANGE-300-750	spoolWorks PLA	2	23	9.2	55.2
9	NA	Self-Healing material	1	1000	0	1000
Total (in Euro)						4468
Total (in INR)						3,70,978

Table 13.1 Cost estimation of this study.