ROBOTICS AND MECHATRONICS

INTEGRATION OF SOFT ROBOTICS AND PNEUMATICS IN AN EDUCATIONAL DIY-KIT

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July, 2025

059RaM2025
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ABSTRACT

This graduation project describes the development of a Do-It-Yourself (DIY) kit that integrates pneumatic cylinders and a soft robotic end-effector to create a robotic manipulator. The goal of the project is to create an accessible and educational tool that introduces users to soft robotics and pneumatic systems. The project followed the Design Process for Creative Technology by applying the Ideation, Specification, Realization, and Evaluation phases. The kit features 3D-printed pneumatic actuators, silicone moulded soft PneuNet fingers, a manipulator arm and a control panel containing pumps and valves. Many prototypes were made for each aspect of the DIY kit to ensure the fulfilment of design requirements. The final prototype was tested with six participants, gaining insight in system usability, educational value, and experience. Tests resulted in an average SUS score of 77,1. Participants expressed an increased understanding in basic pneumatic systems and soft robotics, together with a newfound motivation to learn about pneumatics and soft robotics. The project fills a gap in the current educational landscape by providing an accessible, hands-on learning experience combining soft robotics and pneumatics, contributing to broader efforts attempting to make the emerging field of research of soft robotics more approachable to learners at all stages.

ACKNOWLEDGEMENT

I would like to use this small chapter to extend my immeasurable thanks to my supervisor Vincent Groenhuis and my critical observer Edwin Dertien for their feedback, encouragement, and patience. Without their inputs, guidance and help, this project would not have been possible.

Likewise, my parents and my brother have been immensely supportive throughout the entire process of this Graduation Project and long before. I would not have been able to get as far as I have without their help. Thank you so much, Mom, Dad and Tom.

I would be remiss if I did not also voice my unwavering appreciation for my friends who have helped in many ways over the course of this project. Thank you, Matt Hassing, Onne Iping, Euripides Christofides, Yana Volders, Patrik Tuka, Emma Sanders, Femke Stockmann, Maja Lamminga, Carlijn le Clerq, Hauk Jacobsen, Sophie Brodkorb, Anna Hornman, Badr Boubric, and Theoni Constantinou. Your presence alone has been incredibly comforting and inspiring.

And to all others who have assisted me both directly or indirectly, even if you are not mentioned here by name, thank you very much. This work would not have been possible without you.

CONTENTS

CHAPTER 1: INTRODUCTION

Science, technology, engineering, and mathematics (STEM) education is becoming increasingly important due to the increasing demand for technical skills in the job market [1]. However, traditional lecture-based methods often fail to motivate students properly, which limits engagement and educational outcomes. Robotics-based educational structures have been shown to improve understanding and engagement due to the hands-on nature of robotics projects [2][3]. While educational Do-It-Yourself (DIY) robotics kits exist, very few focus on soft robotics, despite its rapidly increasing significance in research and industry over the years [4]. This lack of accessible, educational DIY-kits that focus on soft robotics presents a gap in STEM education, which restrict the public's exposure to this advancing field.

Robotics-focused educational structures are commonly used to teach topics in STEM fields [5]. Robotics-based learning provides aspects from many areas that relate to the different elements of STEM, such as electrical engineering, programming, math and more, making it an effective medium for STEM-education [1]. Moreover, hands-on methods of learning have been shown to improve learning outcomes significantly as opposed to traditional methods, which makes DIY kits an amazing possible medium for learning robotics [1]. Soft robotics opposes the traditional rigid qualities of robots by offering compliant and adaptable systems that can more safely interact with irregular or fragile objects or humans [6]. This compliance comes from the materials and actuation methods commonly used in soft robotics. A frequently used example of such actuation methods is pneumatic actuation. Ever since soft robotics' emergence in 2008, an increasing number of papers have been published on the topic [4]. Despite the growing interest in soft robotics, together with its potential for safe human interaction, there still exists a gap of accessible, educational soft robotic DIY kits. To bridge this gap, this project aims to develop a DIY kit that integrates pneumatics and soft robotics to provide an interactive learning experience.

To guide this project, the main research question has been formulated as: **"How can soft robotics and pneumatic motors be integrated in a Do-It-Yourself robotics kit that engages learners and supports STEM motivation?"**

To explore this research question in a more structured way, it has been divided into the following sub-research questions (SRQ):

- **SRQ 1:** What is the current state of the art for robotic DIY kits & soft robotic end effectors?
- **SRQ 2:** How can soft robotics and pneumatics be integrated in the creation of a Do-It-Yourself kit?
- **SRQ 3:** How does the DIY-kit influence learner's engagement and motivation to learn about soft robotics and pneumatics?

Chapter 2 of this report is dedicated to the background research needed for the development of this project. This chapter aims to answer SRQ 1. A literature review is conducted with regards to existing robotic DIY kits; soft robotic end-effectors and their fabrication, integration and actuation; and any technical foundations needed for this project. Chapter 3 details the design process that was applied to better structure the answering of the main research question of this project. Chapter 4 outlines the Ideation phase of the project and discusses results of brainstorming and doing background research in the forms of a stakeholder analysis, market research, exploratory sketching and moodboards, and an expert interview. The results of these exploratory methods were used to synthesize the final concept for this project. Chapters 3 and 4 aim to answer SRQ 2. Chapter 5 details the translation of the findings from previous Chapters into concrete design requirements. These design requirements are further appended by findings made from the prototyping done in this Chapter. These design requirements were gathered in a concrete List of Requirements. Chapter 6 describes the production of the final prototype for this project that aims to abide by as many design requirements as possible. Chapter 7 shows how the final prototype was evaluated based on system usability, educational value, and engagement. Chapter 8 is where the results from Chapter 7 are discussed and interpreted. This is where the project is reflected upon based on successes, limitations, and potential future improvements or implementations related to this project. Chapter 9 concludes this graduation project by answering the main research question concisely based on the work detailed in this report.

CHAPTER 2: BACKGROUND RESEARCH

To support the ideas introduced in Chapter 1, background research has to be conducted. This chapter discusses topics such as soft robotic end effectors, methods for pneumatic actuation, and information about DIY kits, among others.

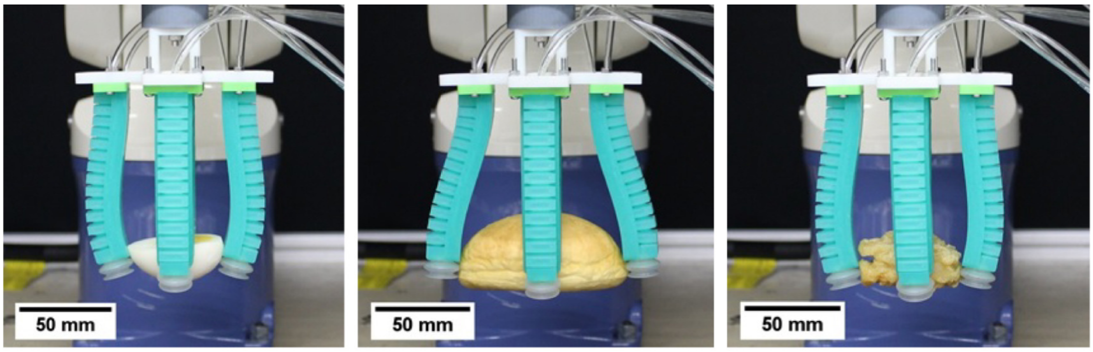
2.1 Soft Robotic End-Effector

There exist many different types of soft robotic end effectors, all with different functions, compositions, and industry applications. These types of end effectors should be explored and investigated to make informed design choices with regard to the main research question. To analyze the current state-of-the-art, this section will delve deeper into the applications, characteristics, and current existing designs of soft robotic end effectors.

2.1.1 Applications

Before the uses of soft robotic end effectors can be properly discussed, it should be mentioned what exactly an end effector is. An end effector is a device or system attached to a robot, that it uses to interact with and manipulate its surroundings [7]. One of the most common types of end effectors are robotic grippers, which are used to grip, manipulate, and place objects [8]. In situations where the location and orientation of an object is irregular, a certain level of compliance is favorable as to not cause damage to the object. Compliant control is used to achieve compliance properties of a controlled system and can be realized in two ways. Active compliant control utilizes sensors and software to control the forces in a robotic system, whereas passive compliant control depends on the material and structures in a robotic system to provide a certain level of compliance [9]. Soft robotics falls under passive compliant control, as it depends on its flexible materials and structures to achieve compliance. The absence of an electronic control system with sensors and integrated software would make passive compliance control simpler and more cost effective. The lack of electronic components also simplifies the system and removes the risk of failure of certain electronic components [10]. A simpler system and a reduced risk of failure are good reasons for integration of a soft robotics end effector in a DIY kit. Simplifying the system could reduce technical barriers of the DIY kit, and a larger success rate would motivate users to keep going, which leads to more engagement.

Many of the applications of soft robotic end effectors are based on the compliant nature of soft robotic systems. This compliant nature makes soft robotic end effectors safer for human interaction and interaction with fragile objects [11][12][13][14]. Safe human interaction makes soft robotic end effectors perfect for clinical settings, integration in wearable devices, and search-and-rescue [11][15]. Safe human interaction also makes them a good possibility for integration in a DIY kit, allowing users to experiment without safety concerns. In addition to human interaction, soft robotic end effectors are also used in situations where objects are irregular and/or fragile. Examples of irregular and fragile objects include food items such as fruits, vegetables, and meats [13][14]. Besides food items, soft grippers have been shown to successfully grasp objects like a MacBook Air, rocks with uneven surface and geometry, and a 20-kilogram weight [13][14].



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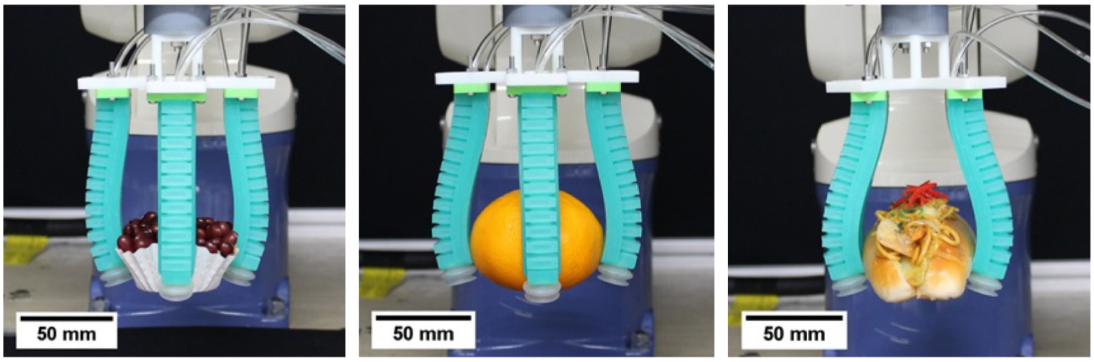

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Figure 2.1: Soft Gripper Gripping a Variety of Food Items [13].

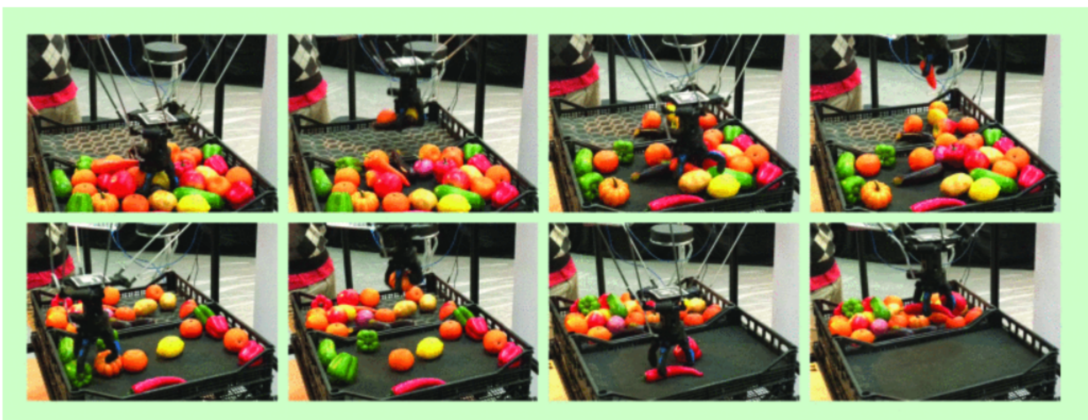


Figure 2.2: Soft Gripper Gripping Toy Fruits [14].

This versatility could provoke experimentation while making a DIY kit. The objects to be manipulated are not limited to a set number of items. This is the case with rigid robotic grippers, because they must perform precise gripping actions to successfully grip due to their lack of adaptability [5].

2.1.2 Key Characteristics

As mentioned in the previous section, soft robotic end effectors are compliant which allows them to adapt to irregular objects. This compliance is primarily realized because of the chosen material or mix of materials. The choice of materials determines the flexibility, durability, and overall performance of an end effector. A commonly used material in the fabrication of soft robotic end effectors are liquid rubbers [4][11][13]. Two examples of different types of liquid rubber used are DS10 and DS30, where DS10 is softer and more flexible, and DS30 is firmer [13]. DS10 and DS30 are just two examples from the company Smooth-On who sell a few more types of silicone rubber [16]. In theory, any kind of liquid rubber can be used to cast a soft robotic end effector as long as it fits the requirements for a particular design.

2.1.3 Existing Designs

There exist many designs for soft robotic end effectors, and a few of those will be explored here in order to outline possibilities. Firstly, the design from a paper by Wang et al [13]. The gripper discussed in this paper utilizes four rubber fingers that were created with so-called PneuNets. A PneuNet is a network of chambers in a flexible structure that inflate and deflate to generate a certain motion. The fingers in this paper are designed to bend when inflated and deflated. The fingers are casted using liquid silicone rubber and 3D-printed molds.

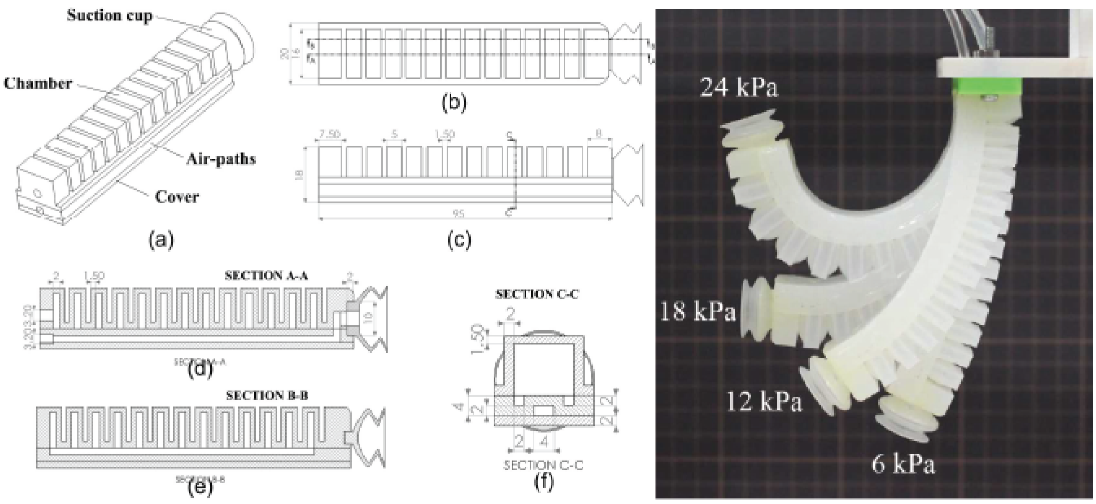


Figure 2.3: Soft Actuator Technical Drawing and Bending Under Different Pressures [13].

Another design for soft robotic end effectors is one from the Soft Robotics Toolkit [17]. Fiber-reinforced actuators do not rely on PneuNets to control their movement. They instead embed a certain level of constraint into the actuator by introducing fibers to its structure. A flexible elastomer bladder is wrapped with inextensible fibers that restrict inflation in a certain direction.

Figure 2.4: Fiber-Reinforced Actuator Bending [17].

2.2 Pneumatic Actuation

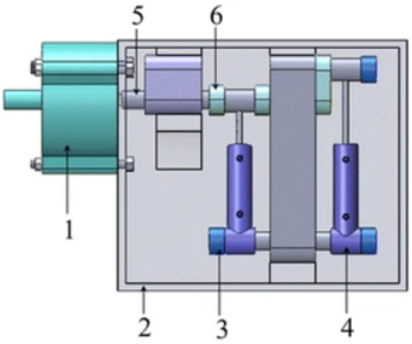
Pneumatic actuation relies on compressed air to generate movement. In these actuators, air pressure is converted to mechanical motion by moving a piston or diaphragm with compressed air. Pneumatic motors are frequently used because of their low cost, compactness, and low maintenance [18]. The following section details the working principles of pneumatic actuation and existing designs with integration possibilities for a DIY pneumatic robotic manipulator kit.

2.2.1 Principles

Compared to electric motors, pneumatic motors have a high power-to-weight ratio. They can reach very high speeds and rely on a simple power transmission by using pressurized air [19]. However, these high speeds usually refer to vane-type unidirectional pneumatic motors, designed to deliver a high number of rotations per minute [20]. These types of motors are not necessarily suitable for a pneumatic robotic manipulator in the context of this report, so the focus for this section will be on pneumatic stepper motors. Pneumatic stepper motors move in design-specified steps. One of these steps is triggered by applying air pressure to a piston or diaphragm which creates movement. A pneumatic system consists of five components [21]. An air compressor generates movement from an energy source like electricity and uses that movement to compress air. A reservoir can be used to store the compressed air for immediate usage when needed. One or more valves can be used to control the direction in which the air flows. The state of the valves is determined by an electric circuit. Finally, the combination of compressed air and the alternating states of the valves generate movement in an actuator. These basic components of a pneumatic system can form a proper basis for the pneumatic workings of the pneumatic DIY robotic manipulator.

2.2.2 Existing Designs

There already exist many types of pneumatic stepper motors, and a few of those designs will be listed here. Hopefully, some of the specified designs can be used as inspiration, or as a basis for certain design requirements. Chen et al. developed a high-torque pneumatic stepper motor, designed for magnetic resonance imaging-guided intervention [22]. Their stepper motor consists of two pneumatic cylinders that are coupled along a rotational axis.



Part	Component Name
1	Planetary gearbox
2	Supporting structure
3	Connecting bush
4	Cylinder
5	Shaft
6	Crank

Figure 2.5: 3D View of Stepper Motor [22].

An activation of one of the cylinders pushes the axis in a step of 90 degrees. The design by Chen et al. uses parts made from acrylonitrile butadiene styrene (ABS), and components from LEGO®. The material used in LEGO® components is also ABS [23], so all components in this papers' design could technically be 3D-printed. However, LEGO® parts are injection-moulded under very high pressures, resulting in a very smooth surface quality [24]. This can be difficult to achieve with regular 3D-printing which might call for a different fabrication method, or an additional treatment step.

Boland et al. created a high-speed pneumatic stepper motor, also for MRI applications [25]. Their design utilizes two pistons connected to a rotational axis as well.

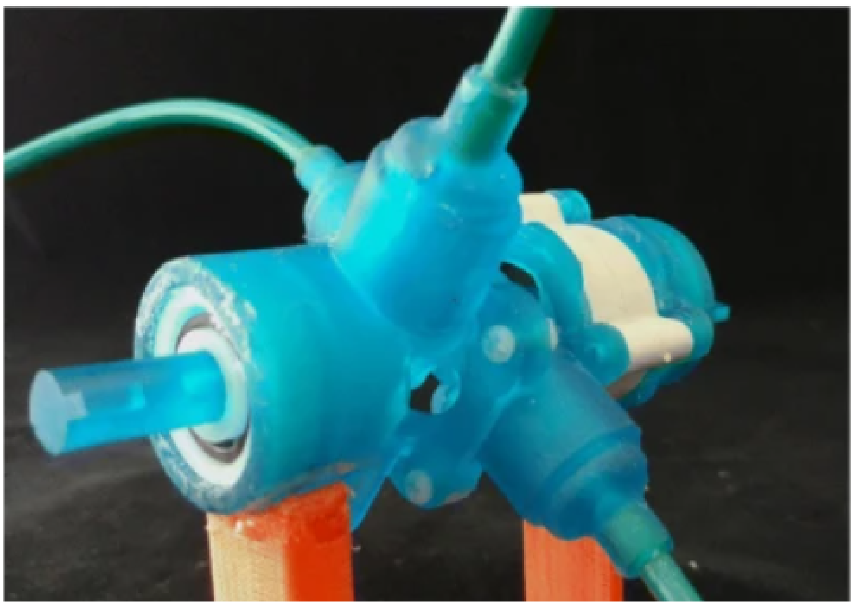


Figure 2.6: Assembled Stepper Motor [25].

Besides its shaft bearings, all components were resin-printed using Tough v4 resin, which is reportedly comparable to ABS.

Stoianovici et al. also developed a rotational stepper motor, called the PneuStep [18]. The PneuStep consists of three pulsing diaphragms used to rotate a harmonic gear drive.

Figure 2.7: Two Stepper Motor Prototypes of The PneuStep [18].

This design consists of many parts that are mostly made from differing materials, making replication more difficult. Comber et al. developed an MR-compatible 2-DOF needle-driver [26]. This device can linearly and rotationally move a needle.

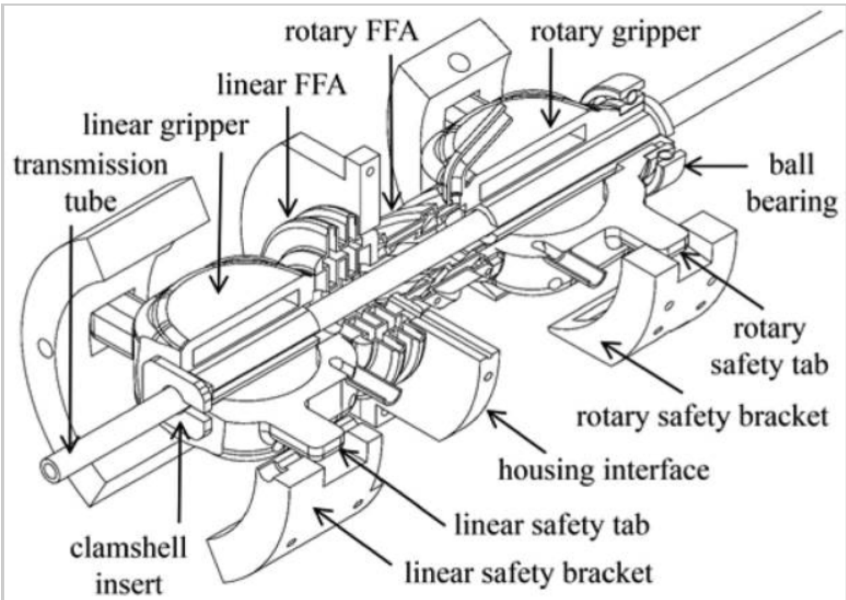


Figure 2.8: 2-DOF Actuation Mechanism [26].

Parts used in this device were 3D-printed using polylactic acid (PLA) and ABS.

In the following paper, Groenhuis et al. have developed an MRI-compatible robot driven by pneumatic linear stepper motors designed to perform biopsies [27]. Two types of stepper motors were used in this design, both of which were made using 3D-printing and laser-cutting parts.

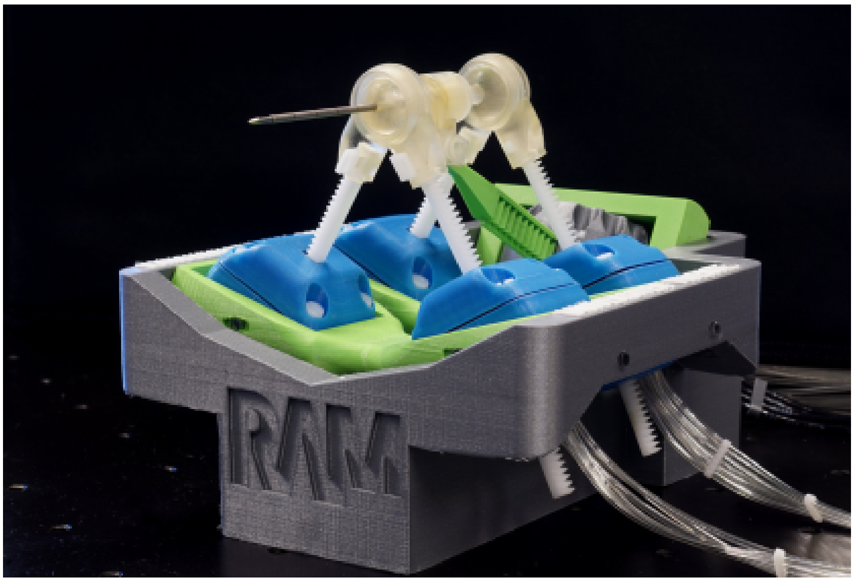


Figure 2.9: Biopsy Robot ”Stormram 3” [27].

V. Groenhuis has many pneumatic stepper motor designs available on his website [28]. These designs are available for non-commercial use only, but as this project is purely research-based, this would not be a problem.

Most of the listed designs utilize 3D-printing or use materials that can be 3D-printed. This is perfect for rapid prototyping during this project, as this type of manufacturing allows changes to be made quickly for the integration of motor designs into the pneumatic DIY robotic manipulator.

2.3 DIY Kits

The following section details existing educational DIY robotic kits to document their strengths and flaws in order to make better informed design choices in later chapters. It compares key features in existing kits and explores the existance or lack of soft robotic DIY kits.

2.3.1 Existing DIY robotics kits

Vandevelde et al. identify a complete robotics platform to consist of three elements [29]. Firstly, electronic components are necessary for control. Microcontrollers, sensors, and actuators are used to process data, sense surroundings, and execute actions. Secondly, a programming environment is needed to program a robot's behavior. This program defines the inputs and their appropriate outputs for a robot. Finally, the robot requires a physical body to interact with its environment. In the same paper, Vandevelde et al. developed a DIY kit that students and teachers could use to create a fire-extinguisher robot [29].

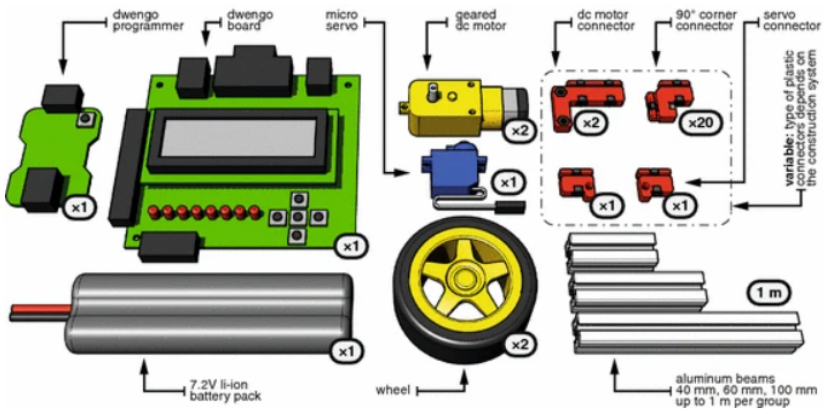


Figure 2.10: Kit Used by Vandevelde et al. [29].

The goal of their research was to analyze three different construction systems for their DIY robot. These systems consisted of laser-cut screw connectors, 3D-printed friction fit connectors, and hybrid 3D-printed connectors that use both friction fit and screw connections. All systems were applied to 15 x 15 mm aluminum T-slot extrusions. All other parts used in the kit were commercial parts. Evaluation concluded the hybrid connectors to be the best iteration of the three designs, as a result from multiple questionnaires. The laser-cut connectors were manufactured quickly, but user found them difficult and slow to use. The 3D-printed friction-fit connectors were found to be easy to work with but proved unstable when subjected to force while the robot was in use.

These findings underline the importance of proper connectors in DIY kits to avoid frustration and make the process of assembly as effortless as possible.

Li et al. developed a low-cost, easy to use open-source DIY liquid handling robot, for employment in STEM educational settings, DIY spaces, and laboratories [30].

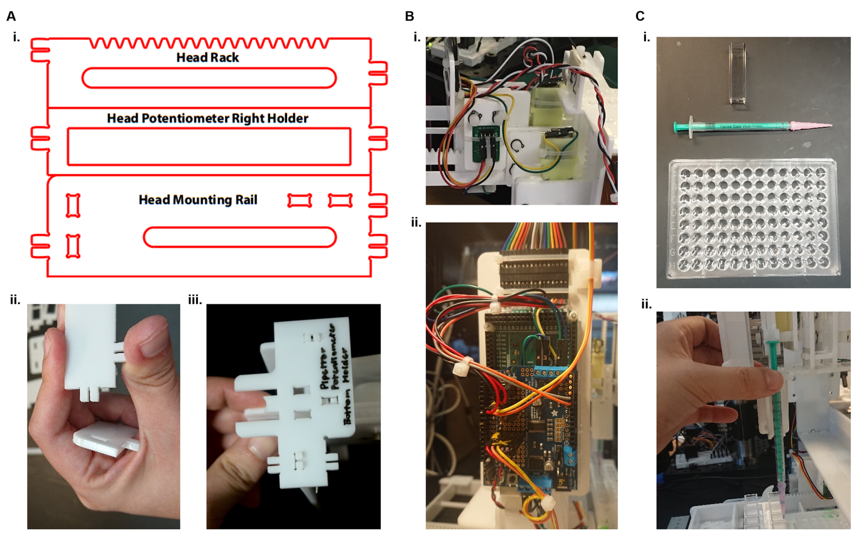


Figure 2.11: Various Parts of The Robot Built By Li et al. [30].

Their design uses laser-cut and purchasable parts. A point of concern brought up by both this paper and Vandevelde et al. is the necessary time needed to construct their designs from their basic parts [29]. Li et al. reports a building time of 1 day, and Vandevelde et al. took a combined 5 days of an organized robotics contest [30] [29].

These immense building times could pose difficulties during the evaluation phase of this project, as participants can most likely not spend one or more days user-testing.

The ”Opitec” Robotarm is also an interesting DIY kit [31]. It uses syringes as pistons to actuate their robotic manipulator. Two syringes are connected via a tube, and pushing in one syringe creates air pressure that extends the other syringe. The system utilizes wood as a construction material, and has the user produce the necessary parts themselves using the supplied wood and templates. This requires a lot of external tools though, making the product less accesible for beginners and people without proper tools. However, the possibility of users manufacturing their own parts for the DIY kit is interesting. Using syringes as pistons is also a compelling method for pneumatic actuation brought up by this DIY kit. The delegation of manufacturing to the user does allow for a much cheaper price of 17,25 €, which increases accesibility.

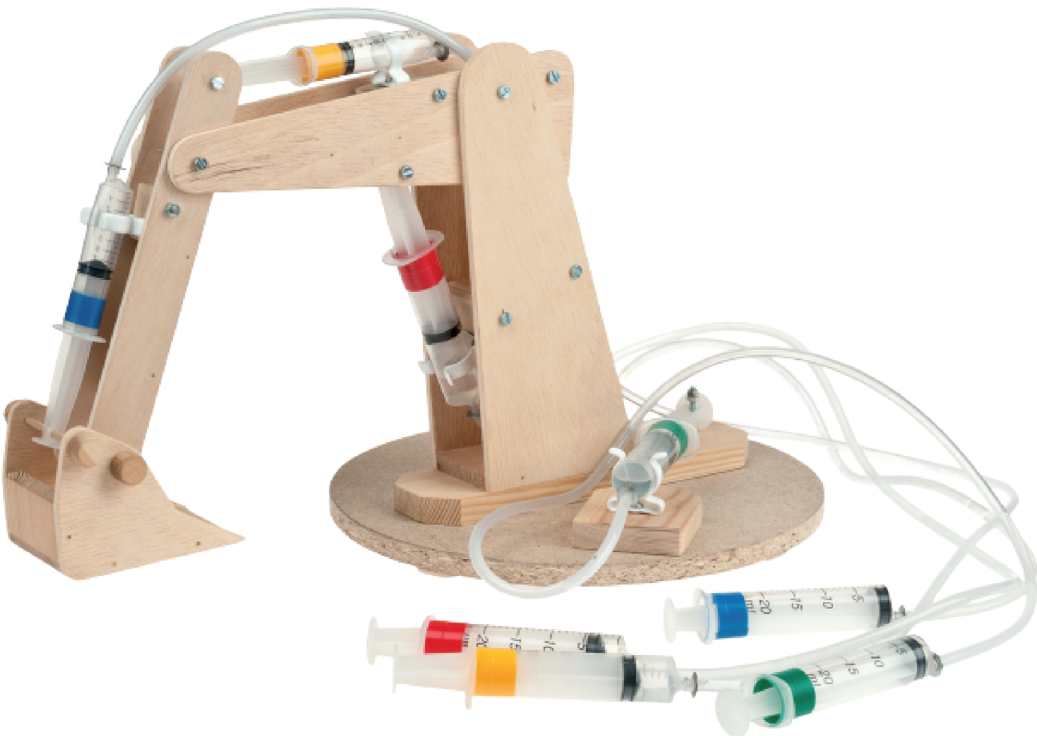


Figure 2.12: Opitec Robotic Manipulator [31].

The ”Octopus” Hydraulic Robot Arm also uses pistons to actuate their robotic arm [32]. But these pistons rely on hydraulic actuation instead of pneumatic actuation. The main difference between these, is that liquids are much less compressible than gasses. This DIY kit is on the more expensive side of 59,95 €, probably because it consist of 229 parts which would ramp up production costs greatly.

Figure 2.13: Opitec Robotic Manipulator [32].

The ”Profi Pneumatic Power” toolkit by FischerTechnik uses manually generated pressurized air [33]. The air is compressed by a small handpump adn stored in an air tank. Hand-operated valves release the compressed air from the tank to generate motion in another part of the system. This toolkit contains 5 different models and 207 parts which results in a price of 65,90 €.

Figure 2.14: Opitec Robotic Manipulator [33].

To research existing commercial DIY robotics kits, online webstores like Amazon have been investigated to archive some of the most prevalent features from popular kits. To identify common user experiences and design considerations, Amazon reviews of 5 popular DIY robotics kits were analyzed. A total of 120 reviews were inspected and reoccurring themes were categorized into 'Positive' and 'Negative' themes. Each theme was tallied to illustrate the frequency of each positive and negative aspect. The resulting table can be seen in Table 2.1. The reviews were retrieved in March 2025 from the Amazon product pages of [34], [35], [36], [37], and [38]. No individual reviews were quoted. This table will hopefully create an overview of positives and negatives to consider while synthesizing design requirements in later chapters.

Positive	**Amount**	**Negative**	**Amount**
Promotes Learning	28	Fragility	29
Clear Instructions	20	Unclear Instructions	27
Variety	20	Bad Functionality	24
Easy Assembly	12	Difficulty Assembly	20
Performs Well	11	Too Small Parts	14
Motivating	7	Time Consuming	9
Sturdy	7	No Tools Included	2
Good Packaging	3		
Colorful	2		

Table 2.1: Summary of positive and negative themes from Amazon reviews (March 2025)

The first thing that becomes apparent from the table is that there are more negative mentions in the reviews than positive ones. This might be because people are more likely to leave a review if their experience was not up to standard. It might also be because most positive reviews were not very detailed, while negative reviews had specifics to complain about.

The most mentioned positive aspect for DIY kits was the learning aspect. Consumers resonated with the educational theme of the kits and found this to be the most important aspect. Besides the educational theme, many consumers reported to value a certain level of variety in a DIY kit. Instructions were also discussed many times. Difficult and unclear instructions were found to be frustrating. When assembling a DIY kit, a consumer is at the mercy of the instructions. When any unforeseen roadblock is hit, the consumer might benefit from troubleshooting tips. Any difficult terms in the instructions should be explained or simplified, to avoid any unclarities. The most mentioned negative aspect for DIY kits was the fragility of parts. Broken parts ruin the construction experience, and result in a high possibility of not being able to finish the kit. Parts were also mentioned to be too small to handle in some cases. This resulted in a frustrating experience for some consumers, as they were not able to assemble the kit with ease. Reviews underlined the importance of the kit being functional and working as expected. This is an obvious requirement, but it accentuates the kit's need for quality, simplicity and elegance. Reviews reported some kits to be time consuming, which supports the concern brought up by Vandevelde et al. and Li et al. [30] [29]. Aspects that were mentioned only a few times concerned details like the quality of the packaging, the aesthetic appeal of the kit, and the lack of included tools.

2.3.2 Existing soft robotic DIY kits

In order to ensure the novelty of this project, an effort has to be made with regards to the inspection of available soft robotic DIY kits. To investigate the availability of soft robotics-based DIY kits, an exploratory review was conducted across several platforms. Platforms include Amazon, AdaFruit, GitHub, and other relevant robotics platforms. Search terms that were used are ”soft robotics kit”, ”pneumatic DIY robot”, ”educational soft robot”, and combinations of these search terms. The exploratory review yielded a number of more general robotics kits. Amazon searches resulted in a small number of hydraulic-based robotic kits, but no soft robotic, or pneumatic DIY kits. The hydraulic-based kits also relied on manual actuation, instead of some automated method of actuation. One Amazon search resulted in a paperback book that discusses DIY soft robotics projects. AdaFruit posed some general robotics kits, but no soft robotic, or pneumatic DIY kits either. No comprehensive DIY kits that specifically integrate soft robotic end-effectors were found during this exploratory review. While searches on GitHub resulted a few open-source, pneumatic and soft robotic gripper projects, these were not focused on education or introductory use. They lacked supporting instruction materials and easily accessible components, and were not packaged as DIY kits.

A very relevant and interesting website that was found is the Soft Robotics Toolkit [39]. It is a toolkit created for the Harvard Biodesign Lab. This website is a great resource on soft robotics, with open source resources for the design, fabrication and actuation of soft robotic devices. While it is a useful resource, it does not supply any DIY kit for consumers.

A way to control pneumatic wearbles was detailed in a paper by S. de Jong [40]. This project described the development of an Arduino toolkit used for the control of pneumatic outputs. It discusses the design of an Arduino shield together with a dashboard application and Arduino library. The findings from this paper could be used as inspiration during he course of this project.

During the expert interview (section 4.1) with Dr. A. Sadeghi, a soft robotics project by C.M. van Riet came to light [41]. This project created a soft pneumatic circuit toolkit that enables users to create their own circuits that run on air instead of electricity. The project includes a step-by-step instruction manual, a series of soft components used to create pneumatic circuits, and a variable vacuum pump. These components can be great examples to examine for the execution of this project

While the project by van Riet demonstrates a great example of the integration of soft robotics into educational DIY kits, these types of educational DIY platforms remains scarce. There still exists a clear gap in the current educational landscape for DIY kits that make soft robotics approachable, hands-on, and engaging for a broad audience. The growing relevance of soft robotics presents a unique opportunity to enhance STEM education, and this project aims to address that gap by developing a functional, interactive soft robotic manipulator kit that is both educational and accessible.

2.4 Summary

This chapter has given insight of the relevant background information necessary to support the design rationale of this project. Reviewing soft robotic end effectors underlined their compliance, adaptability, and safety. These qualities make them suitable for human interaction and the manipulation of fragile and irregular objects. Investigation into pneumatic actuation provided explanation with regards to pneumatic systems, and gave insight into existing pneumatic stepper motor designs. This highlighted the potential for 3D-printed solutions.

Analyzing existing DIY robotic kits illustrated their valued features. Reviews stated the importance of clear instructions, ease of assembly, educational benefits, and sturdy components. A concern raised by both literature and user reviews was the time required for assembly, which might cause problems during evaluation.

An exploratory review of soft robotics-based DIY kits revealed the lack of integration of soft robotics in educational DIY kits. This gap provides an opportunity for STEM education and engagement.

The findings in this chapter will guide the further developments of this project in making a functional, available, and educational soft robotic DIY kit.

CHAPTER 3: METHODOLOGY

3.1 Design Process for Creative Technology

To guide this project through its different phases, the Design Process for Creative Technology will be utilized, as described by Mader & Eggink [42]. The illustrated diagram for the Creative Technology design process can be seen below in Figure 3.1. It was adapted to fit the methods used in this project. This design process is non-linear, meaning phases can be returned to if any new insights come to light.

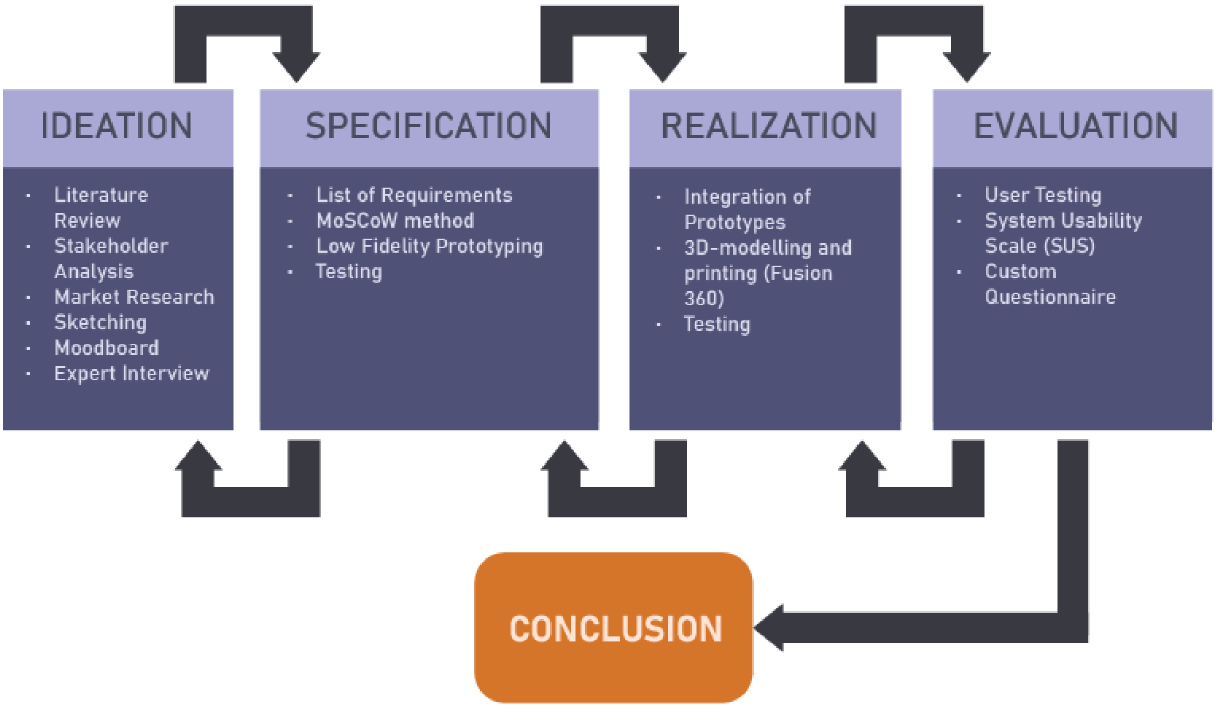


Figure 3.1: Diagram depicting the Design Process for Creative Technology, specified to this project. [42]

3.1.1 Ideation Phase

The first phase of the Creative Technology design process is the Ideation Phase. The goal of this phase is to generate a more concrete project idea. However, this graduation project has already formulated a clear idea in the form of a DIY kit for a pneumatic 3-DOF robotic manipulator with a soft robotic end effector. This phase of the design process will be more focused on exploring user groups and their needs, preliminary sketching, and creating a moodboard. These steps are useful for later phases of the design process. Relevant information in the form of a litarature review and state of the art has also already been conducted in Chapter 2, which can be used in later phases as well.

3.1.2 Specification Phase

Based on earlier phases and prototyping conducted in this phase, an elaborate list of requirements is created. To establish this list of requirements, the MoSCoW method is used [43]. This creates a structured list based on urgency of certain requirements. These requirements state specific components and features that the DIY kit Must, Should, Could, or Will not have. A number of prototypes will be developed to ascertain the effectiveness of certain components of the DIY kit. For example, different iterations of the instructional method can be created and evaluated. Prototypes are discarded, improved, or merged based on evaluations.

3.1.3 Realization Phase

The requirements and findings from Subsection 3.1.2 will be used to develop a final prototype of the DIY kit. All earlier prototypes will be integrated to create a coherent system. Electronic parts and standardized parts will be bought. Structural components will be 3D-modelled using the Fusion 360 software and 3D-printed or lasercut. A program to control the valves that in turn control the pneumatic actuators and soft robotic end effectors will be coded, most likely using Arduino.

3.1.4 Evaluation Phase

In the final phase, the final prototype will be evaluated. User testing will be conducted where test subjects will be asked to construct the kit in its entirety using the supplied instruction manual. Their experience will be measured based on the System Usability Scale (SUS) [44] and a selection of Likert-scale statements. Other evaluation methods might be added or substituted in later Chapters.

CHAPTER 4: IDEATION

At the very start of this Graduation Project, the proposal that was provided was not as concrete as the main question (Chapter 1) is now. To be transparent, the development from the original project description to the current main question will be quickly detailed here. The initial project description detailed the creation of a novel, useful, or cool device or product that integrates pneumatic motors in its design. The technology of pneumatic motors was used as a starting point for the Ideation phase. Uses and advantages of pneumatic motors were investigated. Through the shared relation of pneumatic actuation, the topic of soft robotics was uncovered as another motivating force. After getting a better grasp on the possibilities of pneumatic actuators and soft robotics, a brainstorm was conducted as a manner of divergence. A number of ideas were generated in this phase, including but not limited to prosthetics, art installations, a musical instrument of some kind, and of course the DIY kit. After inspecting the idea of a DIY kit, a lack of soft robotics-based DIY kits was discovered. This resulted in the formulation of the main question of this report as seen in Chapter 1.

4.1 Expert Interview

To gather new information about soft robotics to aid during Ideation and this project as a whole, a personal interview was conducted with Dr. A. Sadeghi from the University of Twente. The purpose of this interview was to ascertain appropriate manufacturing methods, receive an expert's vision and ideas on the project, and ensure the novelty of this project. The main takeaway of the interview was to structure the way soft robotics is introduced in the kit on the main purpose of the kit.

On the subject of novelty, Dr. Sadeghi pointed me to a paper by C.M. van Riet [41]. This paper also describes the integration of soft robotics in a DIY kit by creating soft components that can be used to build pneumatic circuits to teach circuit-building principles. The Soft Circuits Toolkit highlights safe and intuitive interaction, which makes users able to learn basic pneumatic principles. While both projects aim to integrate soft robotics and pneumatics with education, the Soft Circuits Toolkit prioritizes abstract circuit-building. The goal of this graduation project is to create a tangible robotic system that dives deeper into the principles behind soft robotics and pneumatics through hand-on assembly. Despite the difference in objective, The Soft Circuits Toolkit provided valuable inspiration. Furthermore, Dr. Sadeghi pointed out the importance of firstly making the user excited to learn by presenting them with a small success. Showing that the user can make something that accomplishes a goal provides a sense of satisfaction which motivates a user to learn.

When talking about manufacturing methods, specifically silicone moulding, it became clear that having a user mould their own pneumatic actuator would be diffcult considering the chance of an error occuring is large. Bubbles could form in the actuator, causing points of weakness which could cause tearing. Also if the user uses up all provided silicone without having produced a working actuator, the rest of the DIY kit would become pointless. Creating a foolproof mould could mitigate these issues, but as this could not fit in the scope of this project, this option was disregarded. Since the main focus of the DIY kit is not to create a soft actuator, the moulding will be done in advance to ensure the user can work with a functional actuator.

4.2 User Groups

There exist a multitude of user groups that might want to use the DIY kit. Analyzing these groups allows for the accomodation of specific requirements for each possible user groups, which results in a better product.

Firstly, students are a primary target group, with a focus on those in secondary education or enrolled in university. Students are likely to use the DIY kit to educate themselves about pneumatics, soft robotics, engineering, coding, and more. Students can possess a range of skill levels, which highlights the importance of clear beginner-friendly instructions. The kit could also provide optional, extra explanations or present different levels of complexity.

Another user group could be educators. Teachers might want to utilize the kit as a tool in the classroom. They would appreciate educational value and reliability. This case also requires a low production cost, if a lot of students were to receive a DIY kit. Use as a classroom tool also calls for reusability to make sure the kit can be used yearly, if it is used frequently and consistently in the curriculum. The time used for construction in this case depends on if the kit will be used in a one-off class, or a series of classes. Educators might also value worksheets or lesson plans included in the kit.

Next to students and educators, hobbyists could be a prominent user group. Hobbyists usually have a higher skill level with regard to robotic DIY kits. This group consists of adults wanting to learn, or are robotics enthusiasts. This group being more adept at constructing DIY kits would require the complexity of the kit to be fairly high in order to stay interesting. This does however not reduce the importance of clear and simple instructions, as difficult and confusing instructions can be frustrating for anyone.

A final user group could be parents, or people looking for a gift. They will most likely not interact with the kit themselves, but purchase it for somebody else. These people, especially parents, would value safety as a feature. Educational benefit is also appreciated by parents, as they want their child to learn. Both parents and regular gift-givers would welcome affordability, calling for simple and cheaper materials and parts.

4.3 Concept Conclusion

Based on the insights that were gained from the background research research, brainstorming, and exploration of user needs, a concrete direction for the development of this project has been formulated. Combining the insights from earlier Chapters resulted in the concept of a **DIY 3 degrees-of-freedom pneumatic manipulator with a soft robotic end effector.**

This concept enables users to explore and build the basics of pneumatic systems, and get introduced to pneumatics and soft robotics in an interactive, hand-on manner. This concept allows the user to learn about the underlying principles of all aspects the DIY kit touches on at every step of assembly.

When the kit is fully assembled, the user would be able to use the system, to experience their newfound knowledge being applied in something they built themselves. The user could safely explore the limits of the soft gripper by manipulating a plethora of items and objects, reinforcing the educational goals for this project.

4.3.1 Moodboard

This section will detail a moodboard created to assist as a visual brainstorming tool. The moodboard will help develop a more tangible vision of the DIY kit. The moodboard will contain inspirations and images for aspects of the project such as:

- **User Experience:** Instructions, DIY kits, components, tools.
- **Educational Value:** Experimentation, hands-on learning, explanations.
- **Soft robotics and Pneumatic systems:** Grippers, robotic manipulators, actuators, valves, pumps.
- **Aesthetics:** Color palettes, shapes, textures, packaging.

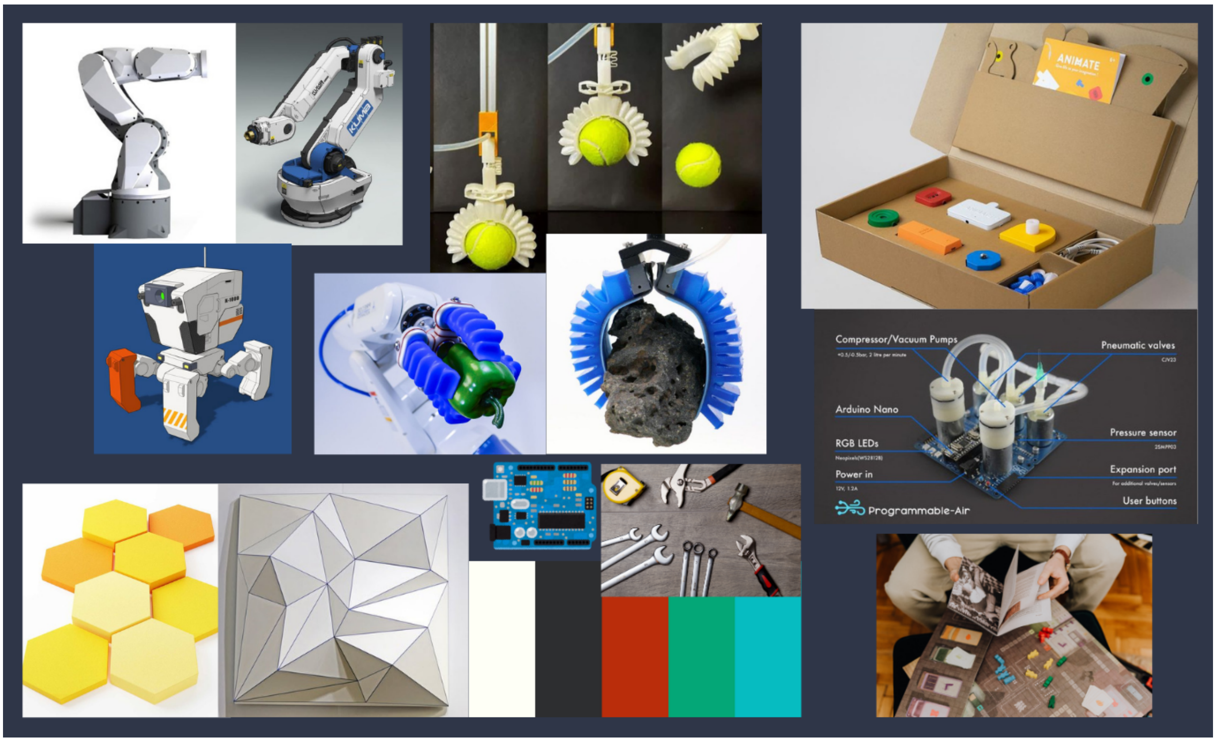


Figure 4.1: Moodboard to visualize the DIY kit features. Images were collected from [45] [46] [47] [48] [49] [50] [51] [52] [53] [54].

4.3.2 Sketches

To explore the different aspects of the kit, several sketches were made. The aspects that were explored are the gripper, control board, instructions, and the base for the robotic manipulator. The sketches can be viewed below.

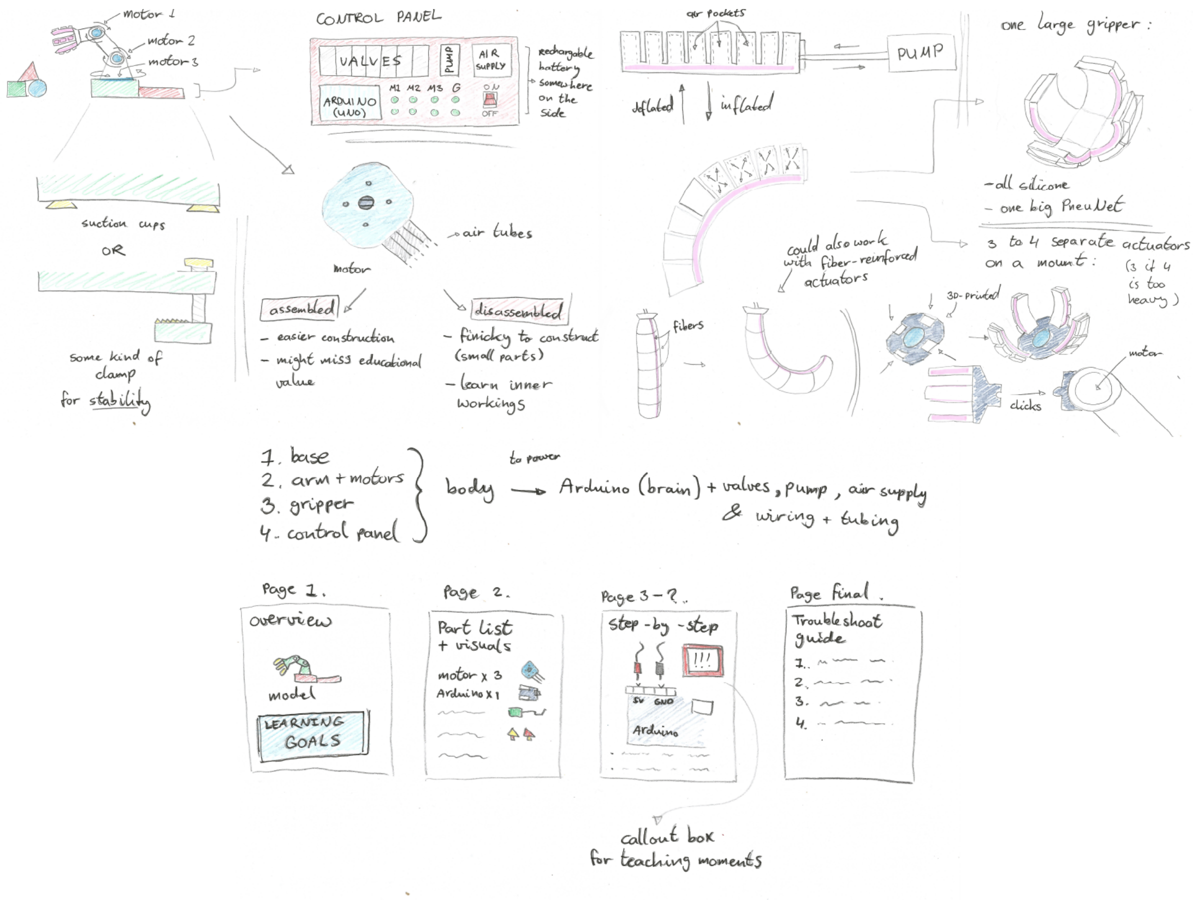


Figure 4.2: Sketches made to explore different aspects of the DIY kit

CHAPTER 5: SPECIFICATION

The goal of the Specification phase is to translate the findings from earlier chapters into clear design requirements for the design of the DIY kit. This chapter will also detail the development of multiple prototypes and their implications on the final design.

5.1 Prototyping

Each aspect of the DIY kit has been prototyped in order to ensure functionality and optimize user experience to create an educational DIY kit. The following section details the prototyping process for every component, and the subsequent requirements these prototypes brought to light.

5.1.1 Pneumatic Actuator: Soft Finger

As a starting point for the grippers' finger, the mould design from the Soft Robotics Toolkit was utilized [39]. The three parts of the mould can be seen on the left picture in Figure 5.1. The right picture shows the mould ready to receive silicone. After the silicone cures in the two-part mould, the finger is released and placed in the rightmost rectangle, also containing a small layer of silicone. This closes off the chambers inside of the PneuNet after the thin layer of silicone cures.

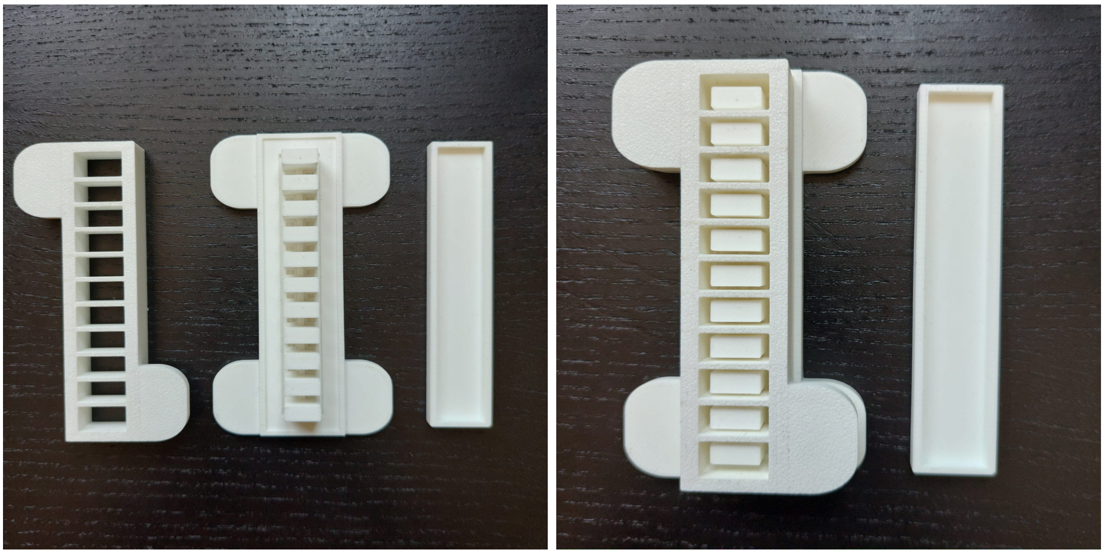


Figure 5.1: Pictures of the first soft finger mould prototype

This mould was 3D-printed using generic white PLA, which worked fine as a first choice of material. The first iteration of the finger used DragonSkin 00-10 silicone. The two components of the DS00-10 were mixed and poured into the mould. No form of degassing was utilized, and the silicone was left to cure. This prototype resulted in a finger with many holes and air pockets, which was not functional at all. The mould contained many small crevices where it was difficult for the silicone to get to without any external help.

For the next iteration, the silicone-filled mould was placed in a small vacuum chamber to degas. After this, the DS00-10 did not fill the mould up to the top, so the mould was refilled and placed back in the vacuum chamber. The silicone was left to set for an hour after degassing. This method removed all air pockets and holes that were present in the previous iteration. Next, the bottom part of the mould was filled with a small layer of DS00-10 and degassed as well. After degassing, the top part of the finger was placed on the setting DS00-10 to fully seal the finger. To create an air-intake, the Soft Robotics Toolkit specifies piercing an end of the finger to form a hole. However, this method quickly resulted in tearing of the silicone, which is not good if the finger is to be used more than once. The finger was also still extremely flaccid, which means the choice of silicone type has to be changed. For the next iteration DS10-NV was used, which is a lot more stiff than DS00-10. This helped, but the finger still bent too much to be able to stand on its own as can be seen in Figure 5.2.

Figure 5.2: Amount of Bending in the first finger prototype

For the next iterations a new mould was designed, changing and including improvements.

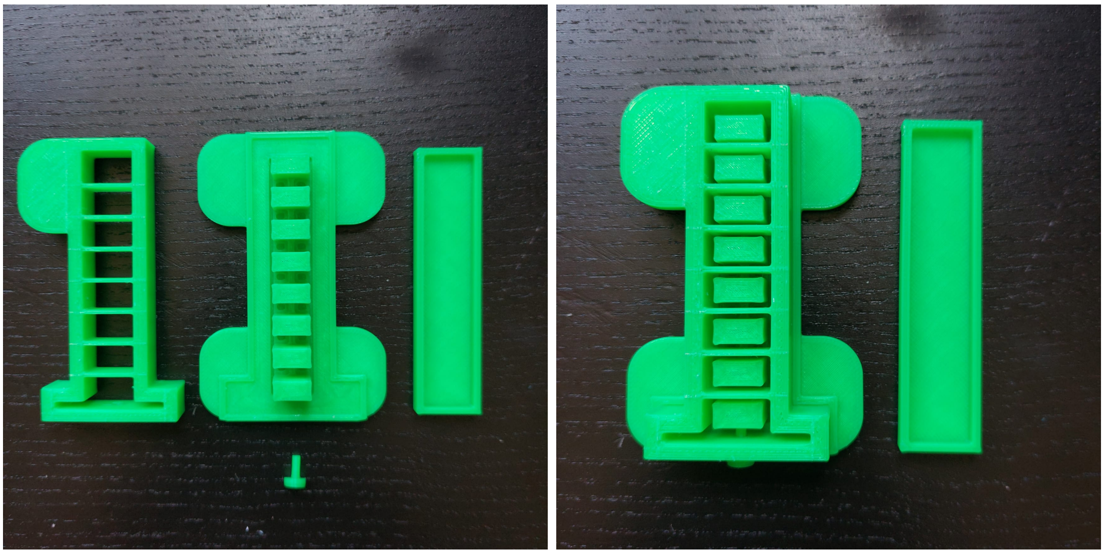


Figure 5.3: Pictures of the second soft finger mould prototype

To decrease the bending of the last iteration, the mould was designed with less chambers along its length. The finger was also shortened as a whole. The bending of the second prototype can be seen in Figure 5.4. To counteract the tearing of the finger due to piercing the silicone wall, an air-intake was integrated in the mould design so the integrity of the silicone does not have to be compromised by poking a hole. Furthermore, the fingers have to be able to be mounted securely to the other components of the robotic manipulator, which is what the protrusions at the end of the mould are for. These small sections of silicone will allow the fingers to be clamped to rigid components. These protrusions also allow the user to stretch the hole for air-intake more easily, which could make assembly more straightforward.

Figure 5.4: Amount of Bending in the second finger prototype

These prototypes highlight the following requirements:

- The soft finger must be able to remain straight when held up from its end.
- The finger should not tear when handling the finger.
- The finger must be able to bend when inflated.
- The finger must be able to be mounted the end of the robotic manipulator.

5.1.2 Finger Mount

The soft gripper has to be able to grasp an object that it happens to find between its fingers. This means the mount to which the fingers are attached has to be able to supply air to them to make them bend. The finger mount also has to securely clamp the fingers to itself so they can not fall off when moving the robotic manipulator. In turn, the mount itself has to be able to attach securely to the rest of the robotic manipulator. First prototypes did not contain a method of clamping, which quickly made the need for one apparent.

These prototypes highlight the following requirements:

- The finger mount must be able to supply air to the fingers' air-intake.
- The finger mount must be able to securely attach the soft fingers to itself.
- The finger mount must be able to be attached to the robotic manipulator.

5.1.3 Pneumatic Actuator: RC-45 [28]

In order for the user to move the joints, an actuator is needed. The RC-45 was chosen for this purpose due to its compactness and ability to provide a lot of torque with limited air pressure. The stepper motor is fully 3D-printed. A few iterations of this motor were made because the first few were assembled sub-optimally which caused leakage of air to occur when the chambers of the motor were pressurized.

Different prototypes can can be seen in Figure 5.5, that were made to experiment with gear-ratios.

Figure 5.5: Two prototypes of the RC-45 with differing gear-ratios

The motors should be able to be attached and detached easily during the assembly process to enhance and streamline user experience. To this end, the RC-45 motor was slightly modified by adding a dovetail connector to its back, as can be seen in Figure 5.6.

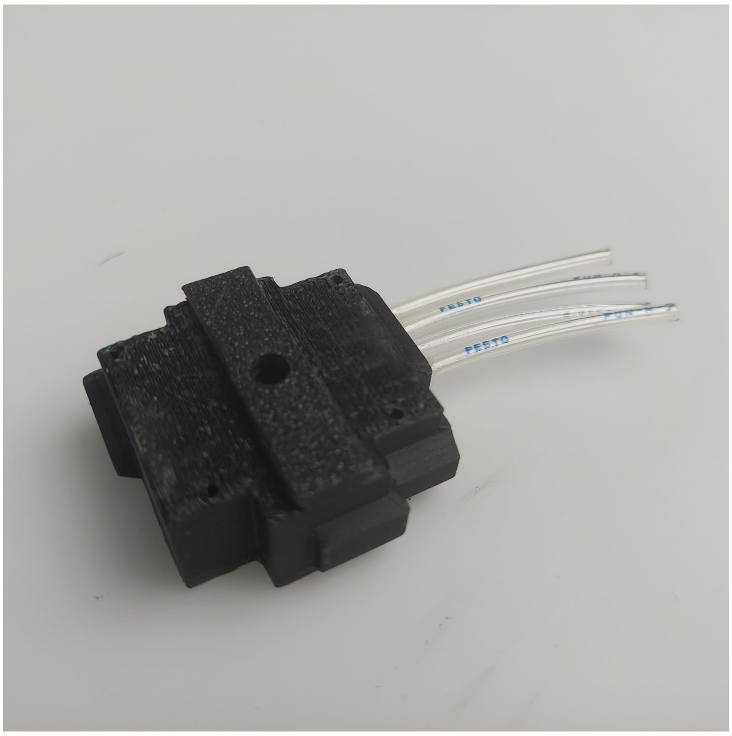


Figure 5.6: Dovetail joint on the back of the RC-45 stepper motor

These prototypes highlight the following requirements:

- The system should not contain any leaks.
- The pneumatic actuator should be able to be attached and detached with relative ease.

5.1.4 Robotic Manipulator

During the course of this project, the degrees of freedom changed between two and three multiple times due to concerns about the scope of the project, and functionalities of prototype designs. The very first iteration of the robotic manipulator operates two degrees of freedom, with a third manual degree of freedom. This first iteration can be viewed in Figure 5.7.

Both joints are controlled using a 3D-printed RC-45 pneumatic stepper motor. The base on which the arm is mounted can be rotated by the user, using the pin on the backside of the base as a small handle.

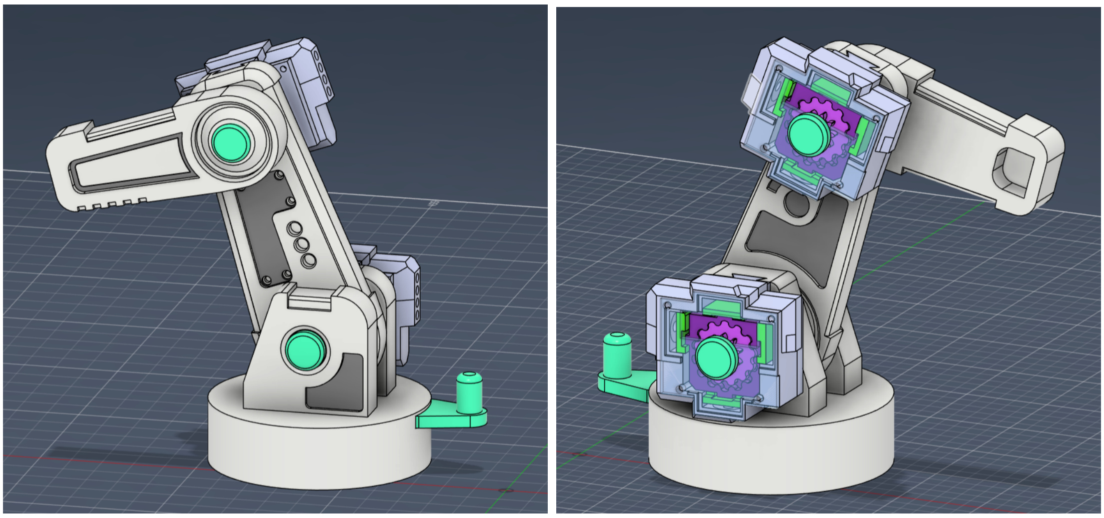


Figure 5.7: Both sides of the first iteration of the robotic manipulator

These prototypes highlight the following requirements:

- The design should be visually appealing to promote user engagement and motivation.
- Different components must be attachable and detachable by hand without tools.

5.1.5 Controller

The controller is needed for the user to interact with and to house different components needed for the functionalities of the robotic manipulator. The first prototype of the controller contained multiple subcomponents, all with different purposes.

Arduino Uno

Because the robotic manipulator uses stepper motors, the system requires some type of timing in order to pressurize the right chambers in the correct order and combination. This can be regulated by using an Arduino Uno. The user would give inputs that tells the Arduino to cycle through valve-configurations, sending pressurized air to the correct chambers.

Vacuum Pump

Initially, a few vacuum pumps were ordered to act as the air supply for the whole system, both the gripper and the RC-45 stepper motors. However, the pumps were not strong enough to provide enough pressure for the stepper motors to move. Nevertheless, the pumps are able to inflate the soft fingers with ease.

Valves

Valves are necessary to direct the airflow in the appropriate direction. In combination with the Arduino Uno, the valve can be turned either on or off, dictating to which chamber air is allowed to flow. Multiple types of valves were tested because a few oversights were made in the process of selecting and ordering valves.

Valves - Small Solenoids

Firstly, small solenoid valves were ordered and used in combination with the Arduino Uno. The first oversight that was made, had to do with the type of valve that was ordered. The first type was a valve that is either open or closed which is not adequate for the required functionality. The valve should be able to switch between two directions of airflow, both to opposites sides of either piston inside of the stepper motor. The desired effect could be realized using this type of valve, but it would require a lot of valves, which would make it expensive, bulky, and inefficient.

Afterwards, small solenoid valves that were able to switch between two directions of airflow were ordered. These were installed in the system and tested. The valves worked, but only for one stroke of the piston. This is because the lack of an exhaust which keeps all chambers pressurized, making both sides of the piston work against each other. These valves could also have worked to realize the desired effect, but again this would require a lot of valves making the project more expensive, bulky and inefficient. Besides those drawbacks, ordering components takes a lot of time, which was not desirable at that point of the project.

Valves - Servo Actuated Valves

Alternatively, valves can be 3D-printed and controlled using electrical servo motors [55]. An assembled servo-actuated valve can be seen in Figure 5.8.

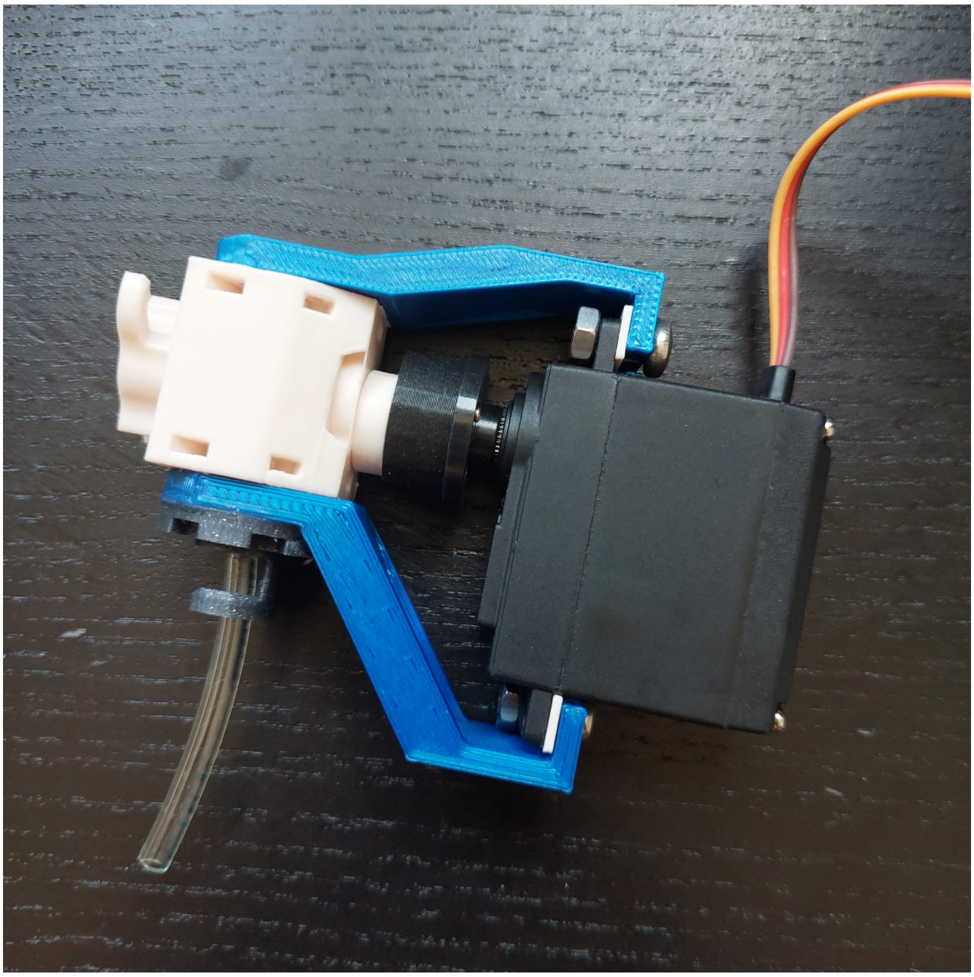


Figure 5.8: System Diagram detailing the pneumatic connections between the foot-pump, air tank, manual valves, and the pneumatic cylinders.

The required parts were 3D-printed and assembled. The valves worked as expected, but the inside of the valves leaked a small amount of air, making the system lose pressure rapidly which refrained the chambers of the stepper motors from being pressurized with enough pressure.

The prototype for this system can be seen in Figure 5.9.

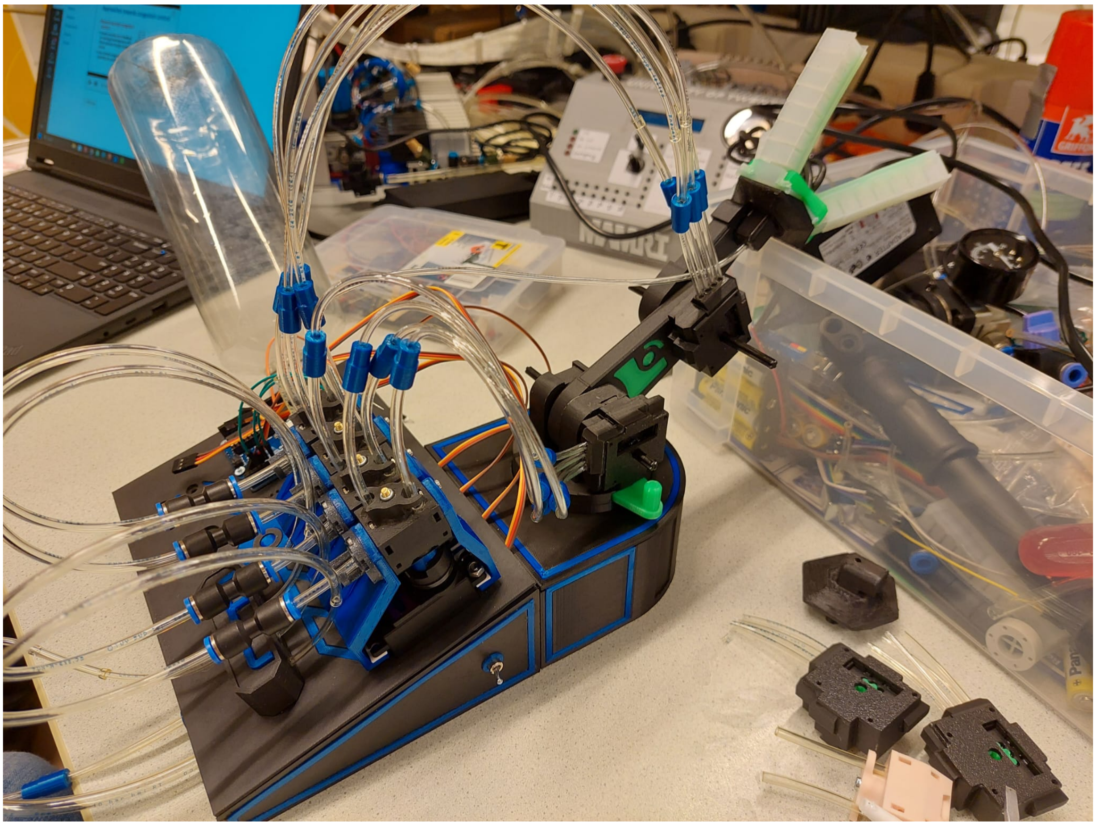


Figure 5.9: Prototype of the full system, utilizing servo-actuated valves controlled using an Arduino Uno, together with the first iteration of the robotic arm using RC-45 stepper motors.

Valves - Industrial Valves

Industrial valves assure that there are no leaks present inside the valve, solving the problem of loss of air pressure. When these valves were tested, no air leaked. However, even without leaks the manually generated air pressure was still not enough to move the robotic manipulator consistently. These valves are also incredibly expensive, which goes against the affordability aspect of the DIY kit. An expensive kit would deject beginners and most of the cost of the kit would be in the valves.

The above prototypes highlight the following requirements:

- The controller must house all functional components of the DIY kit
- All components must be manually attachable and detachable with no tools.
- The air pump must be able to supply enough air to inflate the soft gripper.
- The air supply for the soft gripper and the motors should remain separate.
- Valves must be capable of switching airflow between two directions.
- Valves must include an exhaust.
- Valves must not leak under operating pressure.
- The system will not use RC-45 stepper motors.

5.1.6 Pneumatic Tube Connectors

Because pneumatic tubes of differing diameters will be used and connected to each other, a method of connecting has to be realized. This is necessary because while it is possible to connect two different sizes of tubing to each other during assembly without any extra parts, it is difficult and frustrating. To remedy this difficulty, a small connector tube was prototyped and 3D-printed. The result can be seen in Figure 5.10.

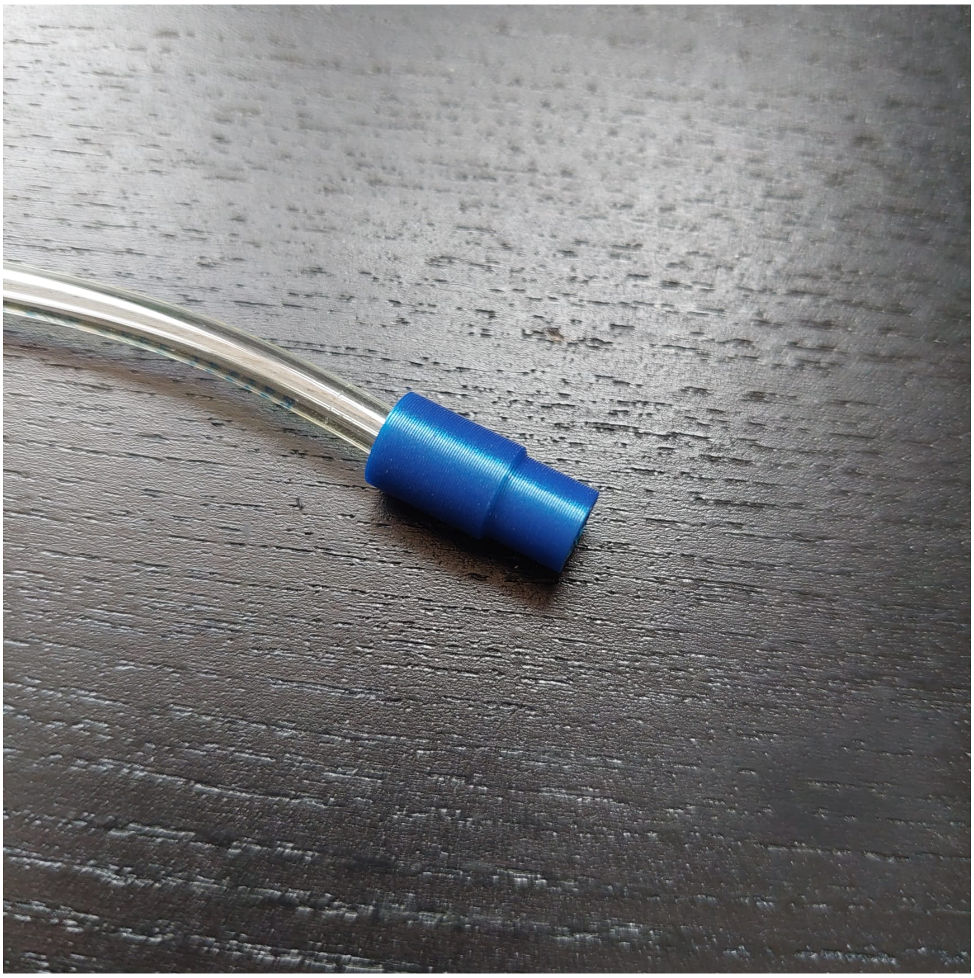


Figure 5.10: Small connector for pneumatic tubing

Tolerances were changed a few times in order to find the balance between ease of connection and airtightness.

5.1.7 Instruction Manual

One version of the instruction manual has been developed during the scope of this project and will be elaborated upon in Chapter 6. While only one prototype has been made, the instructions can still be assisted by the market research conducted in Chapter 2. These specify the importance of clear instructions, and the promotion of learning during the assembly of the kit. These requirements can be promoted by adding facts and learning moments between steps. This means the user learns during the process of assembly, making the instructions more clear as they explain part of the system, and it adds learning value as well.

5.2 List of Requirements

According to the previous chapters, together with the prototyping conducted in this chapter, a comprehensive list of requirements can be constructed.

Category	Requirement
Soft Finger	Must remain straight when held upright
	Must bend when inflated
	Should not tear during handling or insertion
	Must be mountable to gripper base
Finger Mount	Must securely clamp soft fingers
	Must allow airflow into finger's intake port
	Must mount to robotic manipulator
Actuators	System must be airtight and leak-free
	Actuators must be easy to attach/detach
Manipulator	Components must fit without tools
	Assembly should require only moderate force
	System should be visually appealing to engage users
Controller	Must house all functional components (valves, tubing, power)
	Components must be manually removable for easy assembly
Air Supply	Gripper and actuators must have separate air circuits
	Pump must supply enough pressure to actuate gripper
Valves	Valves must switch airflow between two outputs (5/2 valve)
	Valves must include an exhaust output
	Valves must not leak under expected operating pressure
Tubing	Pneumatic tubes of different diameters must connect easily
	Connectors must balance airtightness with ease of use
System	Kit should remain cheap to build
	Kit should be designed with environmentally conscious materials where possible
	Components should be sturdy and durable.
	Components' dimensions should not be smaller than 5mm in any direction.
Usability	Instructions must be clear and visually supportive
	Components must be appropriately sized for handling
	Assembly should require no prior technical expertise
Educational Value	Kit must help user understand pneumatic systems
	Kit should stimulate interest in soft robotics

Table 5.1: Comprehensive List of Design Requirements

CHAPTER 6: REALIZATION

This chapter will detail the final design and creation of the DIY robotic manipulator kit. The design will integrate the specifications and requirements that were described in previous chapters and distill a concrete final prototype as a functional and educational DIY kit.

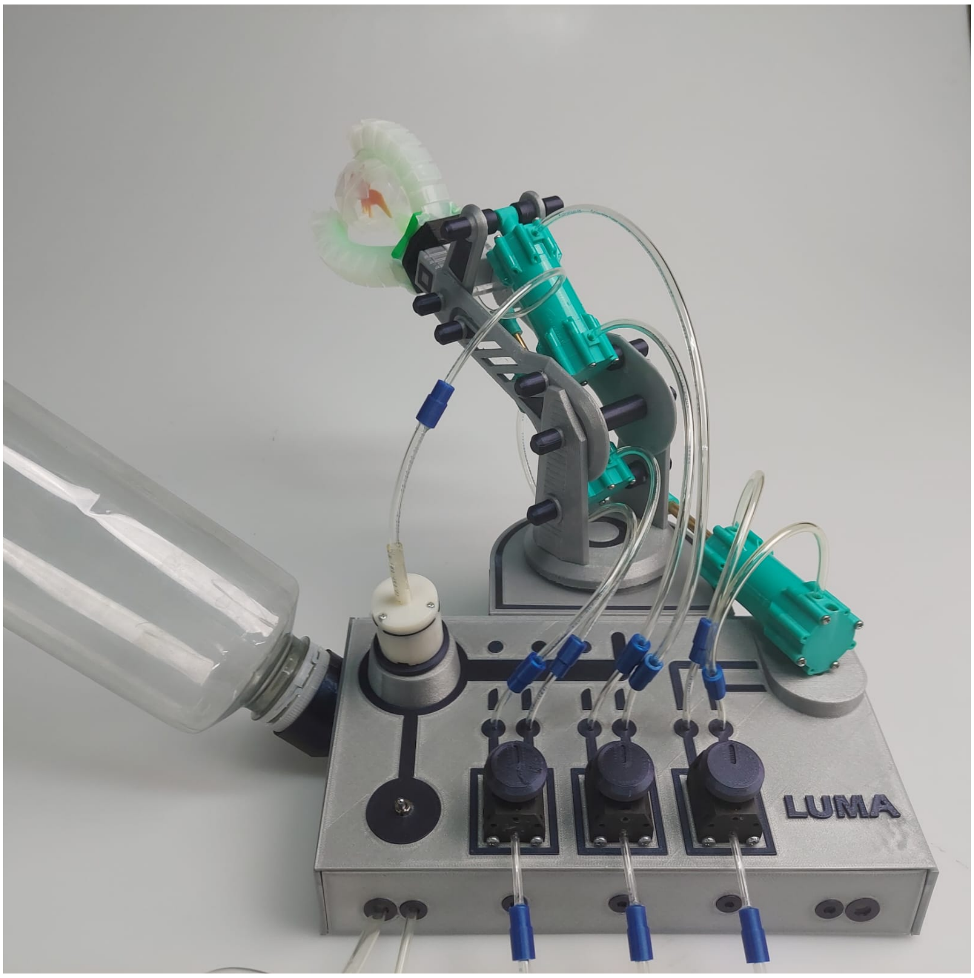


Figure 6.1: Final prototype for the DIY kit

6.1 System Overview

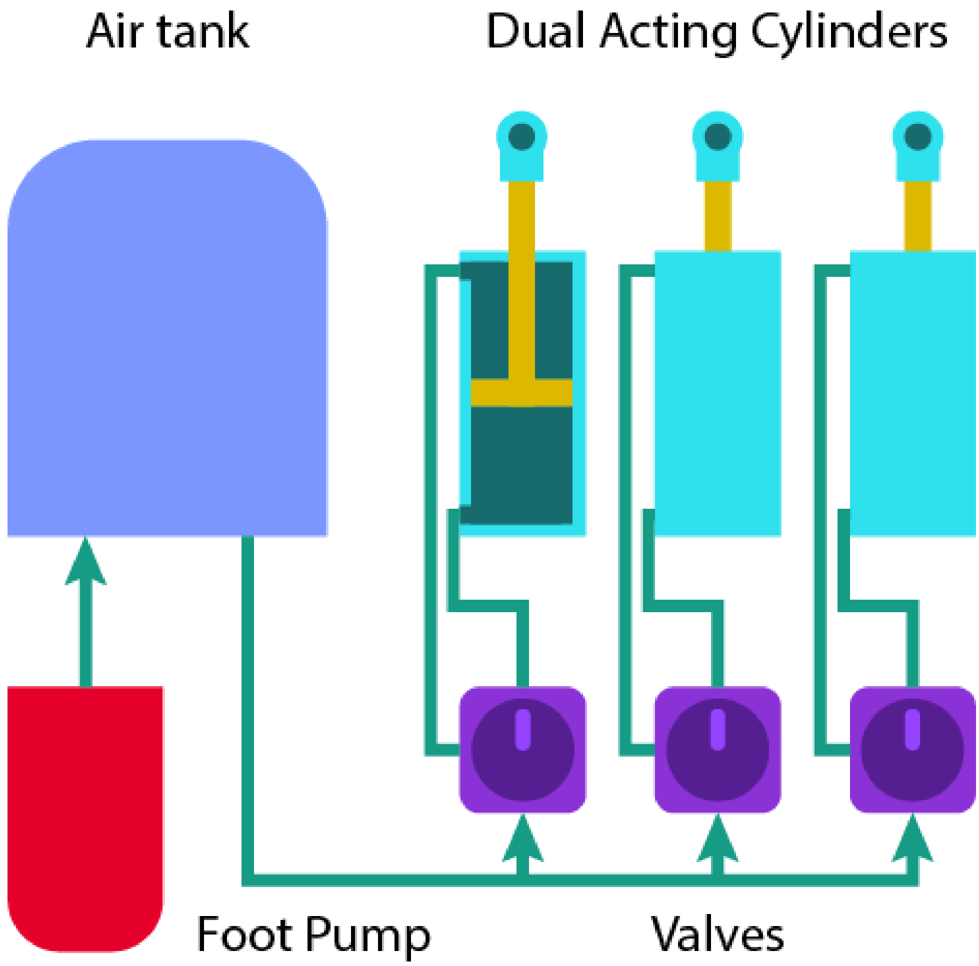


Figure 6.2: System Diagram detailing the pneumatic connections between the foot-pump, air tank, manual valves, and the pneumatic cylinders.

The system uses compressed air generated by a foot-pump to actuate the robotic manipulator. The foot pump can be seen in Figure **??** A PET bottle that functions like an air tank on the side of the controller gets pumped up to about 2 bars of pressure. From the air tank, the air gets directed to the three valves. These valves are the same as the servo driven valves from section 5.1.5 in Chapter 5, but without the servo. One of these valves can be seen in Figure 6.10. The user will turn the knob manually, letting through air to the corresponding chamber of one if the cylinders. This extends or retract the piston which consequently moves a part of the robotic manipulator. The three knobs each correspond to one piston. By turning the knob slightly left or right, air is allowed to flow towards a chamber in the piston. The valve does not leak now, because when the knob is in its neutral position, no air can go through. When the air pressure gets too low to actuate the pistons, the user has to keep using the foot pump. To actuate the gripper, the pump can be turned on using a small switch which connects the pump to the battery pack resulting in air getting pumped into the fingers of the gripper. The diagram for this subsystem can be seen in Figure **??**.

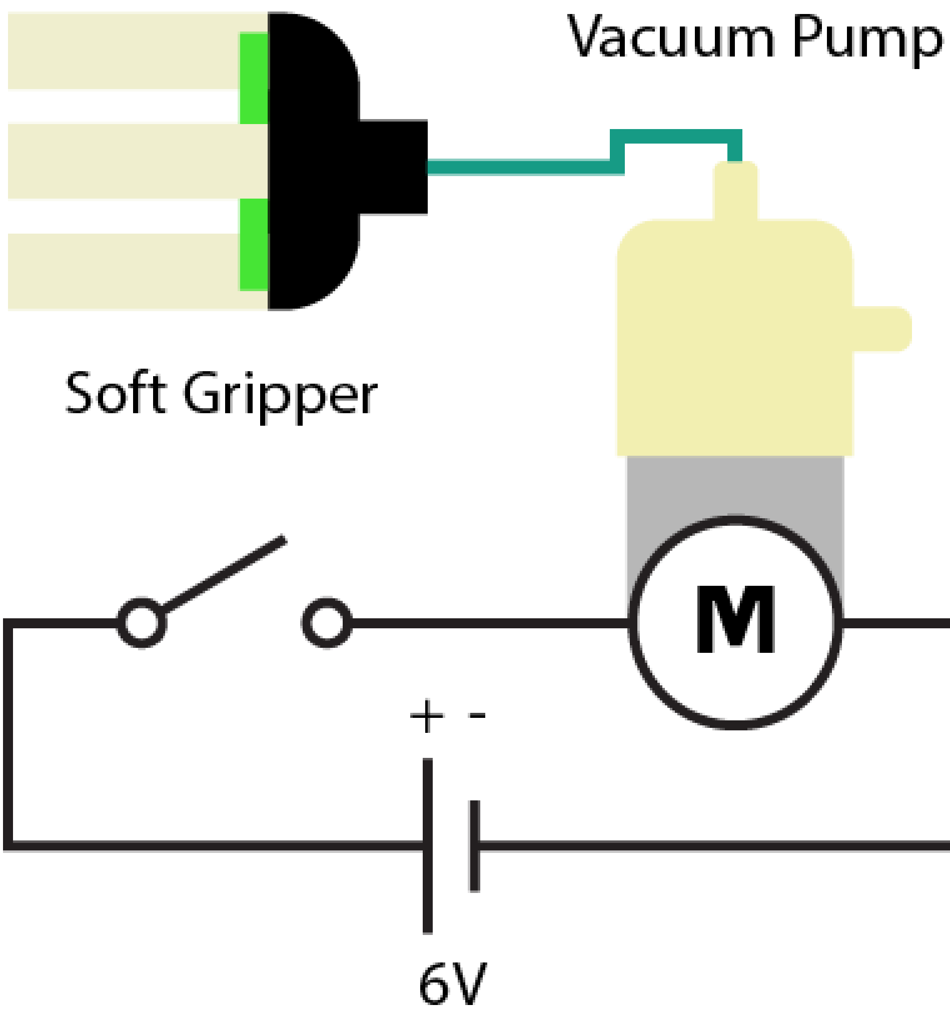


Figure 6.3: System Diagram detailing the electrical circuit responsible for turning on the vacuum pump, actuating the soft gripper.

6.2 Component Realization

6.2.1 Soft Finger

The final soft fingers were cast using DS10-NV using the second mould design as specified in Chapter 5. Using this type of silicone ensures that the finger will not rip or puncture during handling, as it is a very strong and durable material. The finger includes mounting flaps to be able to be clamped to the finger mount, and includes an integrated hole for air-intake. To prevent sagging and unnesessary bending when idle, the bottoms of the fingers were reinforced with a thin strip of PLA during the casting process. The resulting finger can be seen in Figure 6.4. The top of the finger is moulded as normal.

Figure 6.4: Amount of Bending in the final finger prototype

These implementations meet all of the requirements for this component as set in the List of Requirements in Chapter 5.

6.2.2 Finger Mount

The final version of the finger mount contains a clamp that pushes down all of the mounting flaps simultaneously, attaching the fingers to the mount securely. The mount has three nozzles on which the fingers can be mounted and hooked over.

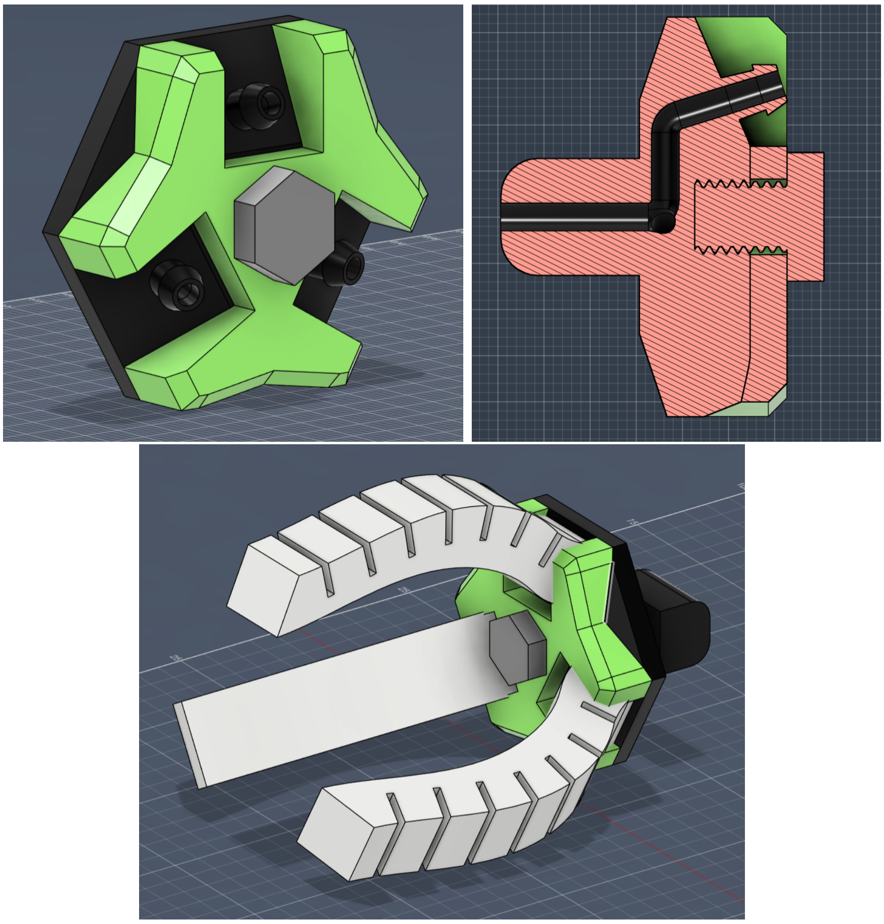


Figure 6.5: Finger Mount final prototype

The finger mount was 3D-modelled in Fusion 360 and 3D-printed on a PRUSA MK3S printer using generic PLA. **These implementations meet all of the requirements for this component as set in the List of Requirements in Chapter 5.**

6.2.3 Pneumatic Actuator

After testing with the RC-45 motor, it became clear that the stepper motor was not suited for a DIY project that relies on manually generated air pressure as opposed to air supplied from a compressor. This is why the stepper motor was replaced by a dual acting cylinder, designed by J. Verhagen [56] and V. Groenhuis [57]. The cylinder requires a lot less pressure to function, and does not require any microcontroller for timing and direction simplifying the system immensely, making it easier to understand for the user. Because the focus is on pneumatics and soft robotics, the electronic components should not be a major part of the functionality of the system. Based on Chapter 2.3.1, cylinders were chosen as actuators. This type of actuation has been used before in DIY kits, showing a solid base for implementation.

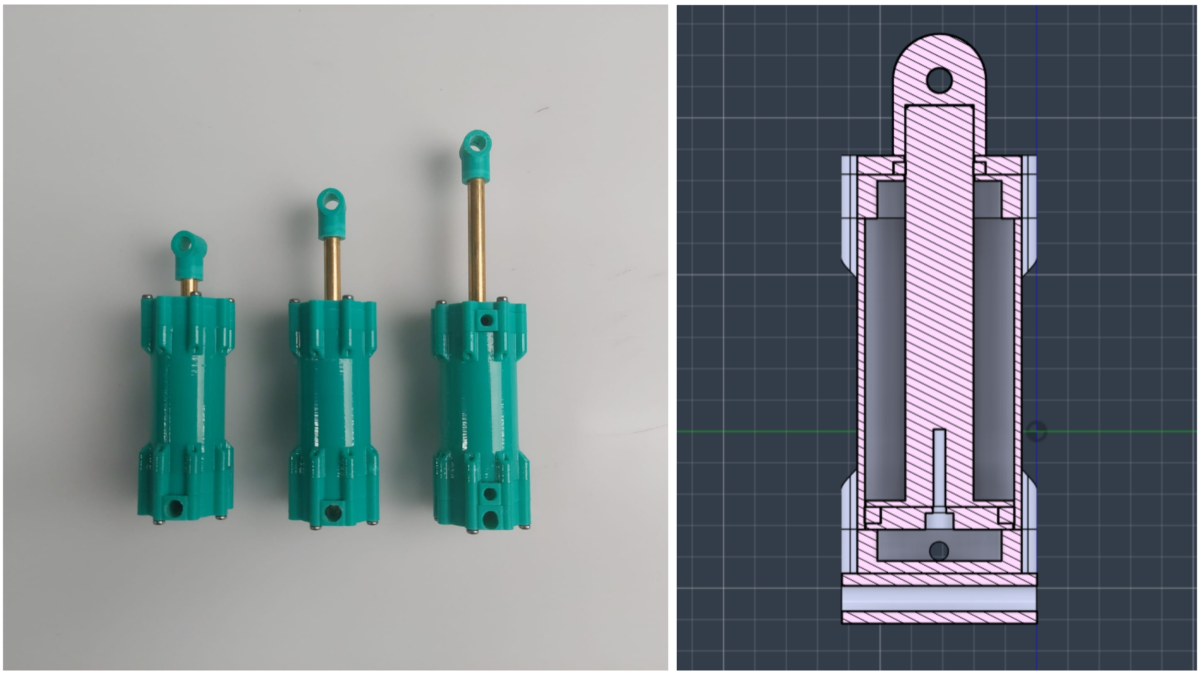


Figure 6.6: Cylinder Design [56][57]

The parts of the cylinder were printed using ASA. This is because the main cylinder of the piston has to be smoothed using acetone smoothening. This ensure a good seal and a smooth surface for the foot of the piston to glide past. Using acetone smoothening also ensures any small holes through which air might leak through are melted closed. To make sure the cylinders are able to be attached to other components of the kit, the mounting holes were widened using a standard chordless drill using a 5mm drill-bit. The rod of the piston is a brass rod that was inserted into the ASA parts using a vice. The foot of the piston, and the hole through which the piston extends, were both sealed using the appropriately sized X-rings. **These implementations meet all of the requirements for this component as set in the List of Requirements in Chapter 5.**

6.2.4 Manipulator

Due to the change in actuator from the RC-45 stepper to the ASA cylinders, the arm of the manipulator needed to be redesigned. The result is shown in Figure 6.7.

Figure 6.7: Final Prototype for the robotic manipulator.

The parts were designed with slits, holes, and inlays that serve no functional purpose other than aesthetic appeal. These details were added to give the arm a slight futuristic look, while also trying to lose a small amount of weight to reduce the working pressure needed for the cylinders. Mounting holes were positioned as such that the cylinders could actuate the manipulator arm when extended and protracted. The left and right side of the arm were distanced from each other in order to fit the cylinder in between them without colliding with them. The right side parts, left side parts, and the cylinders are attached using an axle made of a perspex rod. This material was chosen due to availability, cost-effectiveness, and its smoothness providing a more streamlined assembly process. These perspex rods were cut at lengths corresponding to the different distances between the left and right side parts of the manipulator arm, so that they would not protrude further than necessary. All parts of the manipulator arm were 3D-modelled in Fusion360 and 3D-printed on a PRUSA MK3S printer using generic PLA. **These implementations meet all of the requirements for this component as set in the List of Requirements in Chapter 5.**

6.2.5 Controller

The controller base was designed to house an air-tank, a battery pack, a pump, valves, tubing, and the base for rotation of the manipulator arm. This was done with compactness, aesthetics, and ease of use in mind. The controller is equipped with many holes in which components can sit tightly, and tubing to run through smoothly. To this end, tolerances between parts were adjusted such that components and tubing fit snugly in the controller. The top of the control panel is designed to mimic where tubing should run through and be connected to. The controller can be seen in Figure 6.8.

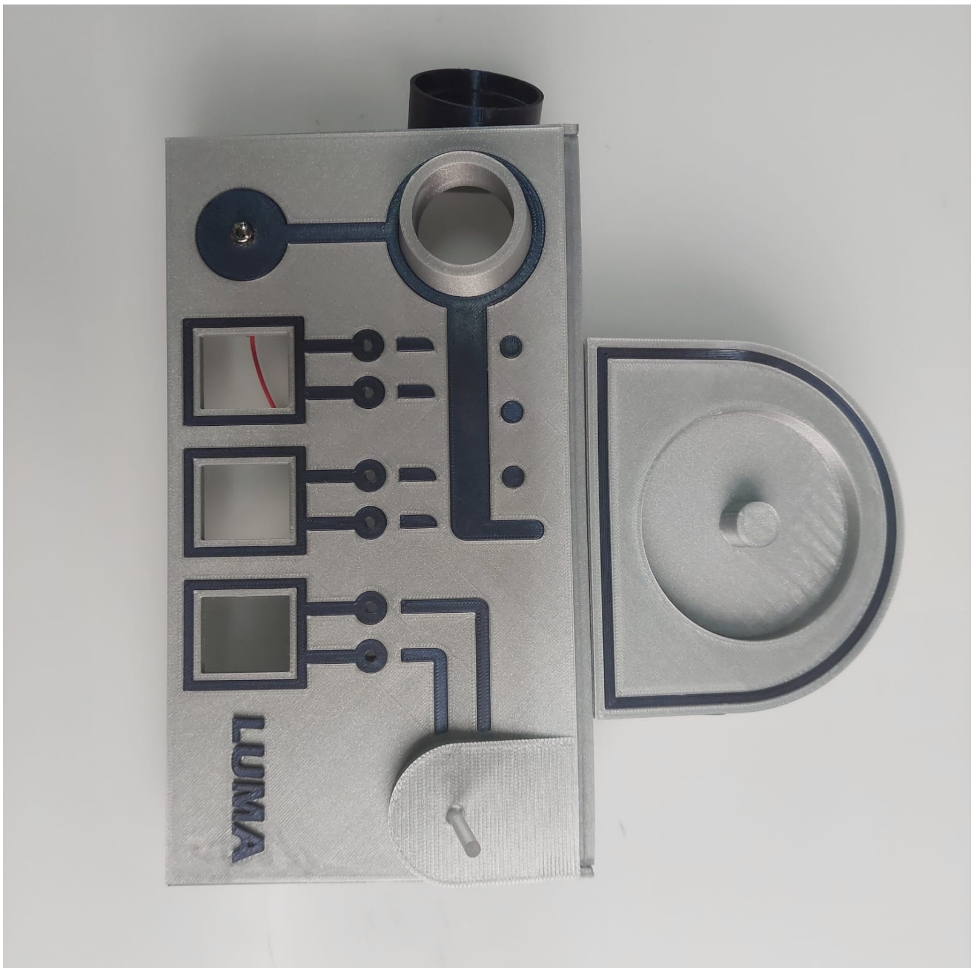


Figure 6.8: Final prototype for the controller base

The left side of the controller base has an upwards facing mount in which the air tank can be inserted.

The front side is equipped with holes through which the compressed air from the foot-pump can run through to the air tank, and from the air tank to the valves.

The backside of the controller has four holes where the base for rotation can be attached, just like a really big LEGO-piece.

The underside of the controller is where the battery pack that powers the pump is permanently mounted, together with the wiring of the switch. To attach any components to the controller requires no screws, clamps, or tools.

All parts of the controller including the inlays were 3D-modelled in Fusion360 and 3D-printed on a PRUSA MK3S printer using generic PLA. **These implementations meet all of the requirements for this component as set in the List of Requirements in Chapter 5.**

6.2.6 Air Supply

The system uses two ways to supply the gripper and cylinders with pressurized air. Firstly, to power the gripper, a small vacuum pump is used. This pump can generate 1,2 bars of pressure and is rated for 6V, which resulted in the use of 4 AA alkaline-batteries, each rated to supply 1,5V. This amount of pressure is more than enough to actuate all three fingers. When pressurized, the fingers curl up quickly but do not get overinflated, as the fingers leak air slightly. This means that the pump can stay powered while actuating the gripper. When the pump is turned off, the fingers return to their original positions.

To provide pressurized air to the cylinders, a foot-pump is utilized. The foot-pump can be seen in Figure 6.9.

Figure 6.9: Foot-pump used to generate air-pressure.

The user manually pumps up the systems' air tank, after which the compressed air can be used to actuate the cylinders. Using two different ways of generating pressurized air hopefully educates the user about that fact. **These implementations meet all of the requirements for this component as set in the List of Requirements in Chapter 5.**

6.2.7 Valves

In the adjustment between RC-45 stepper motor to pneumatic cylinder, the need for electronically controlled valves was voided, as there was no longer a need for specific timing for the pressurization of different chambers in the stepper motors. This means that the system could be simplified significantly by removing the Arduino Uno and solenoid valves. The switch to pneumatic cylinders also removes the usefulness of servo-actuation, as they would only complicate the actuation, while manual control is much more easy and intuitive. Manual control also allows the user to both carefully and quickly extend and retract the pistons by making small or large adjustments in valve-orientation, which would be very difficult to interchange between using servos. The servo-controlled valves specified in Chapter 5 can also be controlled manually by replacing the servo with a manual turning knob. This is exactly the solution that was implemented for the final prototype and can be seen in Figure 6.10.

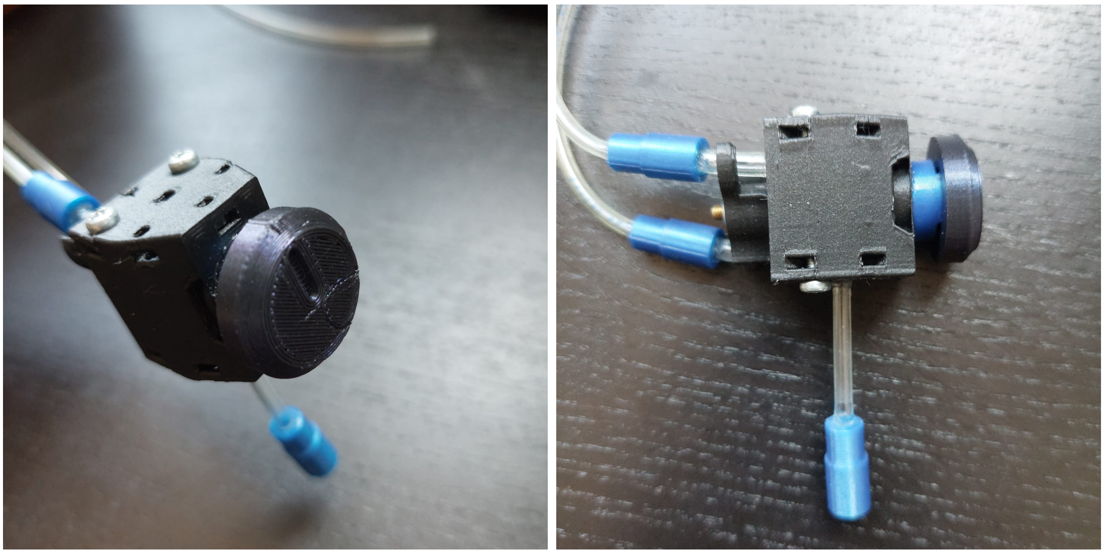


Figure 6.10: Views of the manually controlled valves. By turning the knob, air channels are configured internally.

When the knob is in its neutral position, no air is able to leak out of the system. Air does leak slightly out of the exhaust when the knob is turned to actuate the cylinders, but this does not negatively affect the actuation of the cylinders. All parts except the pneumatic tubing of the valve were 3D-modelled in Fusion360 and 3D-printed on a PRUSA MK3S printer using generic PLA. **These implementations meet all of the requirements for this component as set in the List of Requirements in Chapter 5.**

6.2.8 Tubing

The diameters of pneumatic tubing in the system will include 3, 4 and 6mm. Tubes with a diameter of 3mm can be inserted into a tube with a diameter of 4mm, which can in turn be inserted into a tube with a diameter of 6mm. While prototyping, this method was used frequently but was found incredibly frustrating and difficult especially when needing to be done many times in a row. This growing resentment called for a better method of connecting pneumatic tubing. A small 3D-printed connector was made in order to connect tubing with a diameter of 3mm to tubing with a diameter of 4mm. The connector is much easier to grip than the tubing itself, making insertion a bit more straightforward. Furthermore, the system was designed in such a way that connecting tubing had to be executed a minimal amount of times, and only for connection of 3mm to 4mm tubing, requiring only one type of connector. Other necessary connections of tubing were glued or attached ahead of time. **These implementations meet all of the requirements for this component as set in the List of Requirements in Chapter 5.**

6.2.9 System

The requirements under the section ”System” all concern themselves with different aspects of the system.

Cost-Effectiveness

Firstly, the cost-effectiveness of the system. The materials and production methods should be economical to keep the price of the kit low which stimulates accessibility to beginners, amateurs, gift-givers, and educational institutions. Most parts of the system were 3D-printed using generic PLA, with exception of the cylinders which were made using ASA to allow for acetone smoothening. The total weight (not counting any support material used) of the 3D-printed parts came down to about 344 grams. With a kilogram of PLA commercially being available for about 12 €, the material cost of the PLA would be around 4,13 €. Lengthy print times would drive up this price more because of maintenance costs and time reserved for the printer. The components that were not 3D-printed are the soft fingers, the 1L PET-bottle, the small vacuum pump, the foot-pump, the perspex axes, the battery pack, the switch, and the pneumatic tubing. The soft fingers were made using DS10-NV silicone. The quantity at which this is sold is quite expensive at 41,79 €. However, to fabricate three fingers very little of the full volume is needed. One finger needs about 20 mL of both components of the silicone. One container of a component of the silicone contains about 840 mL. So 60 mL (20 mL for three fingers) is equal to about 2,4% of the whole, which means that the material costs for three fingers would be about 1 €. The PET-bottle, battery pack, switch, perspex rods, and the pneumatic tubing can all be bought for very low prices.

In conclusion, the material costs of the kit are estimated to be around 10 €. This is not taking into account costs related to production, packaging, storage, transport, marketing, labour costs, or any ther unforeseen costs which would drive up the price significantly. However, the requirement that states that the kit should be cheap to build is still satisfied, since 10 € to build the system is not very expensive.

Environmental Footprint

The system is mostly consistent of PLA and other plastics. The parts made with PLA produce waste in the form of support material and potential failed prints. It also takes a lot of power to run the 3D-printers for an extended amount of time. The fingers made from DS10-NV also produce excess silicone, considering spillage and the need to trim away any surplus of sillicone created during the casting process. Silicone takes many years to degrade, or needs to be recycled in specialized treatment plants, but consumers usually throw it out with the regular waste [58]. This means the silicone material is not a very environmentally friendly material to be used in this system, missing the requirement of envirnmental conciousness stated in Chapter 5.

Sturdiness and Durability

Based on the market research in Chapter 2, consumers value sturdy components that do not break easily. All parts of the kit were designed with that robustness in mind. Parts that required force to be applied to their structure were supported with extra material in areas of concern, for instance the inside corners of the controller base. The final prototype has survived transport, manufacturing processes, and user tests without any parts breaking, which speaks to the sturdiness of the supplied parts. This requirement as stated in Chapter 5 was met.

Component Size

No individual component as delivered in the DIY kit was smaller than 5mm in any dimension, except for the diameter of the pneumatic tubing. However, because the value for sufficient component size was based on usability and being able to handle the component easily, efforts were made in this regard in the form of the small tube connectors. These were made larger than 5mm in any dimension with the sole purpose of connecting tubes easier, enhancing usability. With that in mind, the requirement of sufficiently large component size can be assumed as fulfilled.

6.2.10 Instruction Manual

The instruction manual was not iteratively designed. The first version was used in the final prototype, and was based on market research and the expert interview. Based on the reported value of clear instructions, the instruction manual features many colored pictures with arrows pointing to areas of interest, for instance when an axis needs to be inserted. Market research also revealed the importance of the instructions promoting learning, which is why the instructions came with explanations of key aspects of the system. In between the steps, small callout boxes with a star character called 'LUMA' inform the user of tips, facts, and important things to keep in mind while assembling. The star character explains the different key aspects of the system, like the soft finger, cylinder, and the valves. Besides informative, the instructions should also be motivational, which is why the text in the instructions offers words of encouragement frequently. According to the expert interview conducted in Chapter 4, a user should first and foremost be made excited about the kit. This was attempted by constructing, evaluating, and trying the soft gripper at the start of the instructions. To this end, the user would experience a small sense of accomplishment, making them more motivated to learn and finish the rest of the kit. The instruction manual can be viewed in Appendix B.

CHAPTER 7: EVALUATION

To address the requirements from Chapter 5 that were not discussed in Chapter 6, user tests have been conducted to ascertain the successfulness of the remaining requirements. This chapter details the evaluation methods used, together with the results from user testing.

7.1 Evaluation Methods

First and foremost, to determine the usability of the system as a whole, the System Usability Scale (SUS) was utilized. This is a small questionnaire of 10 Likert scale questions [44]. The result of the SUS will give insight in the overall usability of the system. This score will yield a benchmark for determining if users had any difficulty while using the DIY kit. If this results in a system with suboptimal usability, less can be concluded about the rest of the questions the users were asked after the user tests.

To gain insight in the unaddressed requirements of Usability and Educational Value as stated in Table 5.2, a custom questionnaire was offered to the users after filling in the SUS. These questions regarded four aspects: Assembly, Instructions, Educational Value, and Engagement. After this quantitative data was collected, the users were also asked to fill out four open questions to gather a bit of qualitative data. The full questionnaires and their results can be found in Appendix C.

7.2 Test Setup

Users were asked to appear at a reserved room on campus at the University of Twente in which the user tests took place. Participants were asked to read the provided information letter that details the project and the accompanied research, and to sign a consent form. Both the information letter and consent form can be seen in Appendix D and Appendix E, respectfully. After signing, the participants were instructed to construct the DIY kit using the provided instruction manual. The researcher stayed in the room to provide any help, be it physically stepping in or answering any question. Participants were timed and intermittently observed. After assembly, participants were asked to fill in both the SUS questionnaire and the custom questionnaire. After submission of both questionnaires, participants were free to leave or discuss with the researcher present for an impromptu unstructured interview.

7.3 Participants

User tests were conducted with six separate participants. The group was fully made up of student colleagues of the practicing researcher. Participants' ages ranged from 20 to 25.

7.4 SUS Score

The System Usability Scale score can be calculated by a simple formula. The odd-numbered questions are positively coded, so a high result in these questions are positive. The even-numbered questions are negatively coded, so a high result in these questions are negative. Each question has a score contribution. For the odd-numbered questions, this is the reported score minus 1. For the even-numbered questions, this is 5 minus the reported score. After these score contributions are calculated, all scores are added together. This number is multiplied by 2,5, resulting in a usability score between 0 - 100.

The SUS score for each individual participant was calculated and can be seen in Figure 7.1.

Participant	P1	P2	P3	P4	P5	P6	**Average**
SUS Score	65.0	90.0	85.0	75.0	80.0	67.5	77.1

Table 7.1: SUS Scores Per Participant

The average SUS score of this system was calculated to be **77,1**. According to a curved grading scale based on 241 usability studies, proposed by Lewis & Sauro, this system would grade a B with a SUS score of 77,1. This score falls just below the mark of a B+. A mark of B is not bad but it is also not particularly great. It shows that there are definitely improvements to be made with regards to usability. Hopefully the results of the custom questionnaire will shine some light on there shortcomings.

7.5 Custom Questionnaire Results

Since the questions were structured based on system aspect, the results will be structured in the same way, starting with Assembly.

7.5.1 Assembly

The average scores for the Assembly category ranged from 2,83 to 4,17 out of 5. The participants found the sizes of components to be sufficient (4,17), and appreciated that the assembly process was fairly straightforward (3,67). They also felt confident without any external help (3,67). However, a point of attention lies in the ease of putting components together, with a sightly below average score of 2,83. Some tolerances or parts require refinement.

Statement	Average Score	Std Dev
I was able to assemble the kit without any external help	3.67	0.82
Different components of the kit fit together without difficulty	2.83	0.75
The size of the components made them easy to handle	4.17	0.75
The assembly process was straightforward	3.67	0.52

Table 7.2: Average Scores – Assembly Section

7.5.2 Instructions

Statement	Average Score	Std Dev
The instructions were clear and easy to follow	3.83	0.41
The explanations about the different parts of the system helped me understand the system	4.83	0.41
The pictures in the instructions helped me during the assembly process	4.50	0.84
I understood what each step was asking me to do	4.50	0.55

Table 7.3: Average Scores – Instructions Section

According to Table 7.3, participants responded positively to the instruction manual. The highest score of 4,83 indicates that the technical explanations helped participants' understanding effectively. The provided visuals in combination with the textual instructions proved to be a great assistance in understanding of the participants, both with a score of 4,50. The lowest score of 3,83 suggests some improvements are still in order with regards to the clarity of the instructions. Statement 3 has slightly more variance than the other questions, meaning some participants found the pictures less helpful or more helpful than others.

7.5.3 Educational Value

Statement	Average Score	Std Dev
I now understand the basic components of a pneumatic system	4.83	0.41
I learned something new about soft robotics using this kit	5	0.00
I could explain to someone else how this DIY kit works	5	0.00
This kit makes me want to learn more about soft robotics and pneumatics	5	0.00

Table 7.4: Average Scores – Educational Value Section

Participants responded incredibly positive to this section of the questionnaire. Most participants reported to understand the basic components of a pneumatic system with a score of 4,83. All participants scored a 5 for the other 3 questions. This indicates all participants learned something new about soft robotics using the DIY kit, and they feel as confident as to say that they would be able to fully explain the DIY kit to someone else. They also report the DIY kit motivates them to want to learn more about soft robotics and pneumatics, which is perfectly in line with the research questions asked in Chapter 1.

7.5.4 Engagement

Statement	Average Score	Std Dev
I enjoyed building this kit	5	0.00
I would recommend this kit to others	4,38	0.41
I think this kit would be helpful in an educational setting (e.g. classroom)	5	0.00
The appearance of this system engaged me in the assembly of the kit	5	0.00

Table 7.5: Average Scores – Engagement Section

This section of the questionnaire emphasizes the importance of visual stimulation and engagement with a score of 5 when asked if the appearance of the system engaged the user in the assembly of the kit. Participants also reported to have enjoyed using the kit with an average score of 5 and the urge to recommend the DIY kit to other people with a score of 4,38. Participants also reported their impression that the kit could be helpful in an educational setting, also with an average score of 5. Low variance in both the Educational Value and Engagement sections imply agreement across participants.

7.5.5 Open Questions

Four open questions were asked to the participants in order to gauge their opinions in the DIY kit experience. They were asked about expected age-range, any changes they would like to see, frustrations and limitations, and general comments.

When asked ”Who do you see as the target group for this DIY kit, and why do you think that?”, most participants reported a younger age range, saying elementary to high school students.

When asked ”If this kit was made for you, would you change anything about it? If so, what?”, multiple points of improvement were reported.

- The star character should only include optional additional information, and not critical points of the building process. This makes sense, because people might overlook the callout boxes when only interested in the assembly process. More experienced users might skip these boxes, missing important steps or info for assembly.

- Some pictures were reported to be less clear, so components that look very similar but have different configurations might be confused, like the cylinders.

- Press-fit and tube connectors were found to be difficult to connect. This prompts improvements with regards to tolerances and method of connection.

- The axis rods should be the same length. Most users were slightly confused by this, and sometimes chose the wrong length, causing them to have to restart. To counteract this confusion, the axes could all be made the same length, or the different length can be specified in a more clear manner.

- Improving the swivel on which the robotic manipulator rotates. When the arm fully extends, the rotation base came loose slightly, causing the cylinder to pop off of its pivot. One of the participants suggested adding a bearing and a counterweight that keeps the rotating base in place.

When asked ”Did you experience any limitations or frustrations?”, multiple things came to light.

- The first section in which you attach the soft fingers to the finger mount was found difficult by multiple participants. One participant specified that holding all three fingers at the same time while adding the clamp was very difficult.

- Pneumatic tubing was reported to be difficult to attach together and string through the control panel. Also related to the tubing, there is a page in the instructions specifying a good way to attach pneumatic tubing using the small connectors. Participants confused this page with the first step of the instructions, causing slight trouble.

- Two participants mentioned color coding or numbering to be implemented in order to make it more clear where the components that look very similar go.

When asked ”Do you have any comments or suggestions about the DIY kit as a whole?”, participants gave a range of responses. First and foremost, it was mentioned that the experience was fun and cool. One participant said that the process would go a lot smoother with just a few minor tweaks. Furthermore, some more suggestions were given. One participant proposed the addition of a small part list before every step to specify exactly what parts are needed where. Finally, a participant mentioned that the kit is too basic for university level students, and would more quickly see it used in lower levels of education.

CHAPTER 8: DISCUSSION

This chapter aims to provide critical reflection on the project, including its limitations, unexpected challenges, and opportunities for future work.

The main goal of this project was to explore how soft robotics and pneumatic actuators could be integrated into an accessible, engaging, and educational DIY robotics kit that motivates users to want to learn more about soft robotics and pneumatics. The results from Chapter 7 suggest that this goal was mostly met. Participants reported high scores with regards to educational value and engagement. A SUS score of 77.1 indicates generally good usability with room for improvement. Soft robotics and pneumatic actuation were succesfully implemented in a DIY robotics kit in the form of a three-fingered PneuNet soft gripper, and three dual acting cylinders respectfully. The supplied instruction manual contributed to the knowledge gain of the DIY kit together with the increase in motivation to learn more about soft robotics and pneumatic actuation.

While overall usability was found to be sufficiently high, specific aspects of the assembly process and instruction manual caused a certain level of frustration and confusion.

Components that rely on press-fit were found to be cumbersome to assemble, with the most common remark being about the pneumatic tubing. These findings highlight the necessity for improved tolerances in 3D-printed components together with a new, more streamlined design for the connectors for pneumatic tubing. To reduce component-induced confusion, it could also be very helpful to color-code or number any components that look similar. It was reported that attaching the soft PneuNet fingers to the finger mount was difficult, both due to fear of breaking the finger, and because the finger would often fall off of the nozzle of the finger mount when wiggled too much. To better manage this action, the size of both the fingers' air-intake and finger mounts' nozzle could be increased. While the clamping mechanism worked well overall, this design could be improved by creating a three separate clamps for all fingers. The fingers could then be attached one by one. This would eliminate the need to have all fingers loose and balancing on the nozzles, which caused them to fall often.

While the instructions were found to be sufficiently clear and helpful, some steps, visuals, and call-out boxes caused confusion. This indicates the need for some slight improvements. To reduce the error of switching out similar components, images could be made with increased quality so the difference in components can be seen better. This problem can also be relieved by paying more attention to specifying exact components using arrows or circles. The call-out boxes were sometimes overlooked by users, causing them to be unaware about particular importances in a step. Call-out boxes should only be used to provide the user with extra information about the system, an underlying principle, or "fun facts". To make instructions more intuitive and clear, the manual could be made digital in the form of a website, app, or a text document. This would accomodate the manual to include videos, maneuverable 3D-models, or short animations.

Evaluation results with regards to educational value showed a positive response by all participants. Scores indicated increase in knowledge and interest in relation to soft robotics and pneumatic actuation. However, participants consisted fully of university students. These participants identified the intended demopgraphic of the kit to be more suitable for elementary/high school students. This urges another evaluation with participants from that demographic to validate educational value across that age range as well.

The expected demograpghic of elementary- to high school students could be interpreted in two ways. The kit could be focused on that demographic, keeping the design, assembly, and learning goals simple and beginner-level. However, the focus of the kit could also be shifted towards higher levels of education by increasing difficulty of both theory discussed as well as practical skills that have to be applied. Future work could aim to return to the RC-45 stepper motors (or other pneumatic actuators), effectively making the DIY kit more challenging through the need for added electronics, control, potential coding, and valve solution. This could potentially shift the expected target demographic back to high school/university level students or higher.

Besides the abovementioned limitations and improvements that could be made to the physical system, some constraints about the evaluation process should be acknowledged as well. The sample size was limited to six participants, all with a similar educational background. This small sample size together with similarities in participants could have skewed the results from the evaluation. High levels of agreement in the Educational Value and Engagement sections could also have been a result of bias due to the little amount of participants and their comparative educational level. Further evaluation should be done with more participants, both in the same age range as younger age ranges to validate if the agreement holds true. Also, the past experience and uses of DIY kits was not inquired about, meaning that some participants could have had more familiarity and knowledge about the process, altering their experience when compared to other participants. Future research should make sure to ask participants about their past experiences with DIY kits and the subjects discussed in the DIY kit to be researched.

This project demonstrates the potential of accessible soft robotics in educational tools. It adds to a growing body of work that aims to bring emerging technologies to a wider audience through low-cost, hands-on formats. With refinement, such kits could become valuable resources for STEM outreach, robotics workshops, or classroom education.

CHAPTER 9: CONCLUSION

The goal of this project was to answer its main research question, stated as: **"How can soft robotics and pneumatic motors be integrated in a Do-It-Yourself robotics kit that engages learners and supports STEM motivation?"**.

By utilizing the Design Process for Creative Technology, the final concept of a DIY kit for a 3-DOF pneumatically actuated robotic manipulator with a soft robotic end-effector was synthesized. The final prototype for this proposed idea integrates pneumatic motors in the form of pneumatic dual acting cylinders, and soft robotics in the form of a three-fingered PneuNet soft gripper. The robotic manipulator is actuated by extending and retracting the cylinders' piston by the state of three manually controlled valves. Pressurized air is user-generated by the use of a footpump. Users assemble the resulting integrated system by the use of an extensive and educational instruction manual.

The system was evaluated by individually having six test-subjects assemble the DIY kit using the instruction manual, after which the participants were asked to fill in two short questionnaires, gauging system usability, educational value, and user engagement. The first questionnaire resulted in an average SUS score of 77.1, indicating a moderately positive experience with some room for improvement.

The second questionnaire concerned Likert-scale questions, divided into the categories of Assembly, Instructions, Educational Value, and Engagement. Scores from the Assembly category indicated inflicted frustration from difficulty fitting different components together. The assembly-process was found to be moderately straightforward and intuitive with room for improvement. Components size was deemed to be sufficient by most participants. Mainly difficulties with the connectors for pneumatic tubing and components that used press-fit mechanisms were reported. Also, the action of attaching the soft fingers to the finger mount was found to be challenging. Some confusion derived from the axes being different lengths. Scores from the Instructions category indicated an overall positive experience regarding the instruction manual. Clarity and intuition are aspects that can still be improved. In this regard, participants suggested specifically the use of call-out boxes in the instructions to be strictly for additional information. Some of the included pictures could also be made more clear. Included explanations of the system were found to be helpful and constructive, and the step-by-step textual instructions were reported to be clear. Scores from the Educational Value category indicated an incredibly educational and motivating experience. Participants reported to have gained an extensive understanding of the basics of pneumatic systems and soft robotics, even going as far as to say they could explain the DIY kit to an external individual. Participants also detailed the motivation to learn more about pneumatic systems and soft robotics. The age range for this DIY kit was assumed to be quite young with mention of elementary- to high school students, indicating a beginner-level DIY kit. Scores from the Engagement category indicated an overall engaging experience, with participants reporting they enjoyed themselves during the assembly of the kit. Participants would recommend the DIY kit to other people, and could see it being a valuable asset in an educational setting.

In conclusion, this project succesfully demonstrates the integration of soft robotics and pneumatic actuation in an accessible and educational manner, by combining a hands-on experience, engaging design, and explanatory instructions resulting in a motivational experience. While improvements can still be made, this project lays a solid foundation for future work, research, and potential deployment in educational settings.

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Appendices

CHAPTER A: AI-NOTICE

During the preparation of this report, I used ChatGPT and Elicit to help structure content, and find academic sources. After using these tools and services, I reviewed and edited the content as needed, taking full responsibility for the final outcome.

CHAPTER B: INSTRUCTION MANUAL

LUMA: A Pneumatic and Soft Robotic DIY Kit

Learn Soft Robotics & Pneumatics By Building a 3 Degrees Of Freedom Robotic Arm With A Soft Gripper

Contents

Introduction

Welcome to **LUMA: A Pneumatic and Soft Robotic DIY Kit!**

This kit is designed to introduce you to the exciting world of **soft robotics** and **pneumatic actuation**. Whether you're a student, hobbyist, or someone who simply wants to try something new, this kit will guide you through creating your very own **3 Degrees of Freedom robotic manipulator with a soft gripper**.

What you will learn:

- The basics of pneumatic actuation.
- The components of pneumatic systems.
- How soft robotics differs from traditional rigid robotics.

Build Time : 30 - 45 minutes

Skill Level : Beginner

You will follow step-by-step instructions and get a hands-on learning experience with no prior knowledge needed. **Enjoy!**

Component List

Pumps:
- Foot-Pump x1
- Vacuum Pump x1

Soft Gripper:
- Soft Finger x3
- Finger Mount x1
- Finger Clamp x1
- Plastic Screw x1

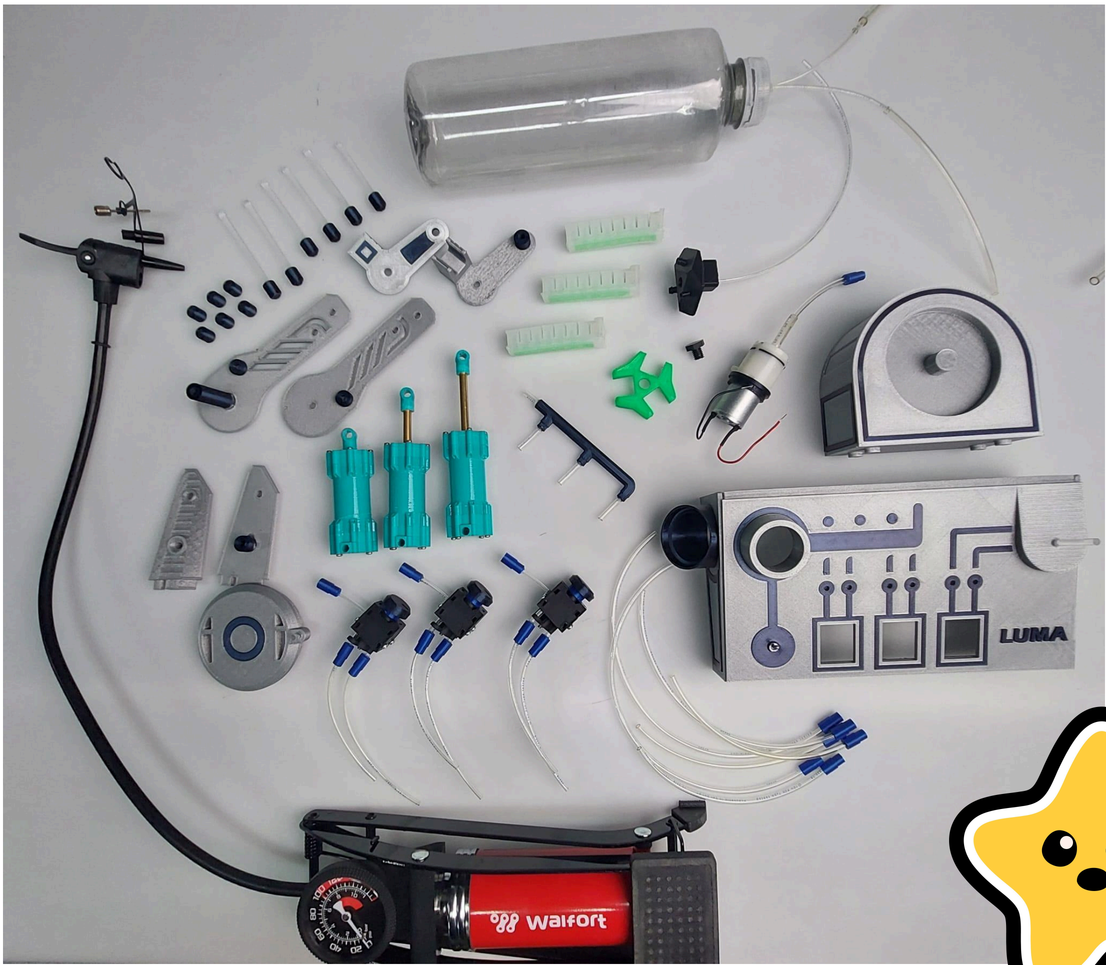
Actuators:
- Piston x3

Control Panel

Rotation Base

Pneumatics:
- Air Tank x1
- Pneumatic Tubing x6
- Three-way Splitter x1
- Valve x3

Manipulator:
- Rotating Base x1
- Base Bracket x2
- Upper Arm x2
- Wrist x2
- Perspex Axis x6
- Axis Cap x6



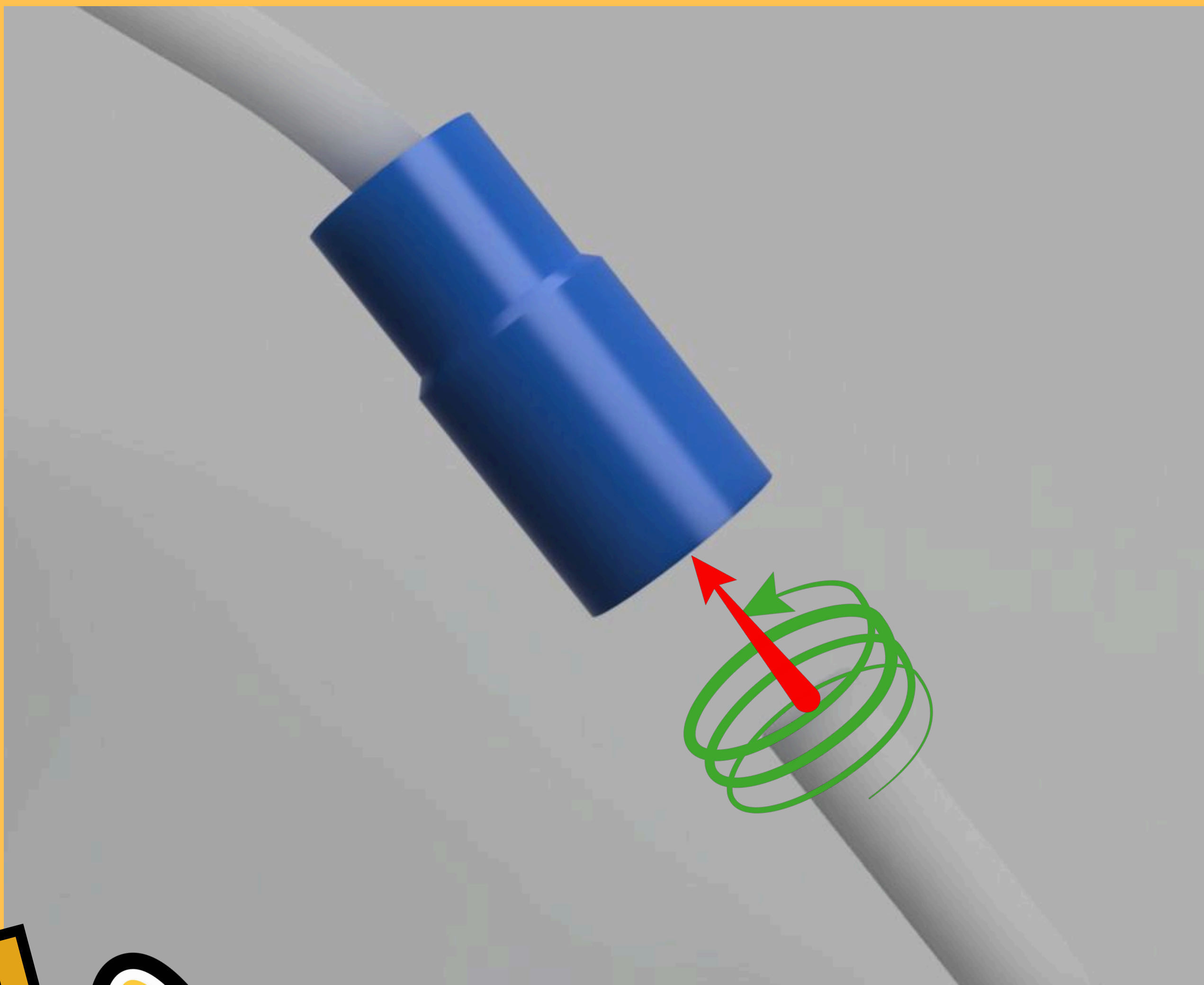
Safety

Some basic rules for safety during the building process:

1. Do not use excessive force while using the foot pump. This could put too much pressure on the system, which might cause damages.
2. Do not point any air flows directly at your face.
3. While operating the robotic manipulator, keep your fingers away from potential pinch points like the joints of the manipulator.

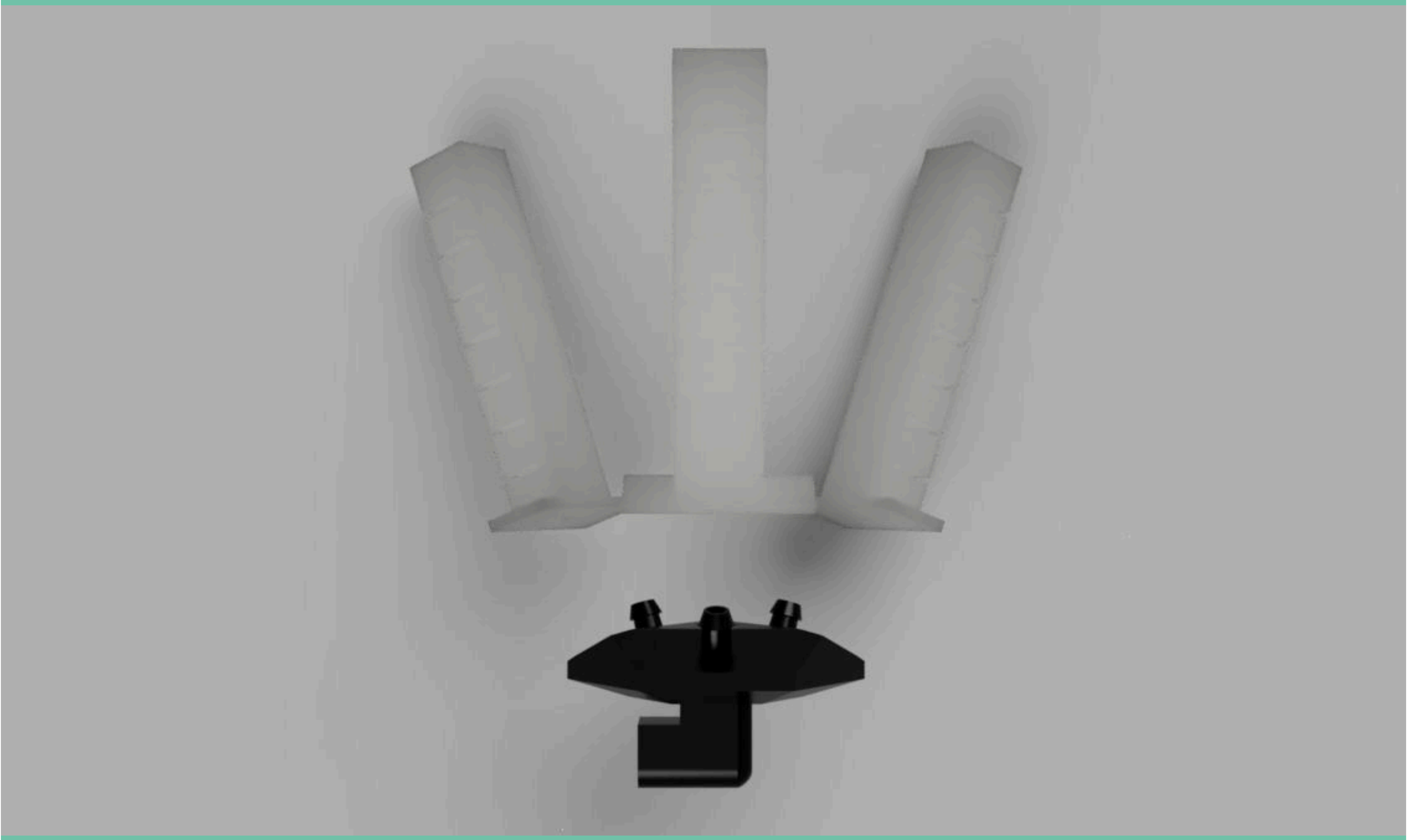
How To Connect Tubing

Pneumatic tubing has to fit tightly in any place where it connects to a different part of the system. This means that connecting tubing can be slightly difficult. To make it as easy as possible, try twisting the tubing while pushing:



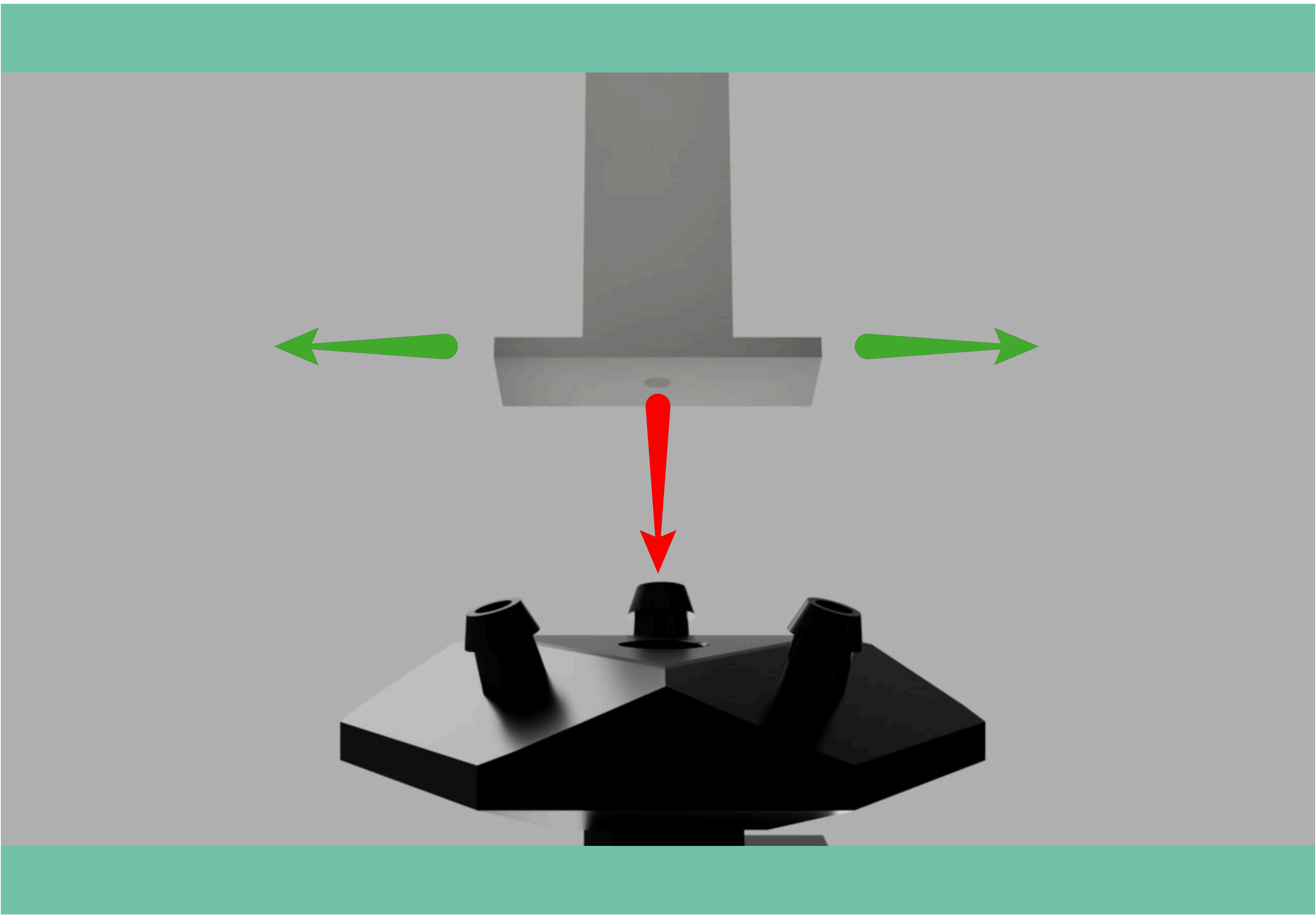
Assembly Guide

Lets start this assembly by looking at the soft gripper.
For this first steps you will need the three soft fingers and the finger mount as seen below.

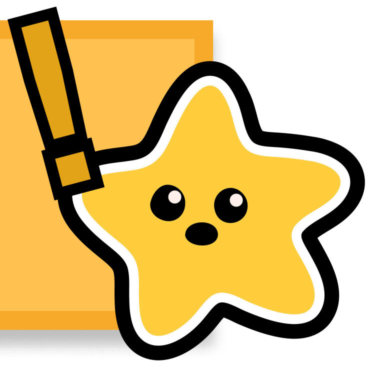


Assembly Guide

The **air intake** of the **soft finger** has to be stretched over the nozzle of the **finger mount**. If this is difficult, try wiggling and twisting the finger a bit while pushing down. Alternatively, you could try to stretch open the air intake by pulling on the little wings at the end of the finger as shown by the green arrows

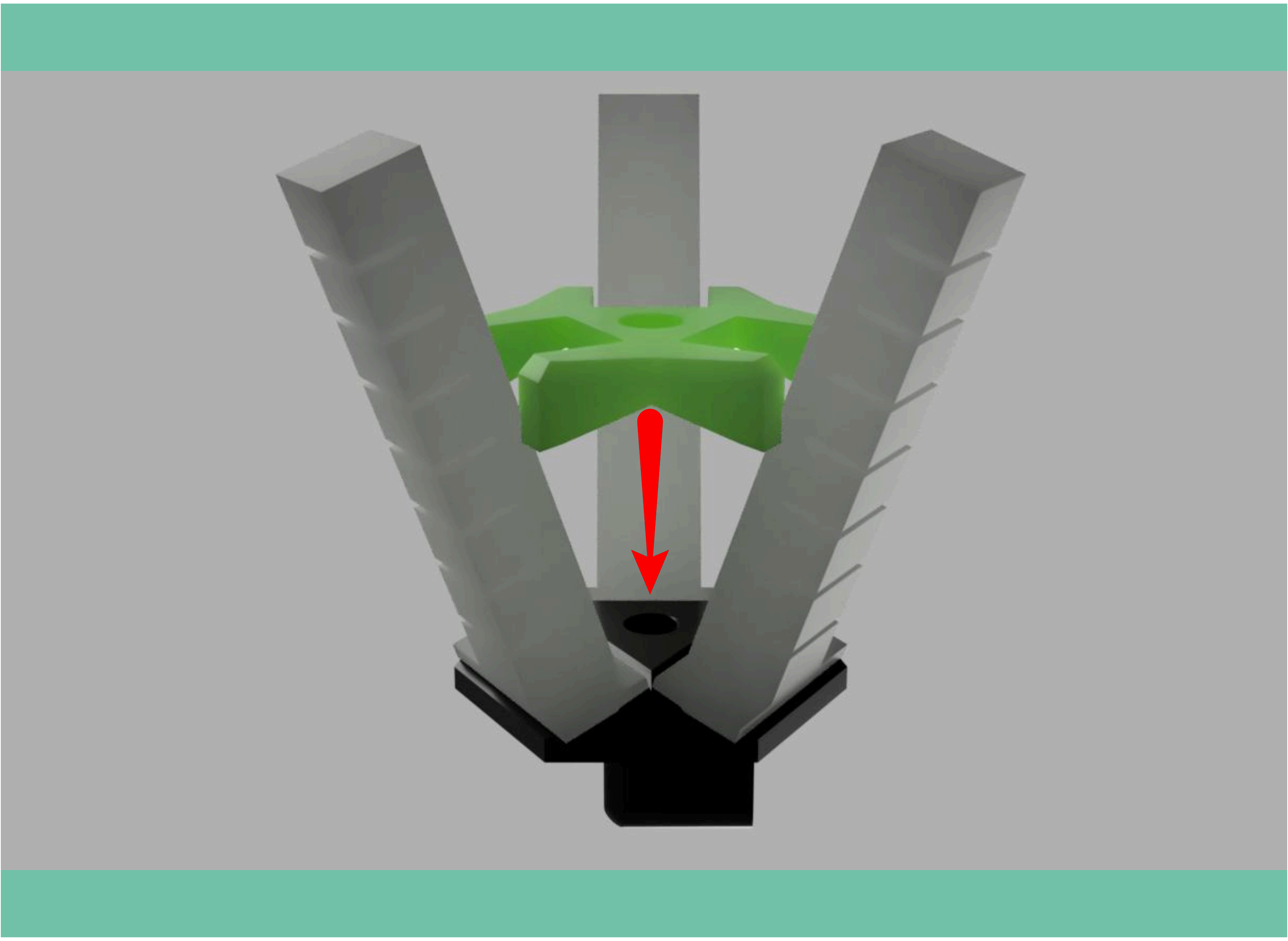


The material that the soft fingers are made out of is called “Dragon Skin” silicone by Smooth-On. That same material is commonly used for movie special effects and prosthetics due to its flexibility!



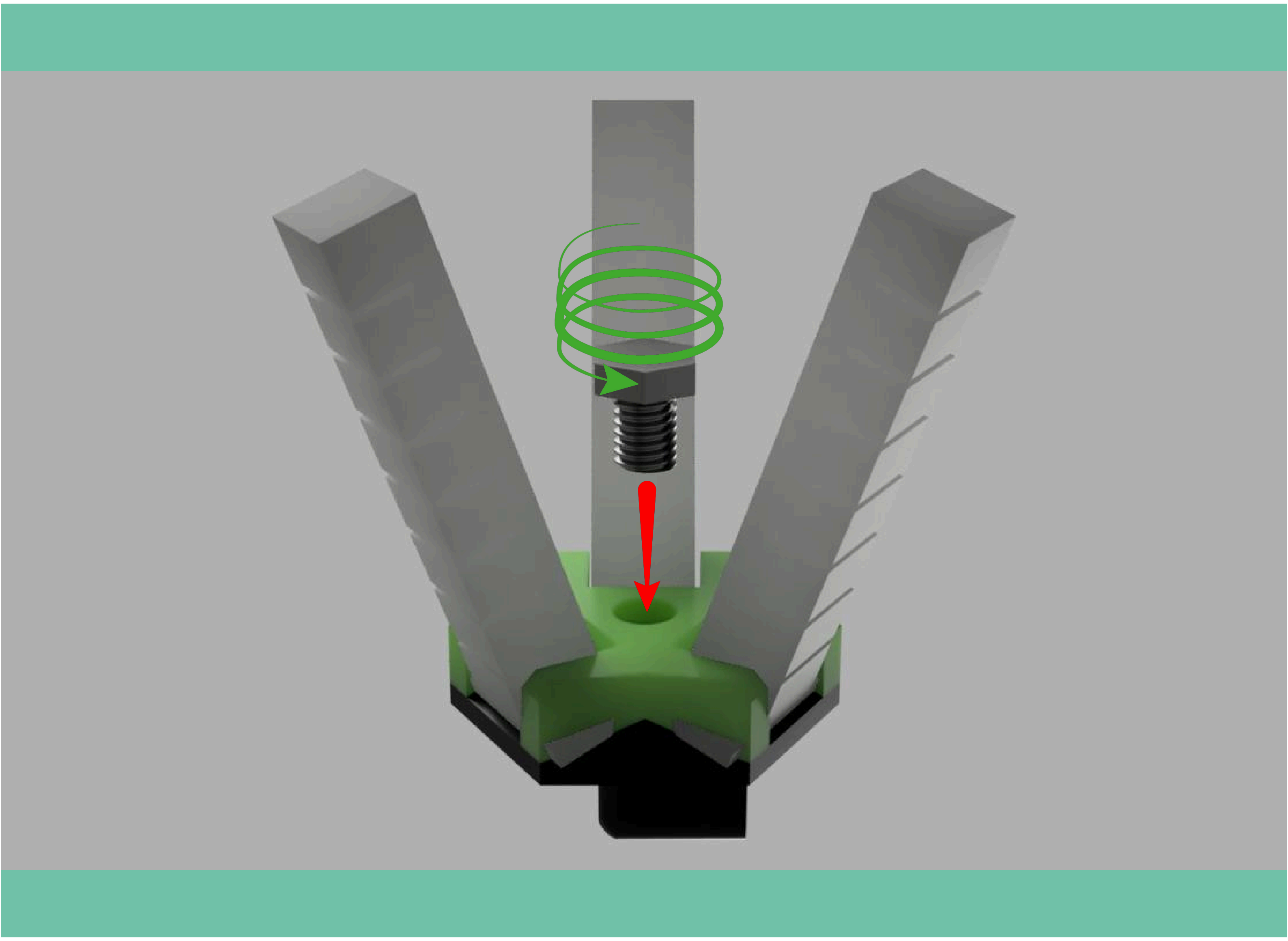
Assembly Guide

If we want the **fingers** to be firmly secured to the **finger mount,** we will have to clamp them down. The **green clamp** attachment will help us do this. Gently position the **green clamp** between the **fingers**.



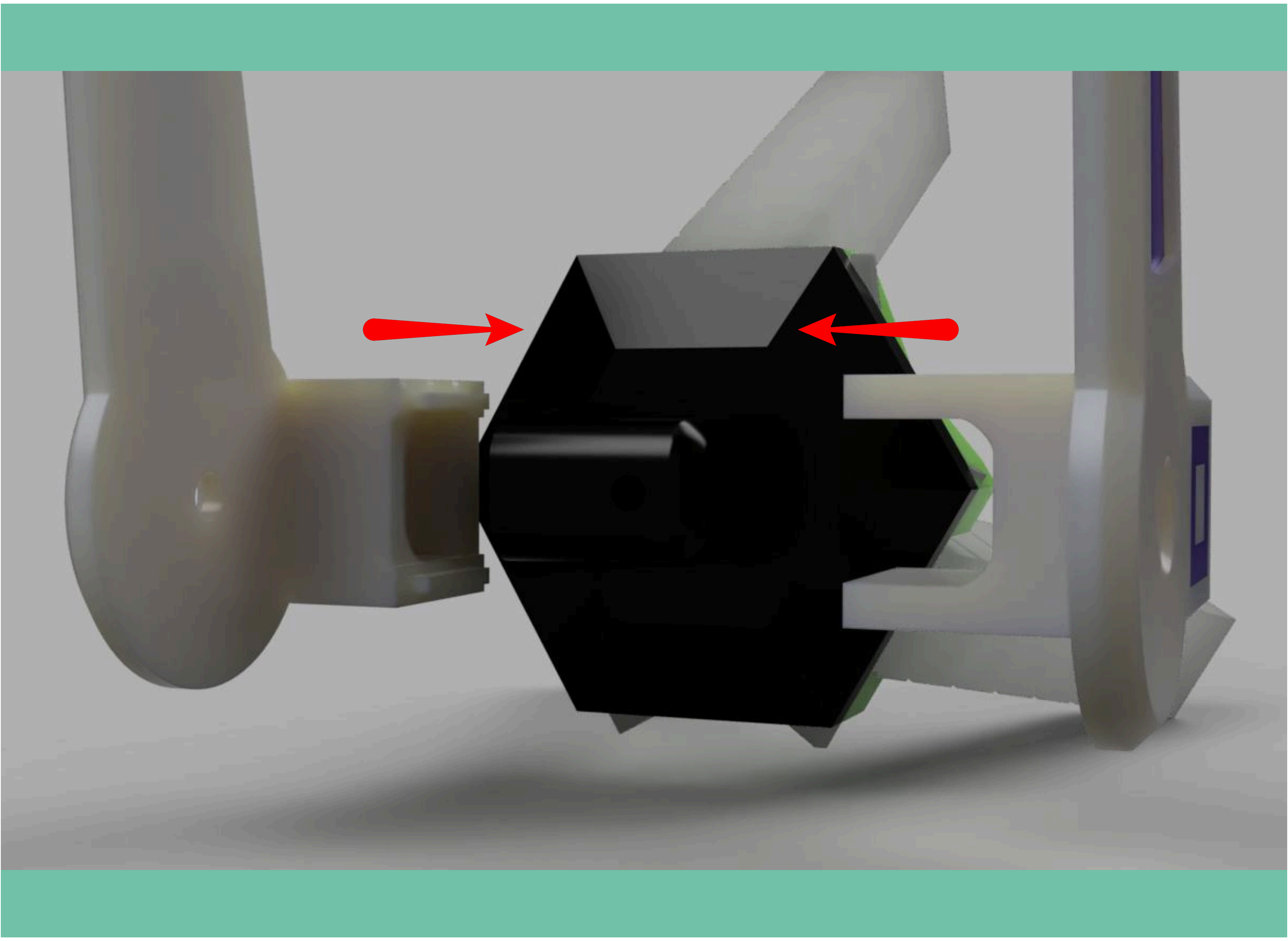
Assembly Guide

To fix the **clamp** in place, we will use a small **plastic screw**. Firmly press the **screw** down into the **green clamp** and twist simultaneously.



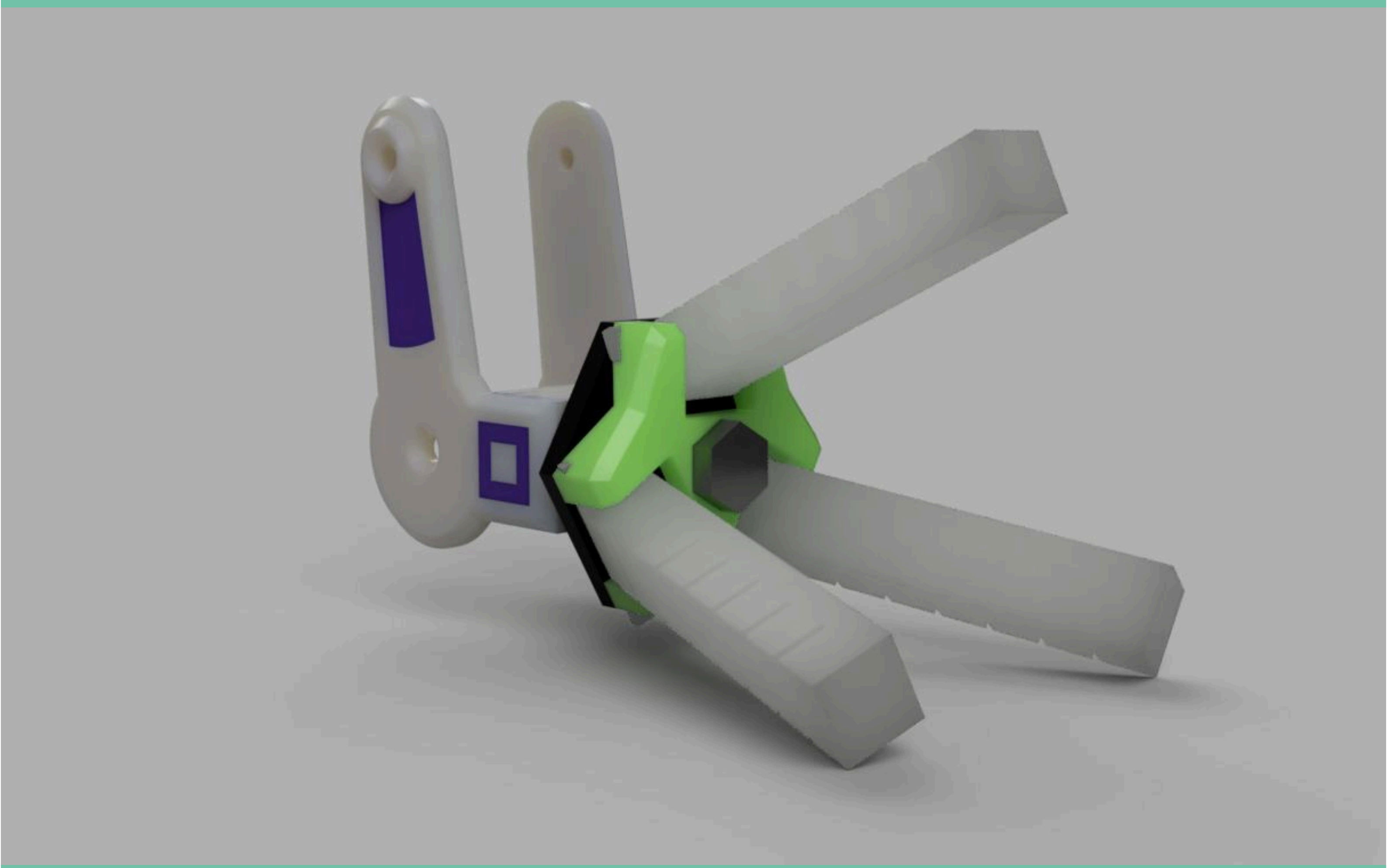
Assembly Guide

Later we will have to attach the **gripper** to the **robotic manipulator**. This attachment will be made possible by the wrist joint. Clamp the **finger mount** between the wrist segments as shown below.



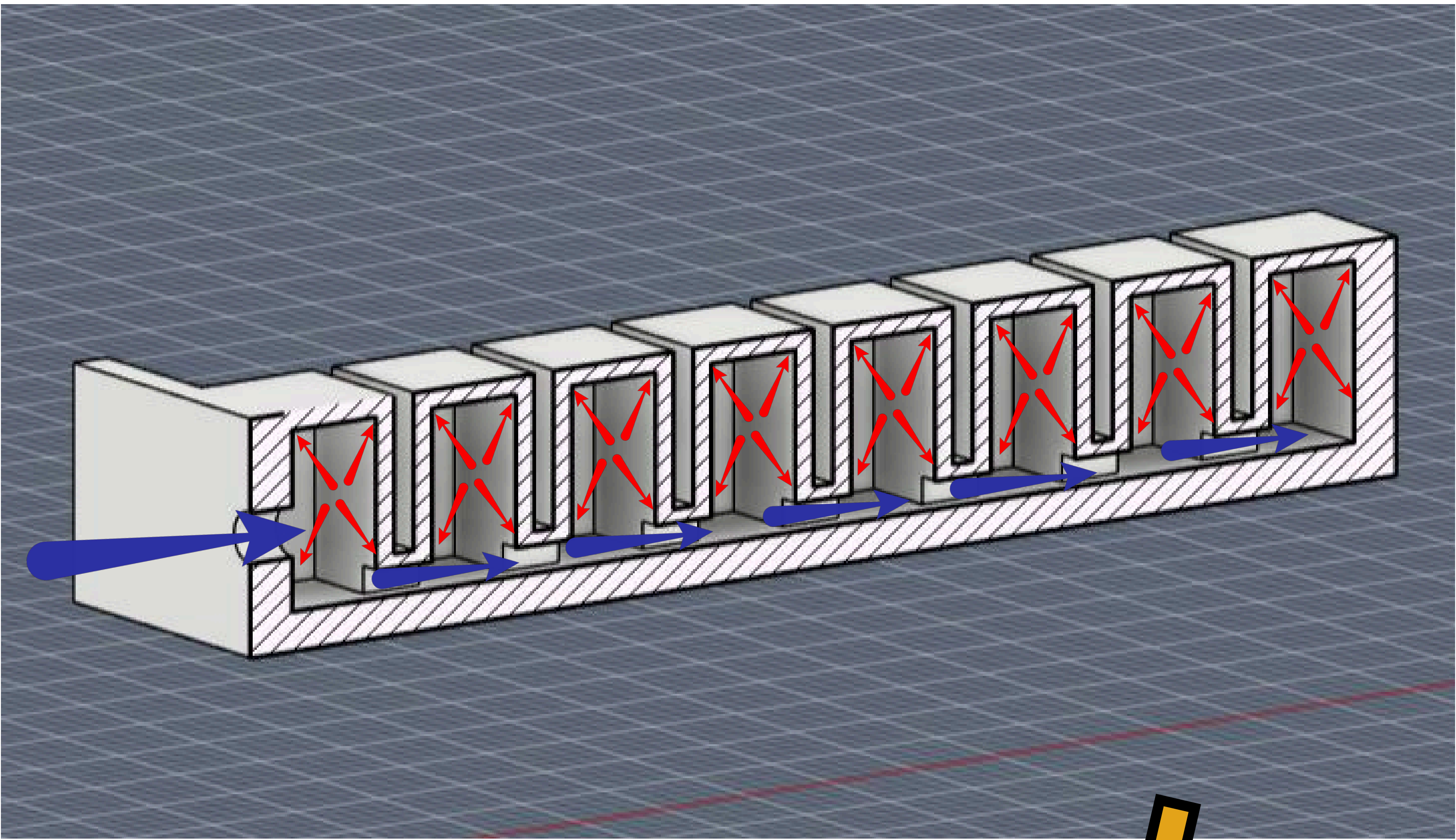
Assembly Guide

Great! Now we have the **gripper** assembled. But we still need a way to move the **fingers**. Let's see how we could accomplish that.

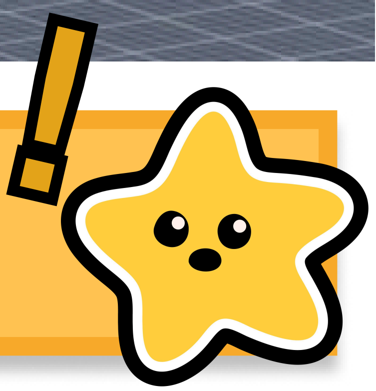


Assembly Guide

This is a cross-section of the **finger**. It contains eight small chambers in its structure. This structure is called a **Pneumatic Network** (PneuNet for short). By filling the finger up with air (blue arrows), the chambers expand (red arrows), creating a bending motion.
Because of the **compliant** nature of air and the silicone, the finger can bend **gently and safely** around objects, unlike rigid robotic grippers that require precise control.

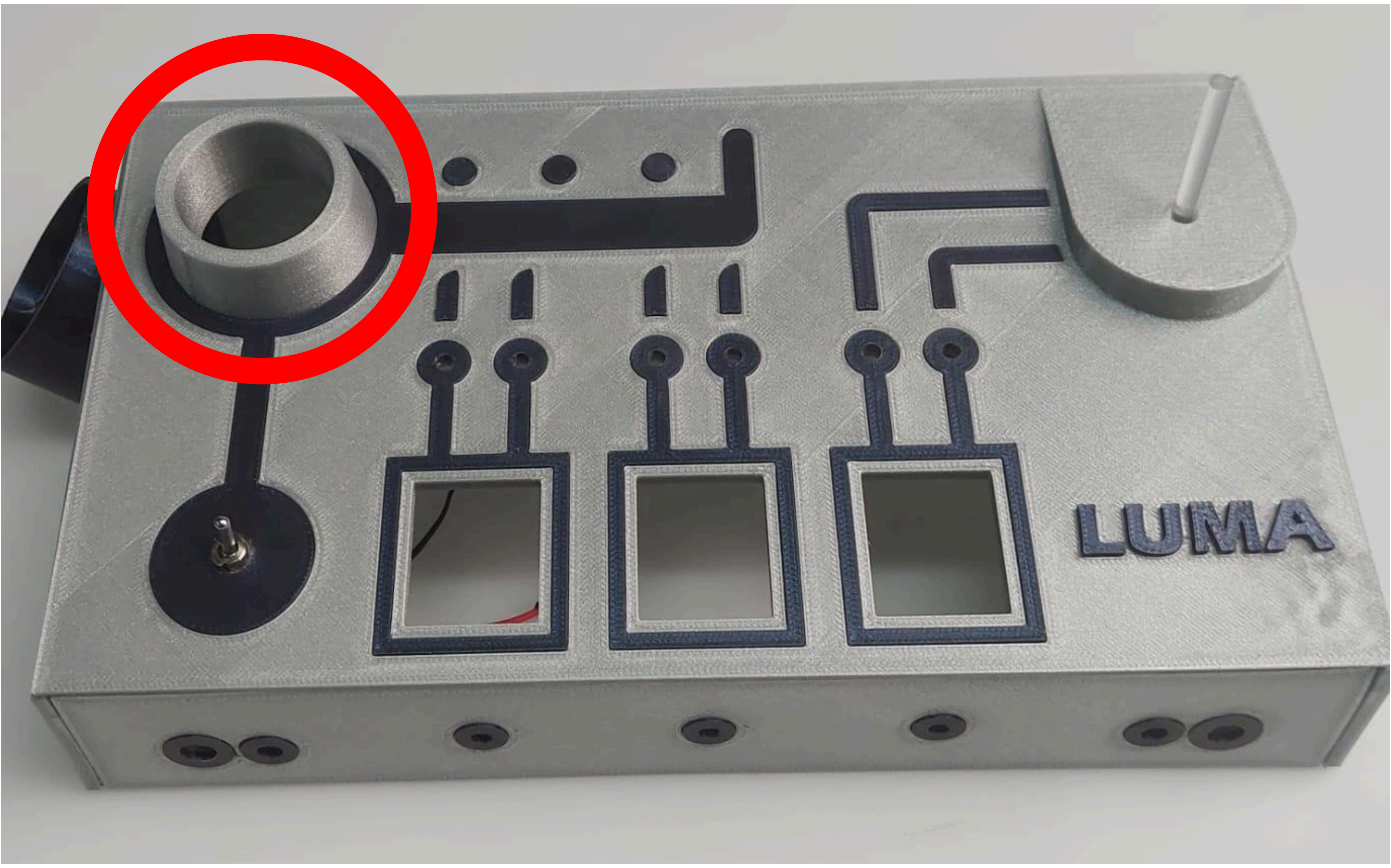


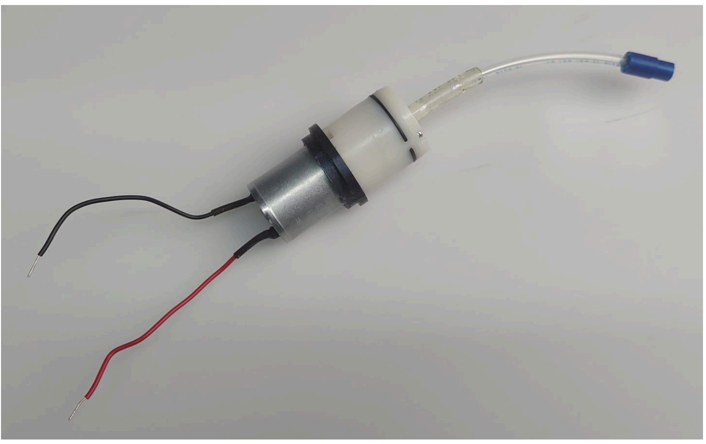
Soft robotics enables safe robotic interaction with **fragile** and **irregular** objects and humans!



Assembly Guide

Now that we know how we can move the **fingers**, lets set up a small **vacuum pump** that can inflate them.

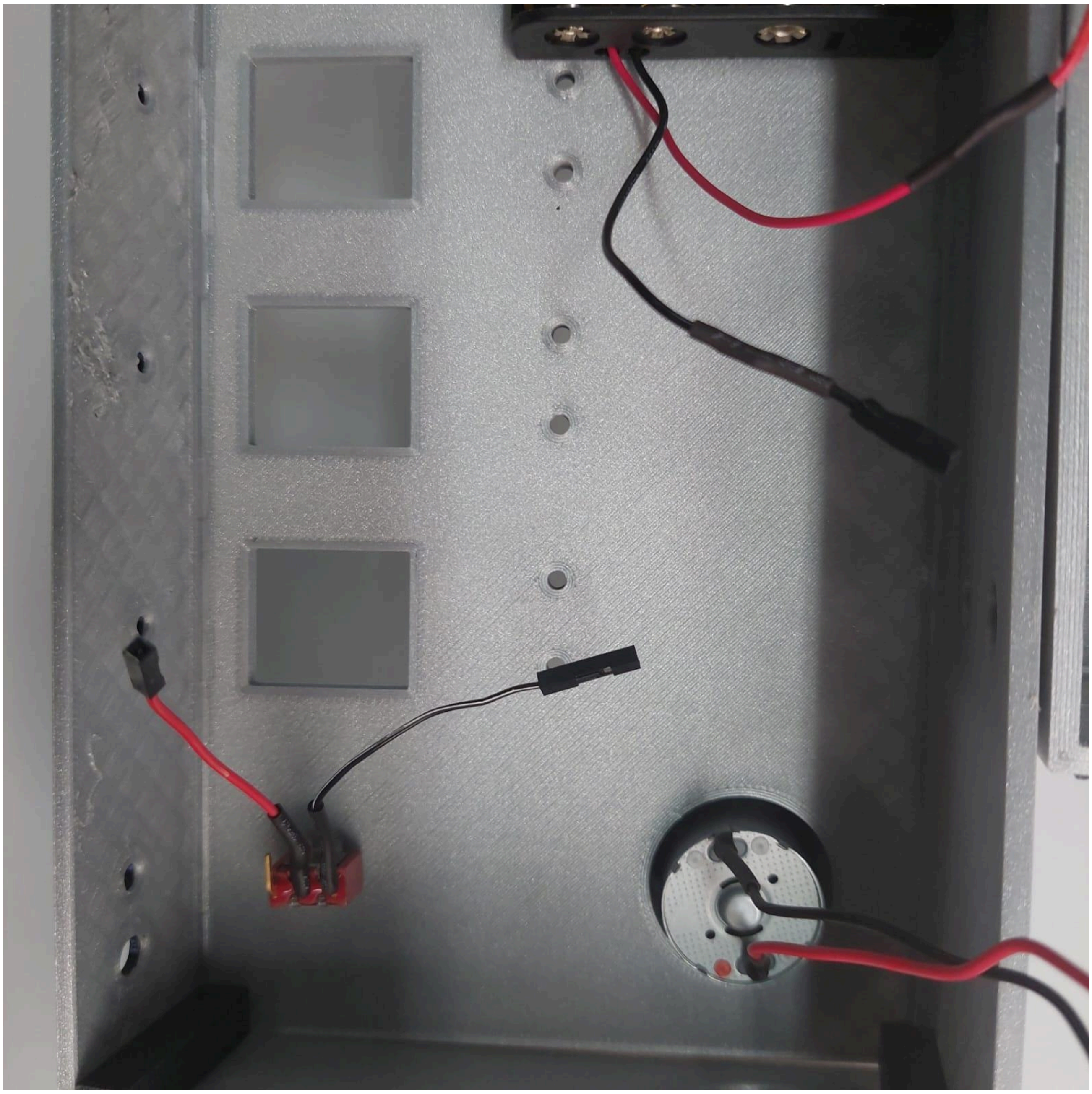




Grab the **pump** and place it with the wires down into the specified hole. Afterwards flip the **control panel** over.

Assembly Guide

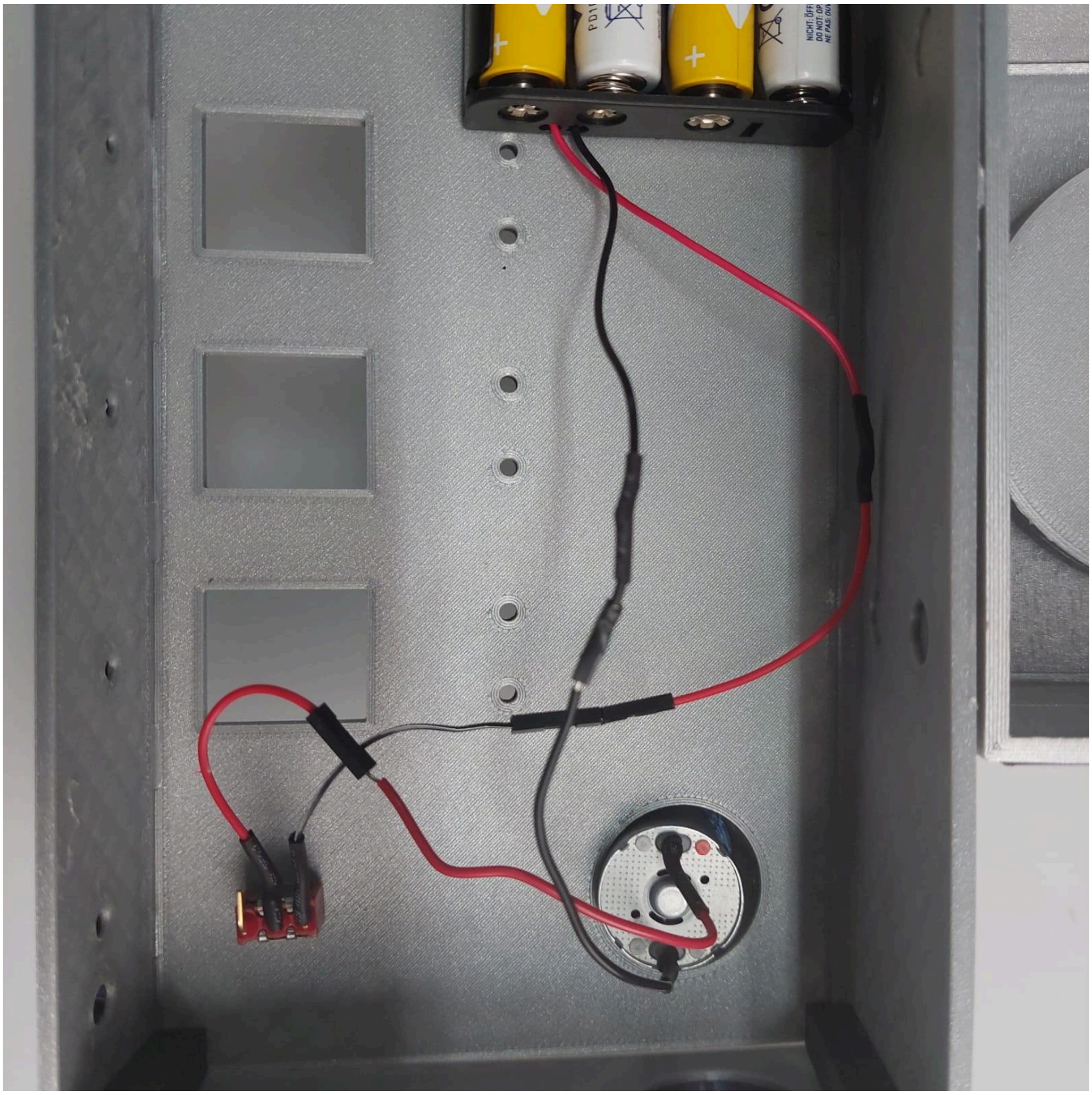
We will have to set up this simple electrical circuit. This simply connects the **battery pack** with the **pump**, with a **switch** in between.



Assembly Guide

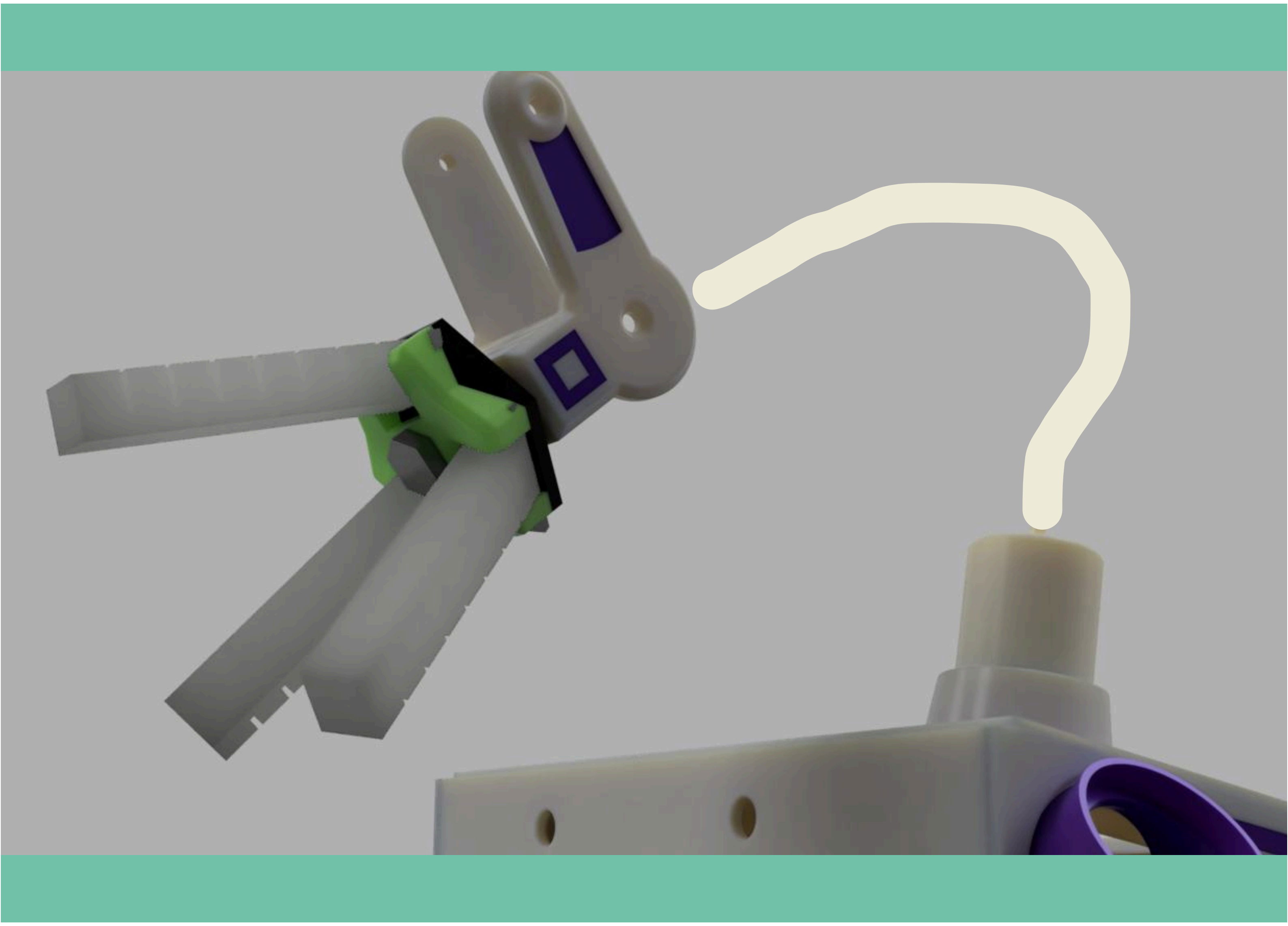
1. Connect the red wire of the **battery pack** to the black wire of the **switch**.
2. Connect the red wire of the **switch** to the red wire of the **pump**.
3. Finally, connect the black wire of the **pump** to the black wire of the **battery pack**.

This allows us to turn on the pump whenever we want using the switch!



Assembly Guide

Amazing! Now we can connect the pump to the intake of the gripper. Try picking up some things with your **newly assembled soft gripper**! :)



Assembly Guide

Now that you have assembled your very own **soft robotic gripper** and actuated it with a **pump**, you have just explored some of the key ideas behind **soft robotics**! You used air to create a **gentle, flexible and compliant motion**! :)

But this **soft gripper** needs some help still. To position the gripper correctly we need to build something else:
A 3 Degrees of Freedom pneumatic robot arm.

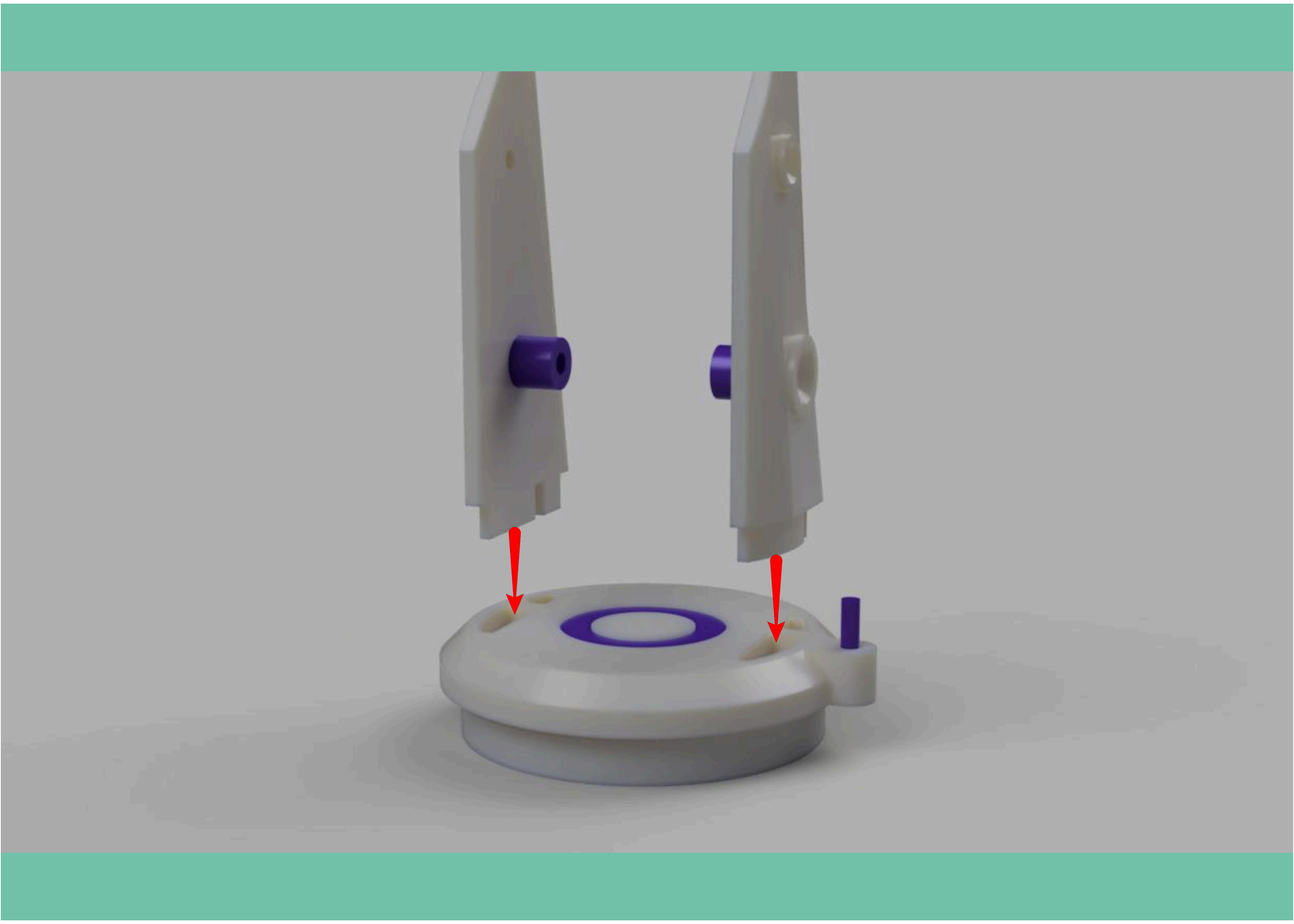
In the next steps you will learn the basics of pneumatic systems:

- How do pneumatic motors work.
- How to control air flow using valves.
- How to generate your own compressed air.

Let's get to it!

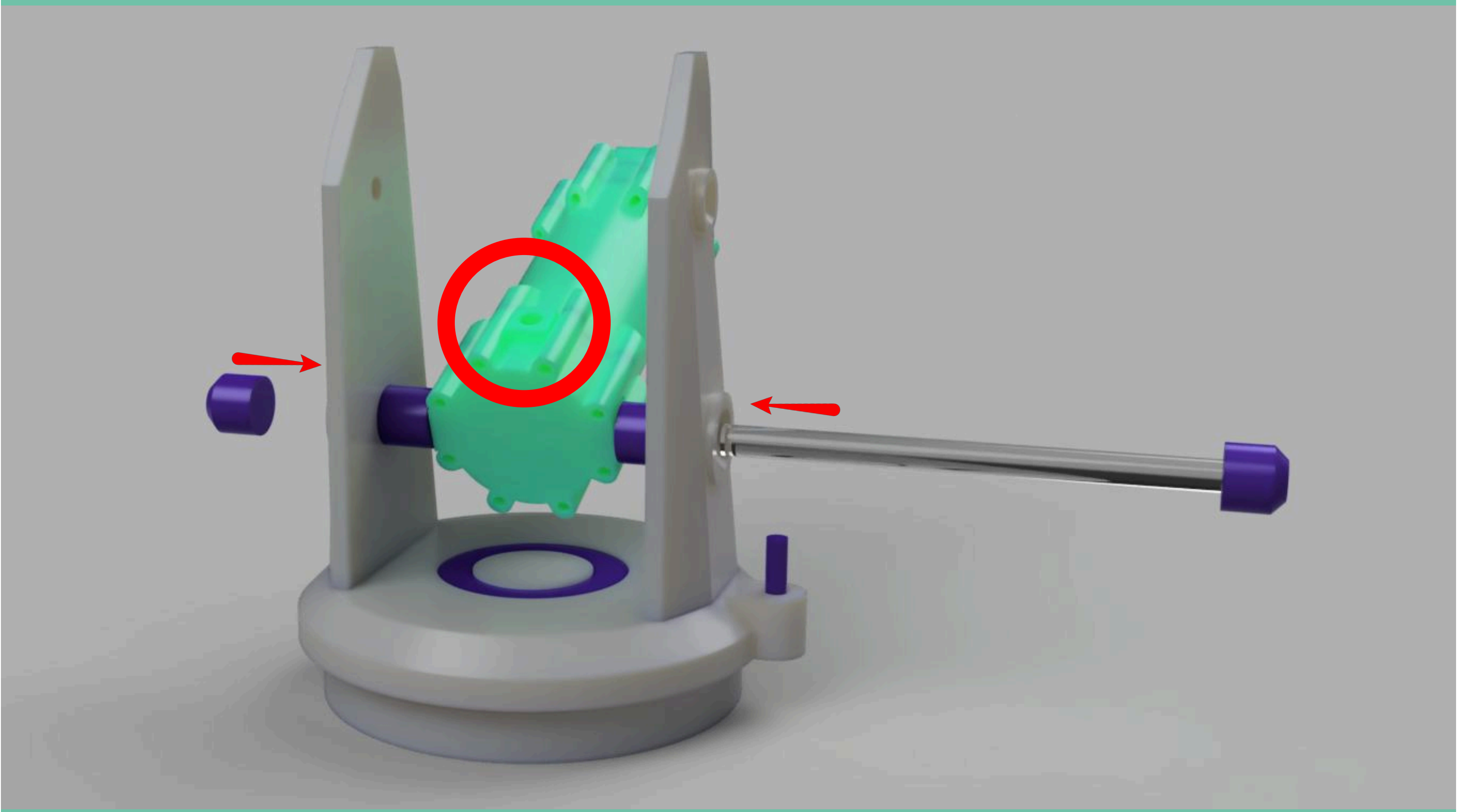
Assembly Guide

Now that we have a soft gripper we will have to build it an arm. Let's start the assembly of your robotic manipulator with the **rotating base**.

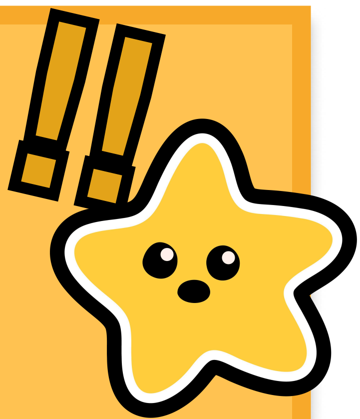


Assembly Guide

To the base we will attach the first **pneumatic cylinder**. Position the **cylinder** between the **brackets** and slide in the **axis**. This **axis** should be the longest one available. With the **axis** through, put on the **cap** at the other end.

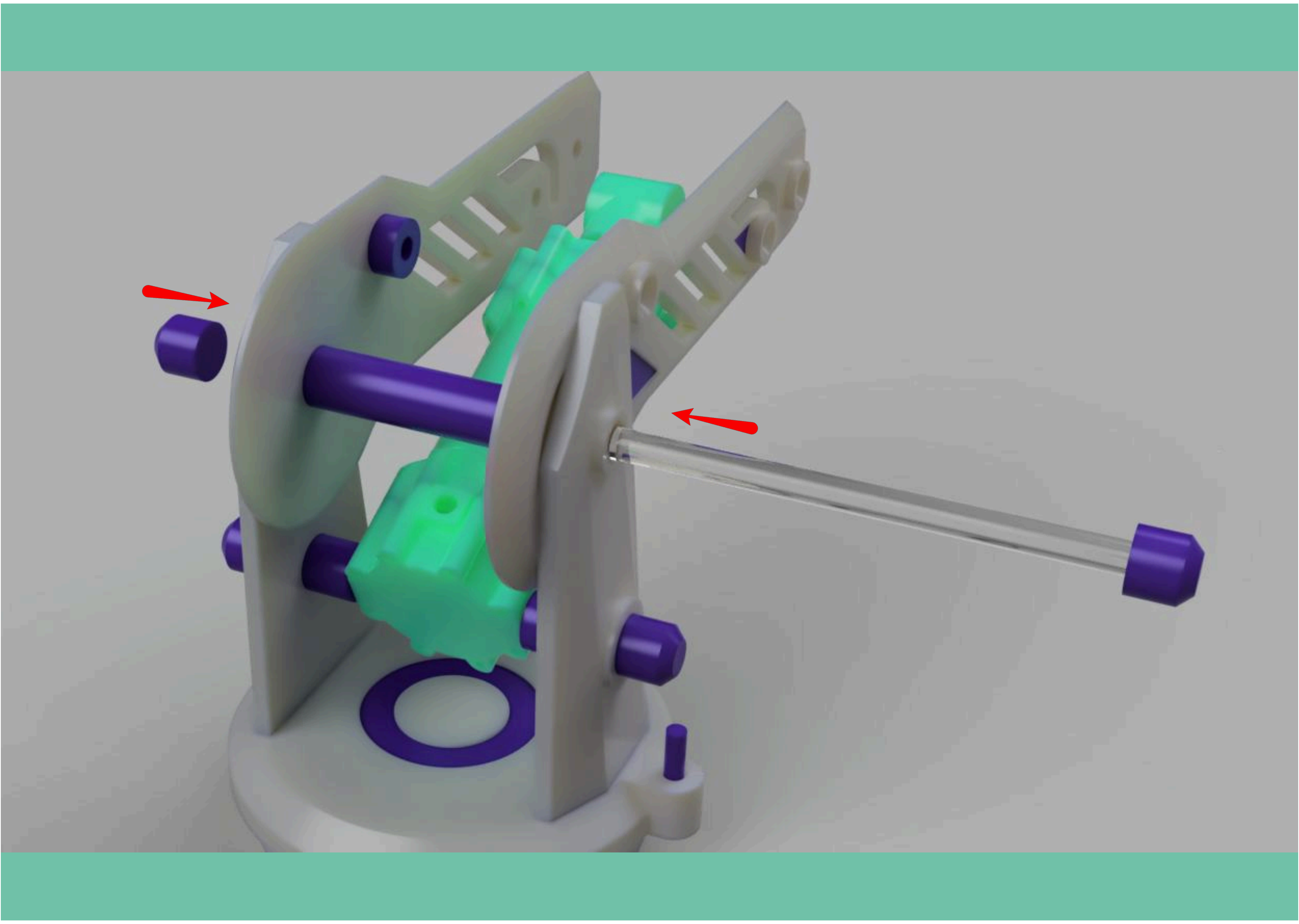


WATCH OUT! All 3 cylinders have distinct configurations. The holes for air-intake are different between them. This cylinder should have opposing air-intakes, with the one closest to the axis pointing up (circle).



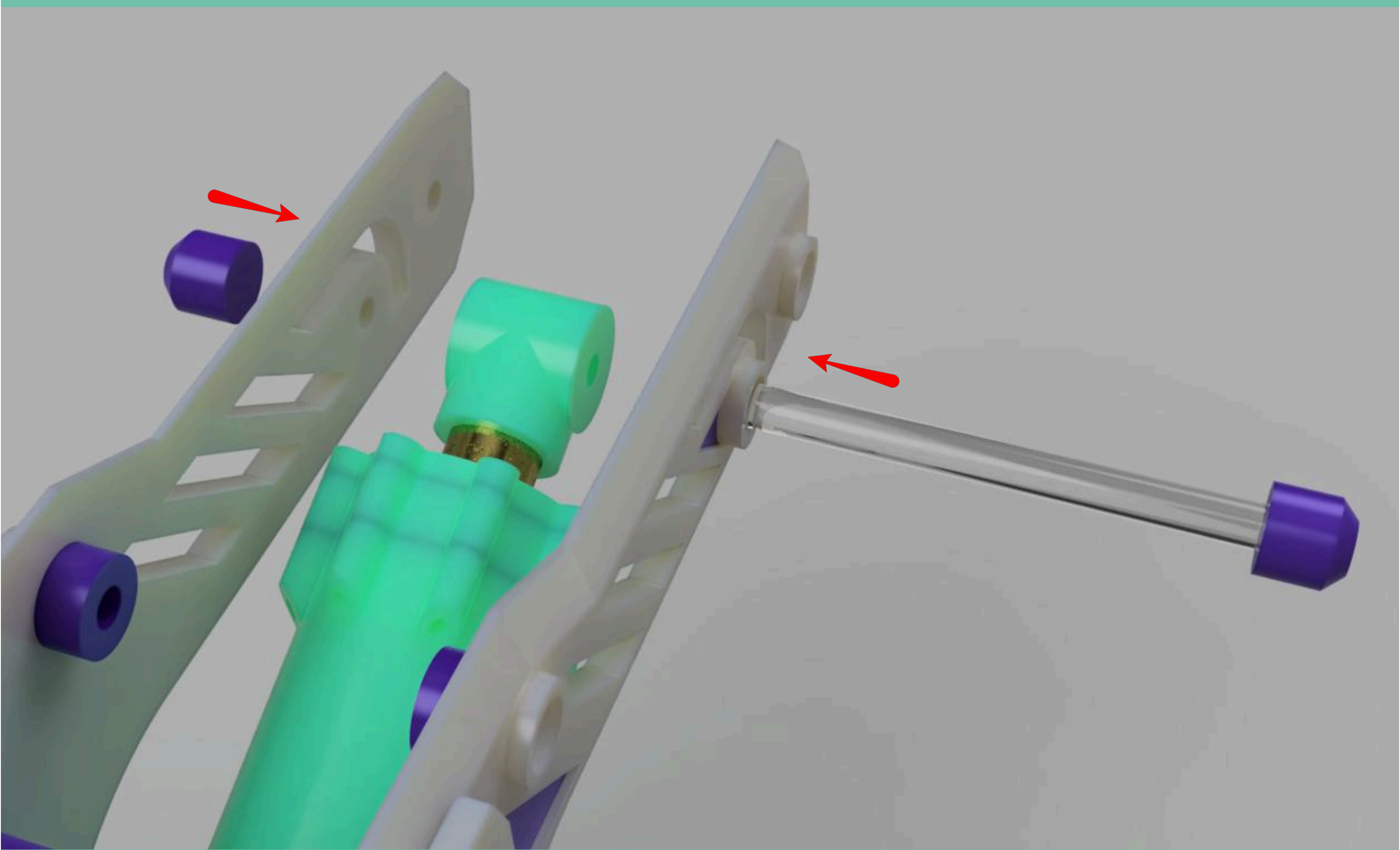
Assembly Guide

Now we will attach the **upper arm**. This is the part that the first **cylinder** is going to move. Position the two parts of the upper arm and slide in the **axis** (longest one now available), Then again, place the **cap** at the other end



Assembly Guide

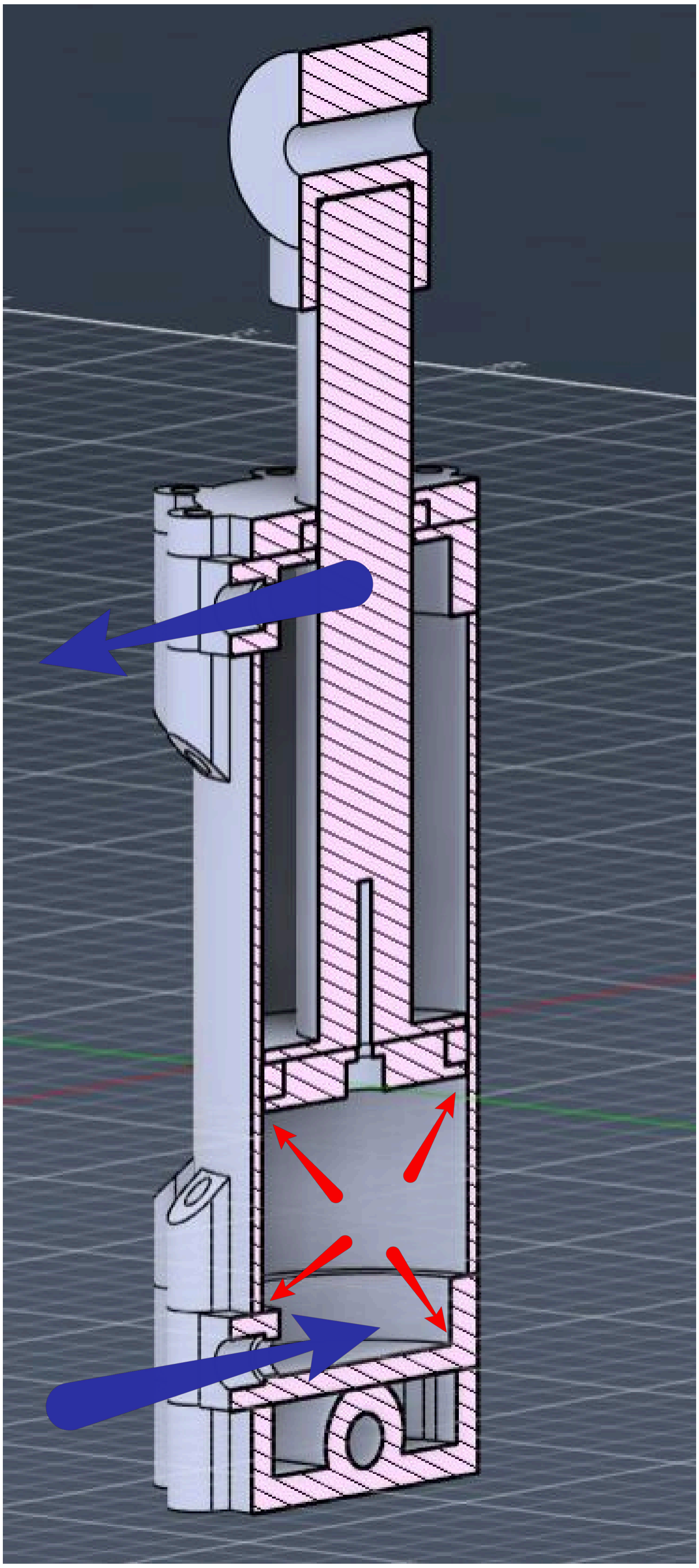
Now we will attach the **piston** of the **cylinder** to the other end of the **upper arm** in the same way as before. Try extending the **piston** yourself using your hands. How is **air pressure** going to move this **piston**?



But how is the piston going to move without using your help?

Assembly Guide

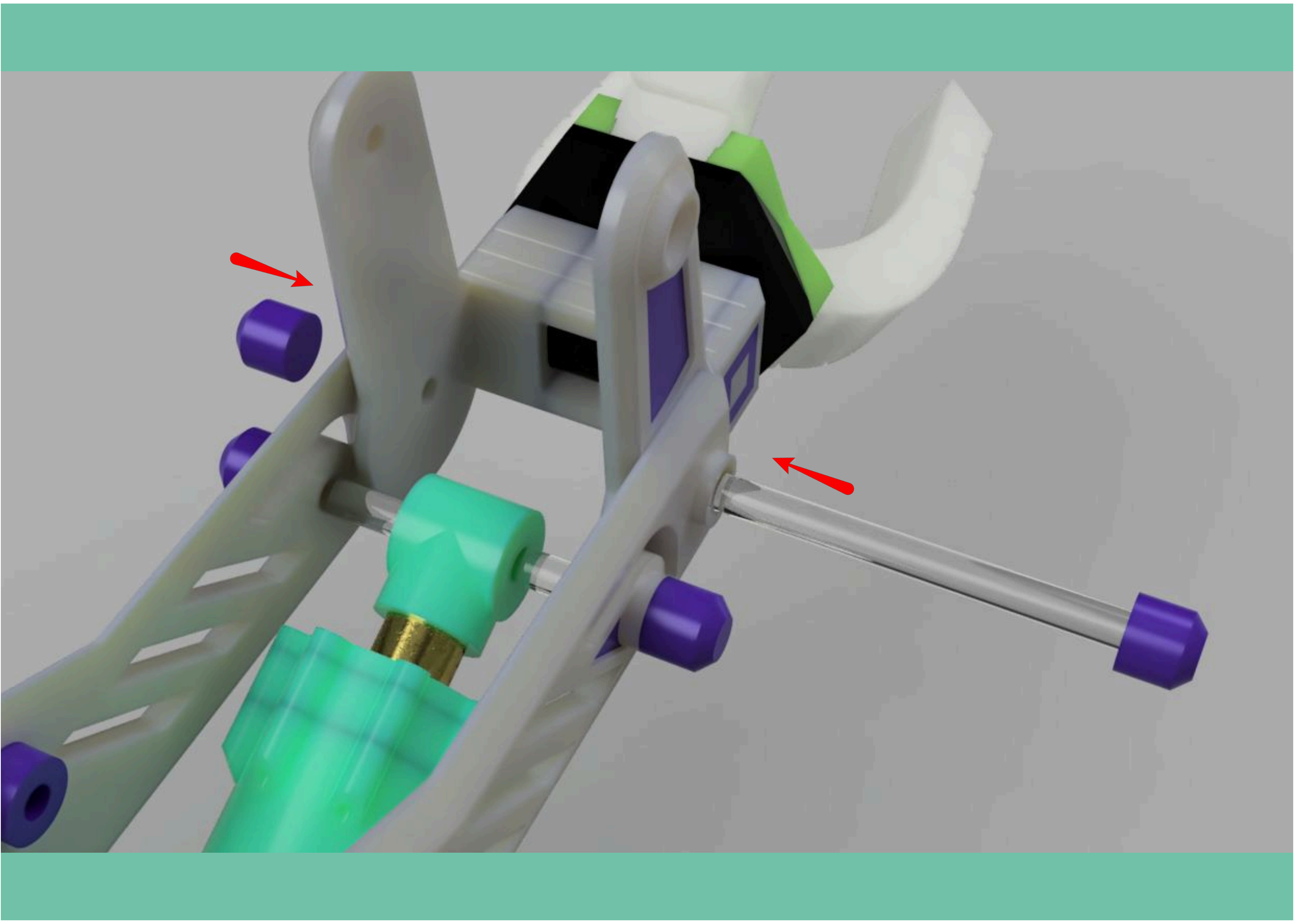
Inside of the **cylinder** is a **piston** that moves when air is pumped into either side of the **cylinder**. Air enters one side and builds up pressure, moving the piston in the opposite direction. The air on the other side is pushed out and exhausted. This piston then pushes against parts of the robotic manipulator, and this is how the robotic manipulator moves!



Try pressing down the piston while keeping the air-intakes covered with your finger and see what happens!

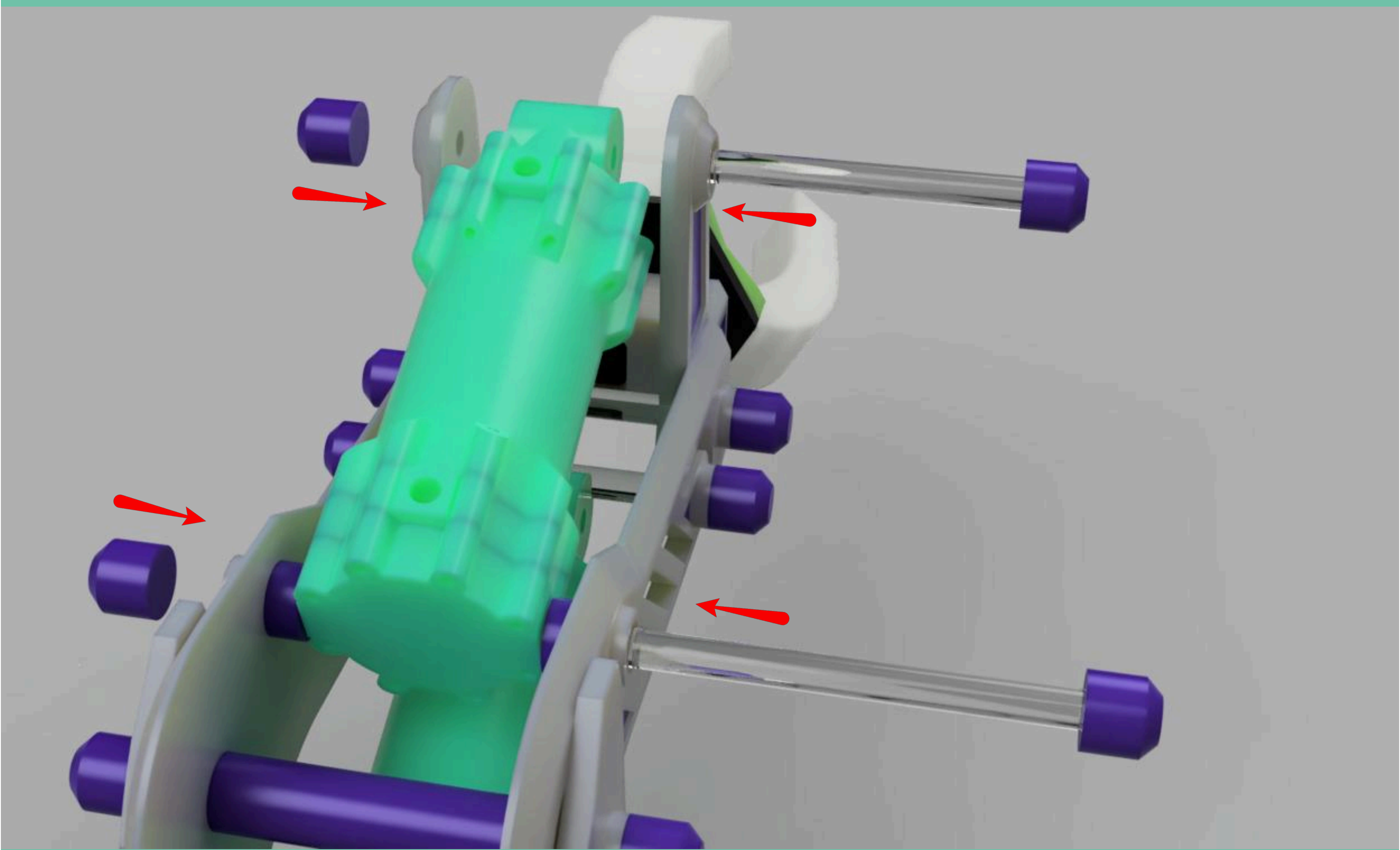
Assembly Guide

Now that we know how the **cylinders** work, lets finish the rest of **the arm**. Attach the **gripper** we made earlier using another **axle**. Slide the axle through like shown below, the same as before.

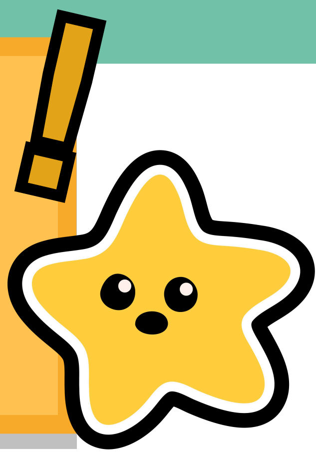


Assembly Guide

Now attach the second **cylinder**. Remember the different air-intake configurations of the **cylinders** like the first one. This **cylinder** should be the one with both air-intakes pointing up

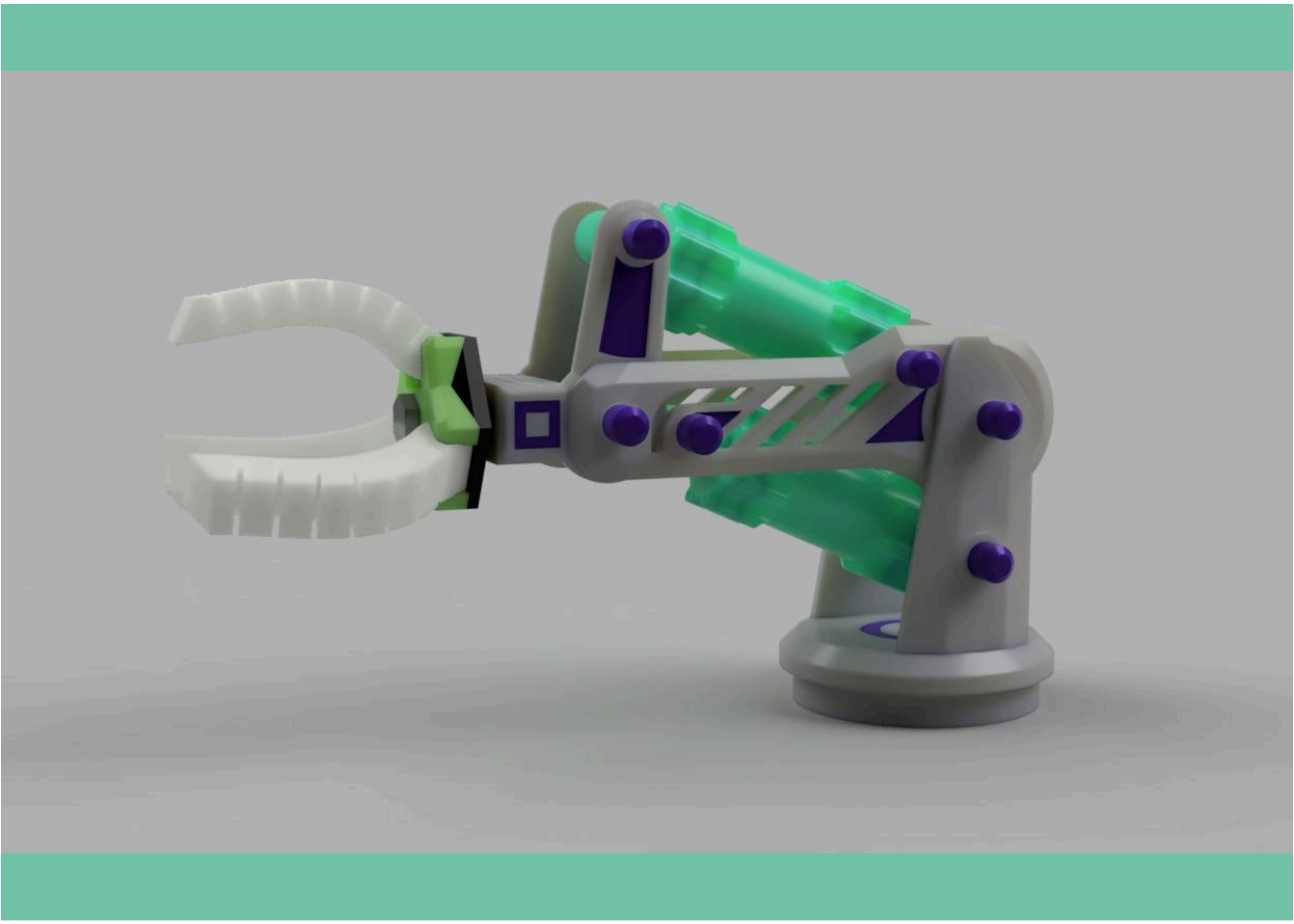


The air-intakes have to be different so it will be easier to insert tubing in later steps.



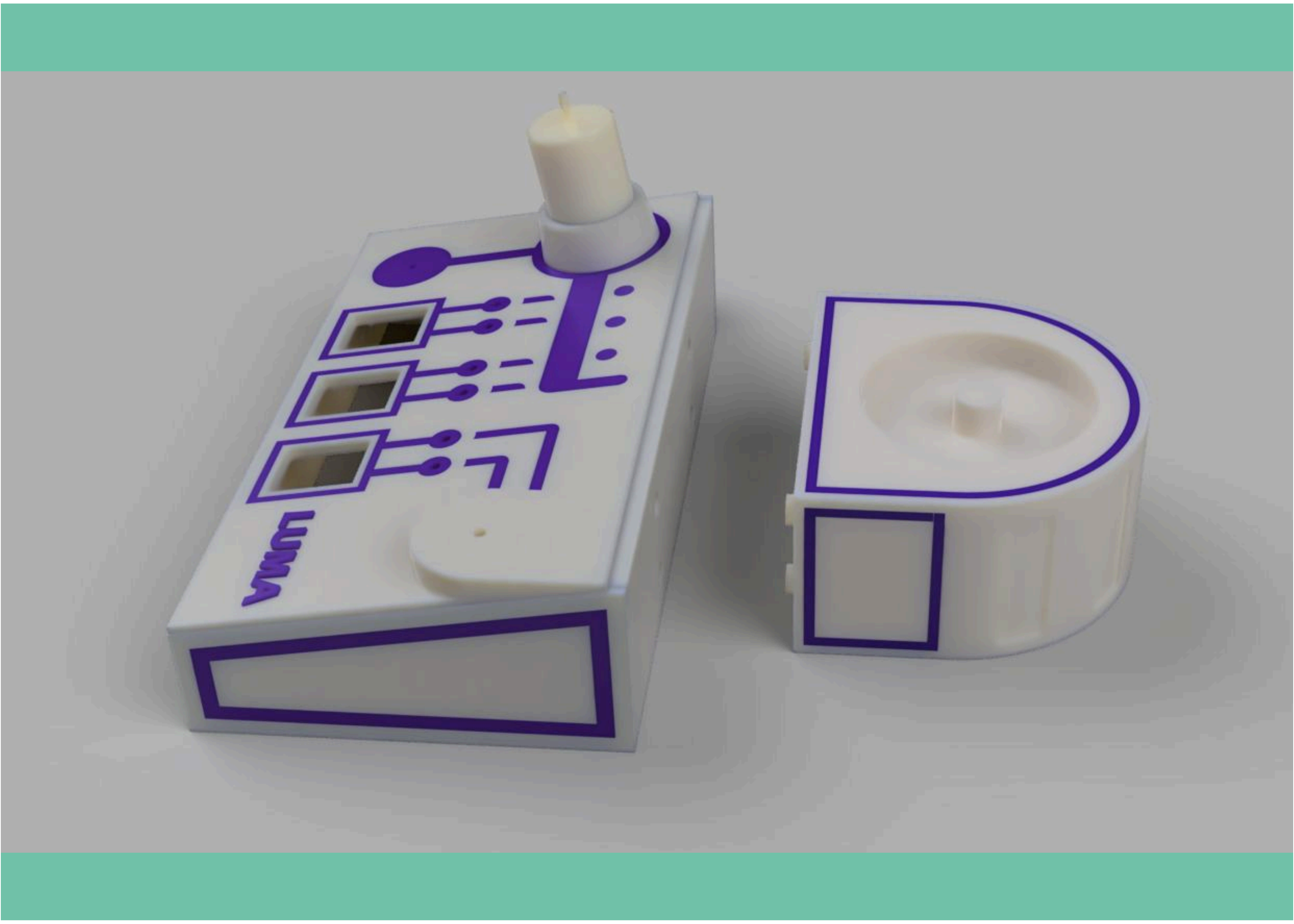
Assembly Guide

Perfect! Now we have a way to position the **soft gripper**. However, we still need to be able to **control** the **cylinders**. Let's see how we can accomplish that.



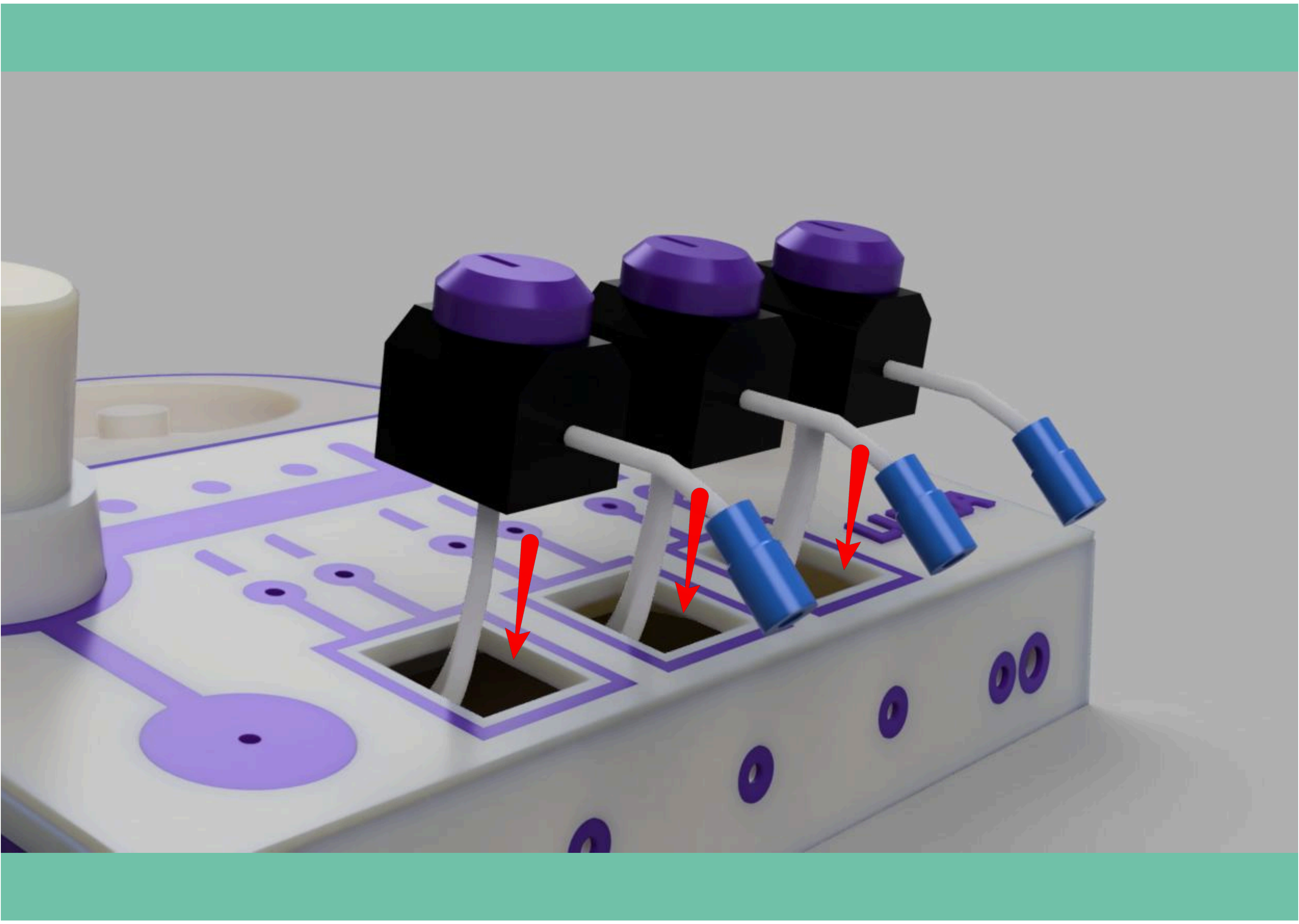
Assembly Guide

First, grab the **control panel** we used earlier to fit the **vacuum pump** for the **soft gripper**. Let's attach the **base** on which the **arm** will rotate



Assembly Guide

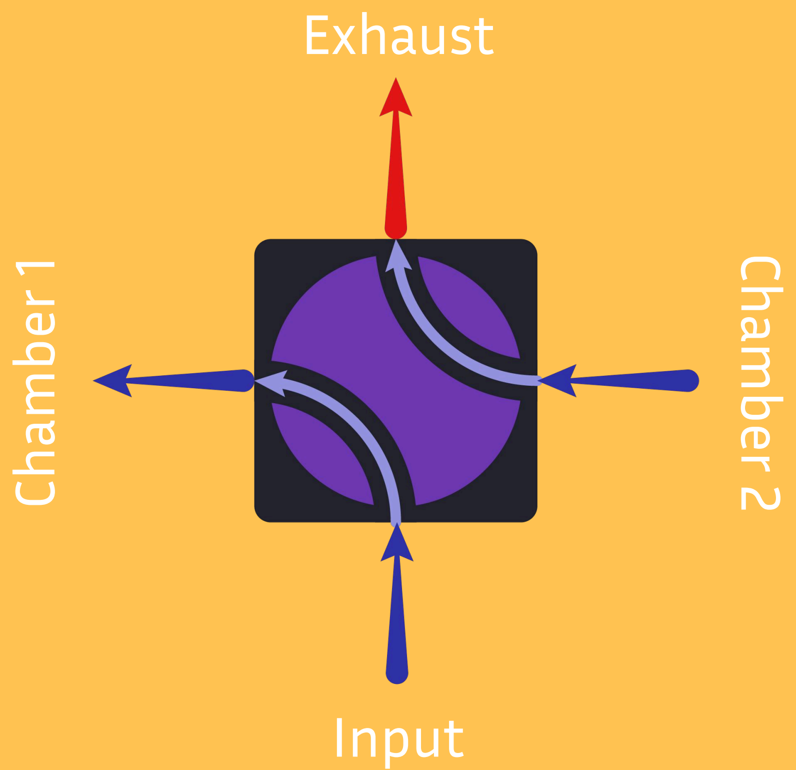
Now let's add some more things to the **control panel**. We now know that the **cylinders** can actuate something using pressurized air. But we still need a way to get that pressurized air to the designated chamber of the **cylinder**. To this end, we will use three **valves**.

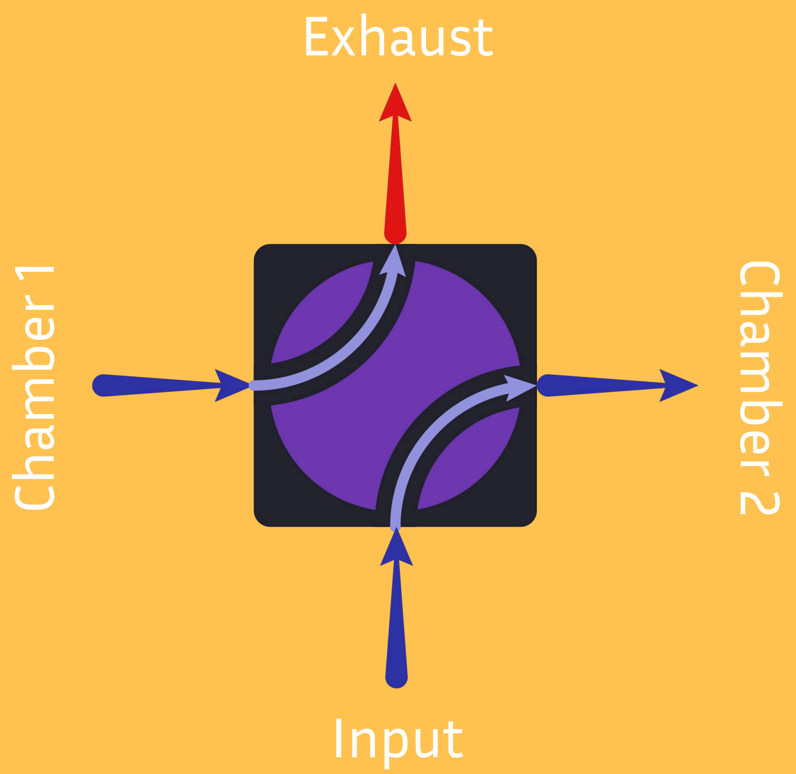


Push down the three **valves** in the rectangular holes on the **control panel**. Make sure the turning knob is pointing upwards, like in the picture above.

Assembly Guide

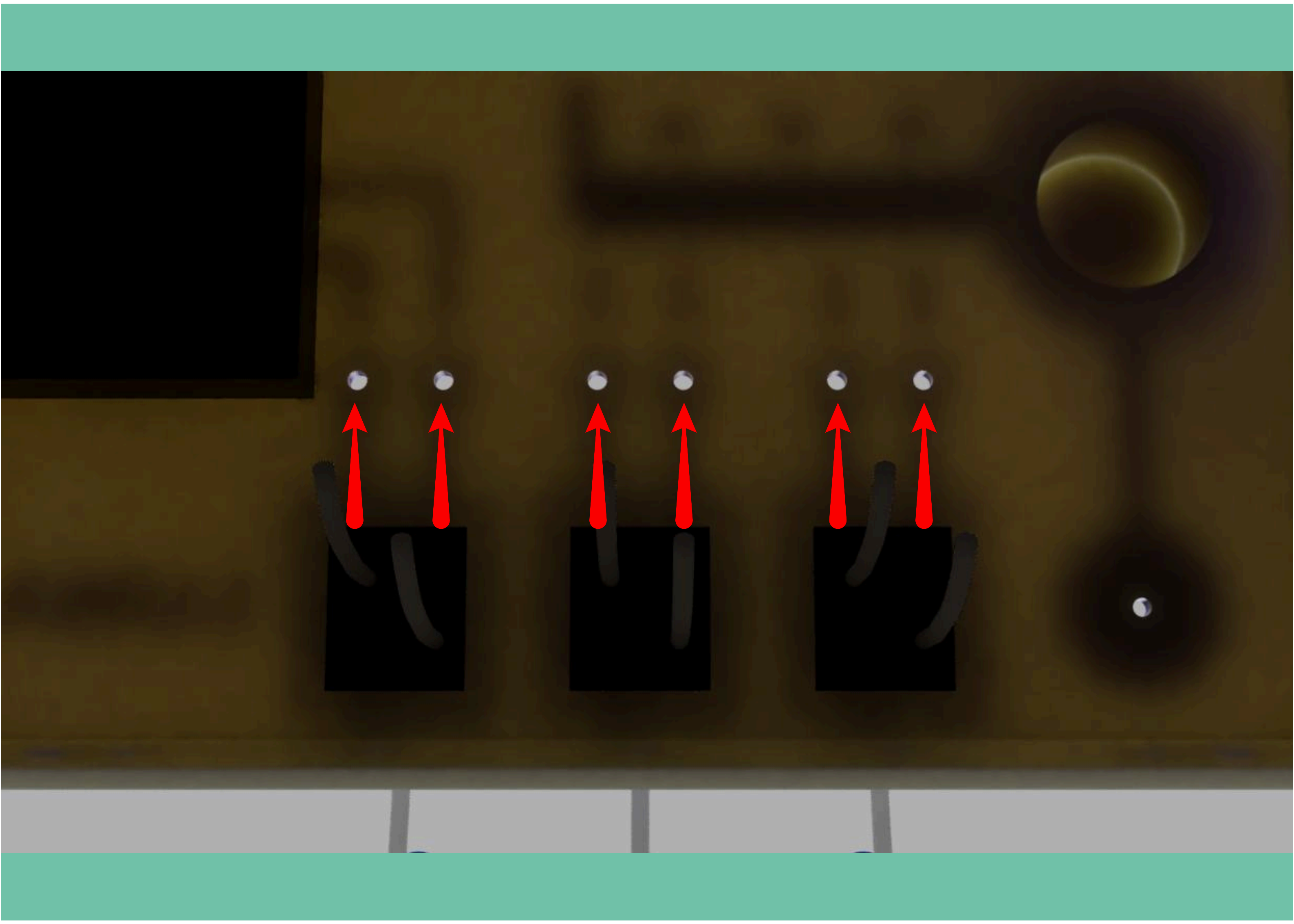
The valves will direct the air flow to the correct chamber inside the cylinder. By turning the knob, the air channels of the chambers are switched between input and exhaust (red arrow).





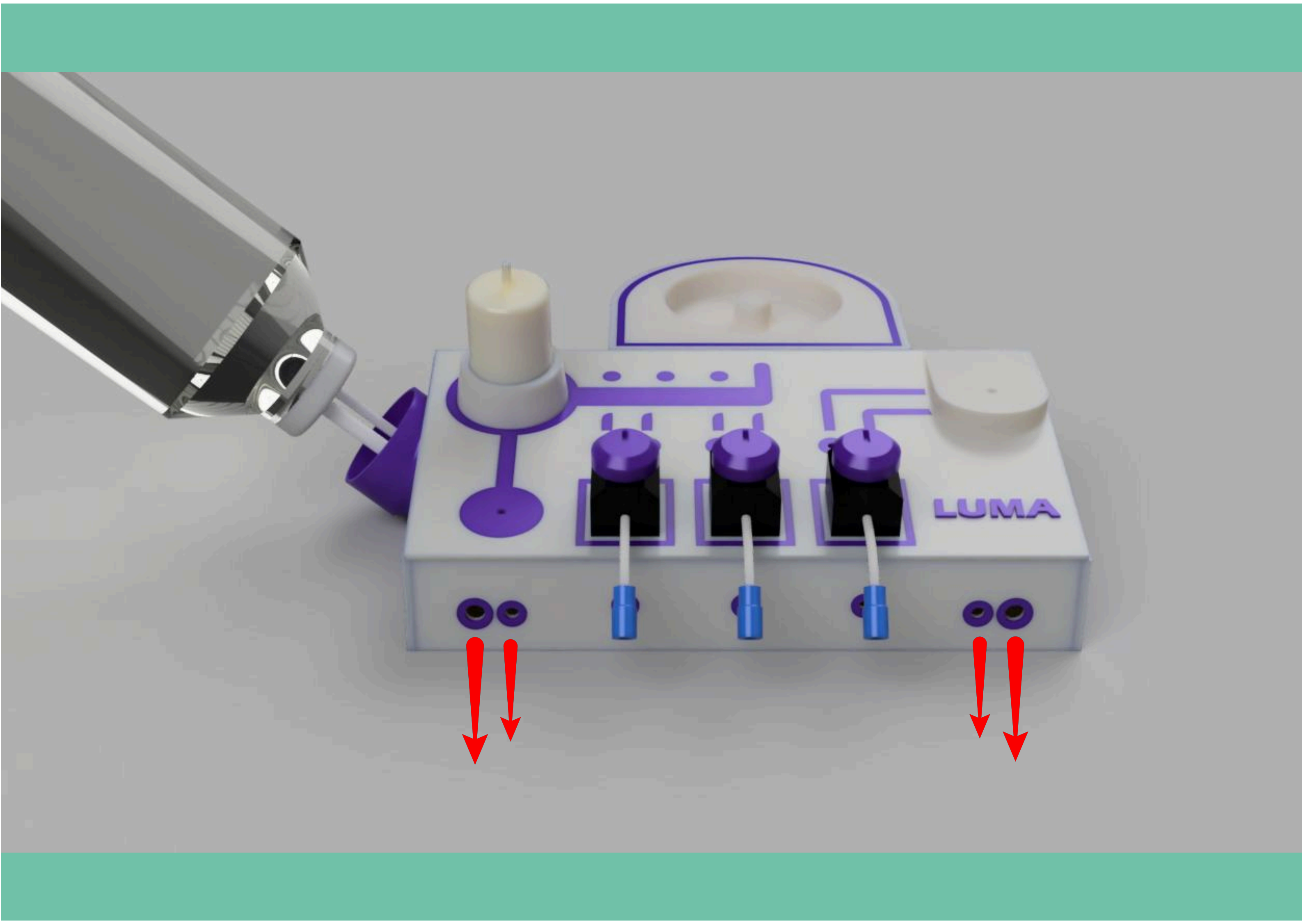
Assembly Guide

Now that we have a better grip on how the valves work, let's finish setting them up. String the tubes through the holes as shown in the picture below.



Assembly Guide

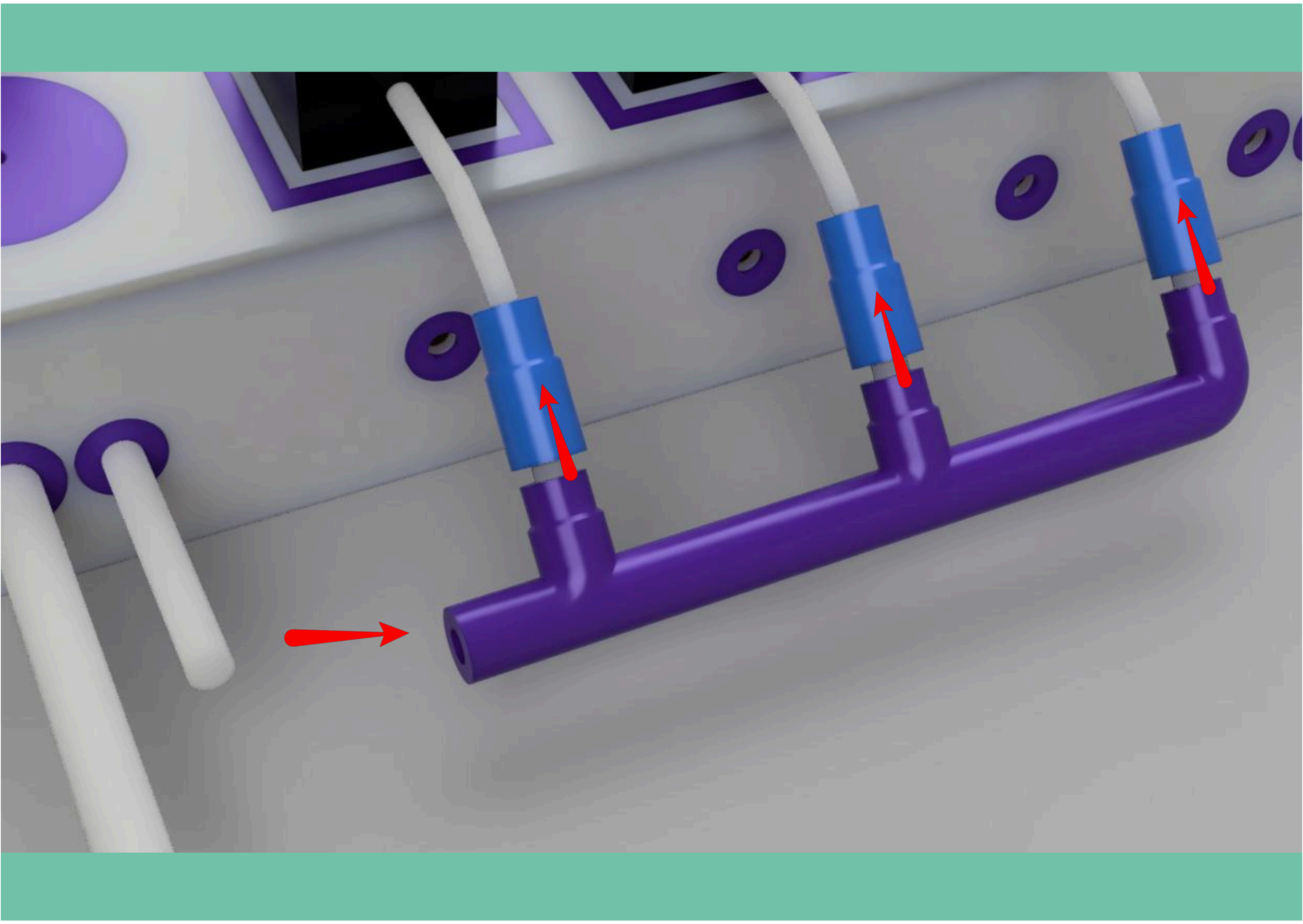
To make sure the **pneumatic system** has a small reservoir of air it can use for a little while, we will have to add an **air tank** in the form of a **PET-bottle**.



Go ahead and run the **tubes** from the **PET-bottle** through either the left or right side holes in the **control panel**. Choose a side based on which leg you want to use for the **foot-pump**.

Assembly Guide

To finish setting up the control panel, we will have to connect the **air tank** to the **valves**. We will do this using the **three-way splitter** shown below.

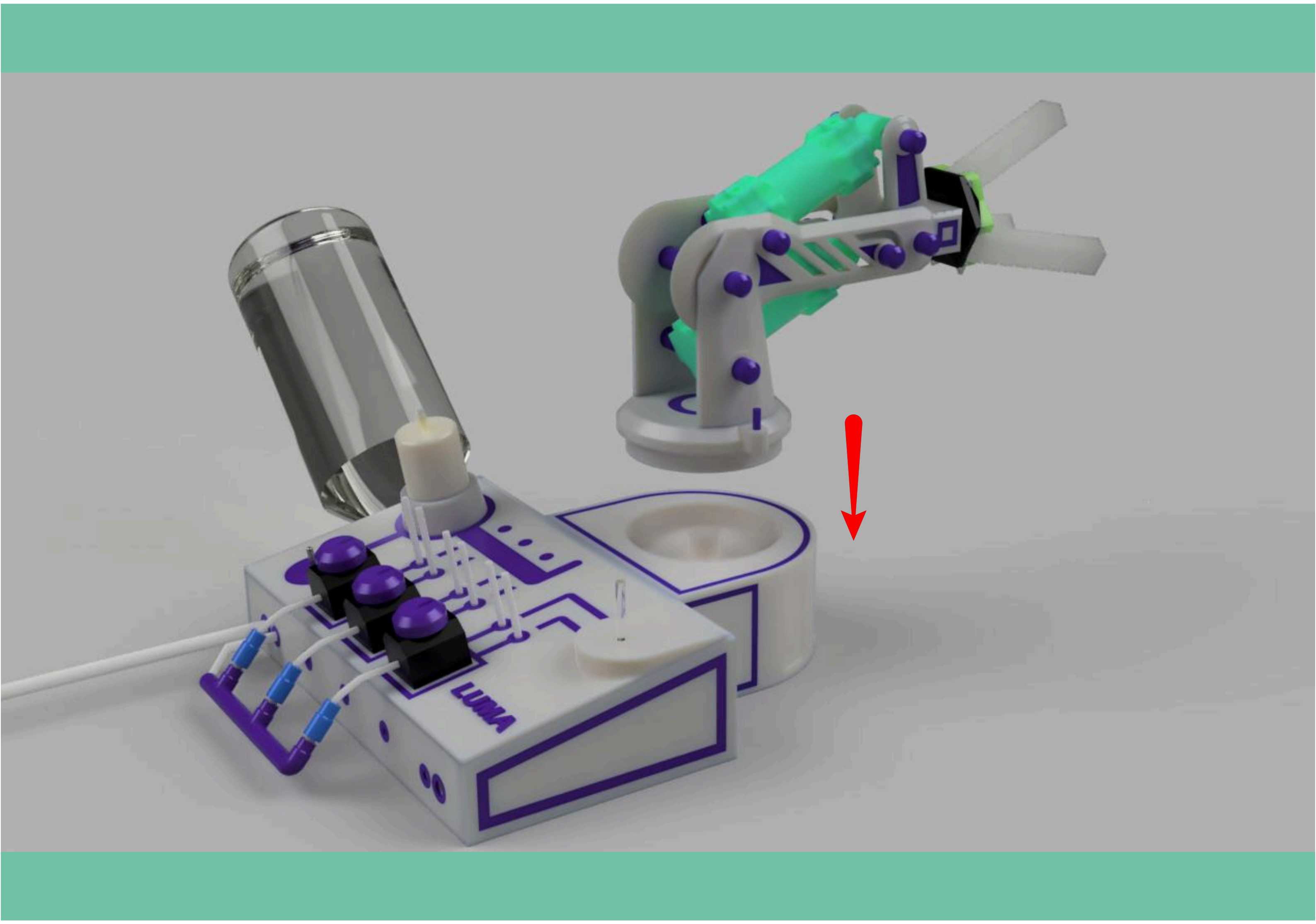


Assembly Guide

Perfect! Now that the **control panel** is finished, we can add the **robotic manipulator** to the **round rotation-base.**

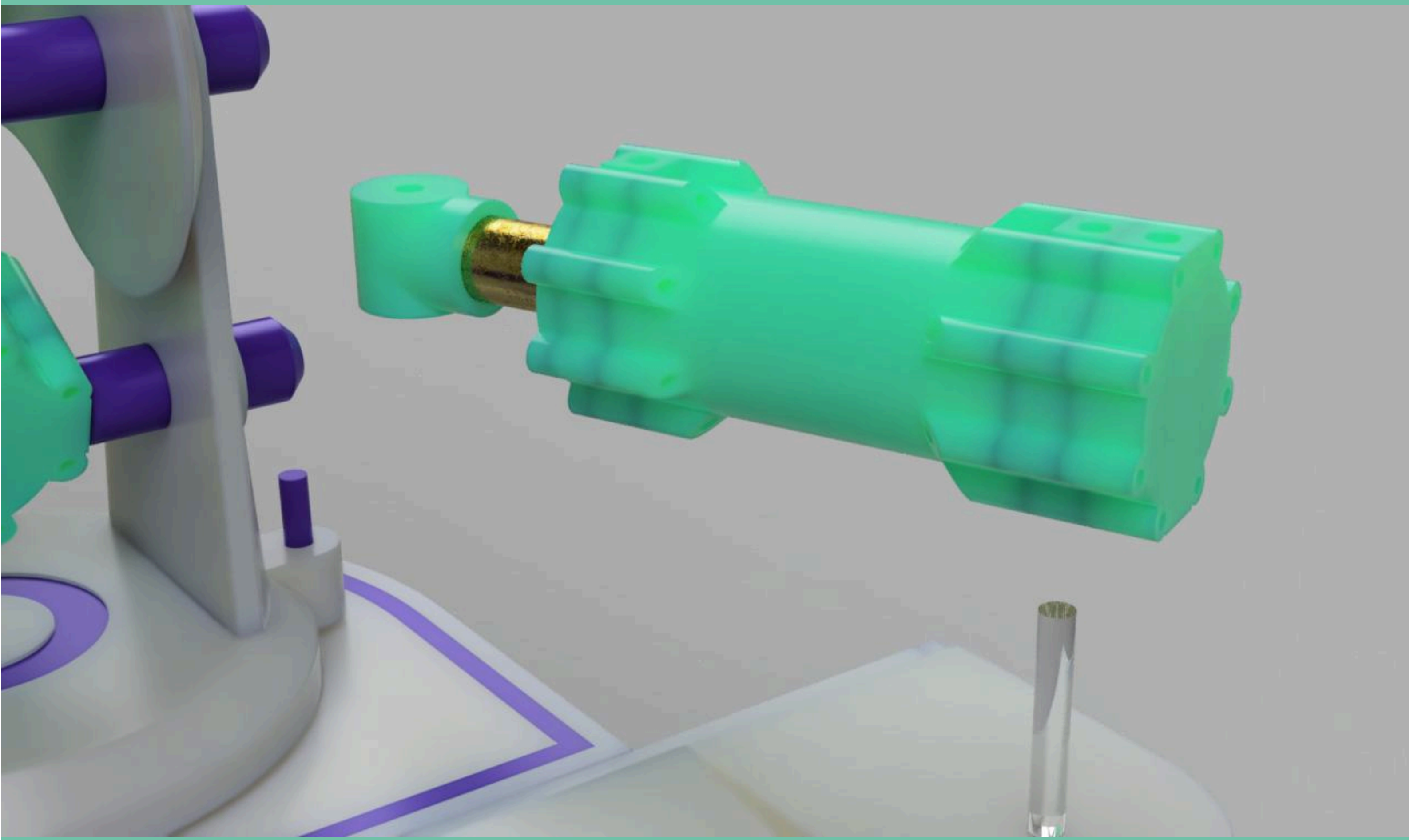
Assembly Guide

Insert the round base of the **robotic manipulator** into the **control panel**.

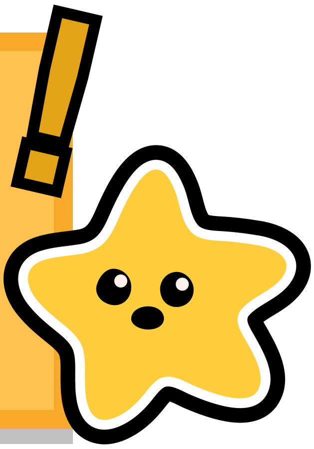


Assembly Guide

Now add the final **cylinder** to connect the **robotic manipulator** to the **control panel**. This **cylinder** will be responsible for rotating the entire arm.

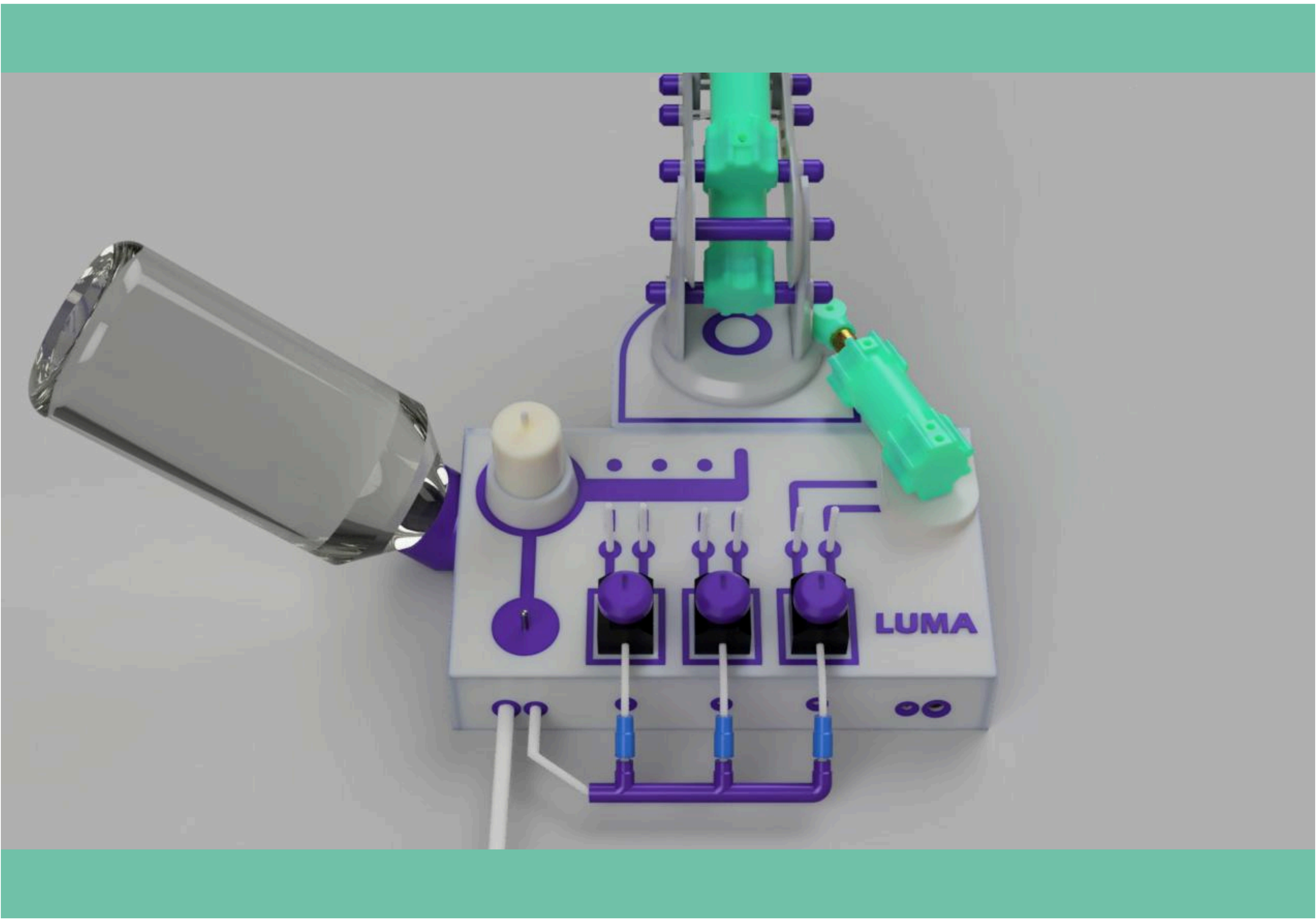


Make sure the air-intakes for the cylinders are pointing up!



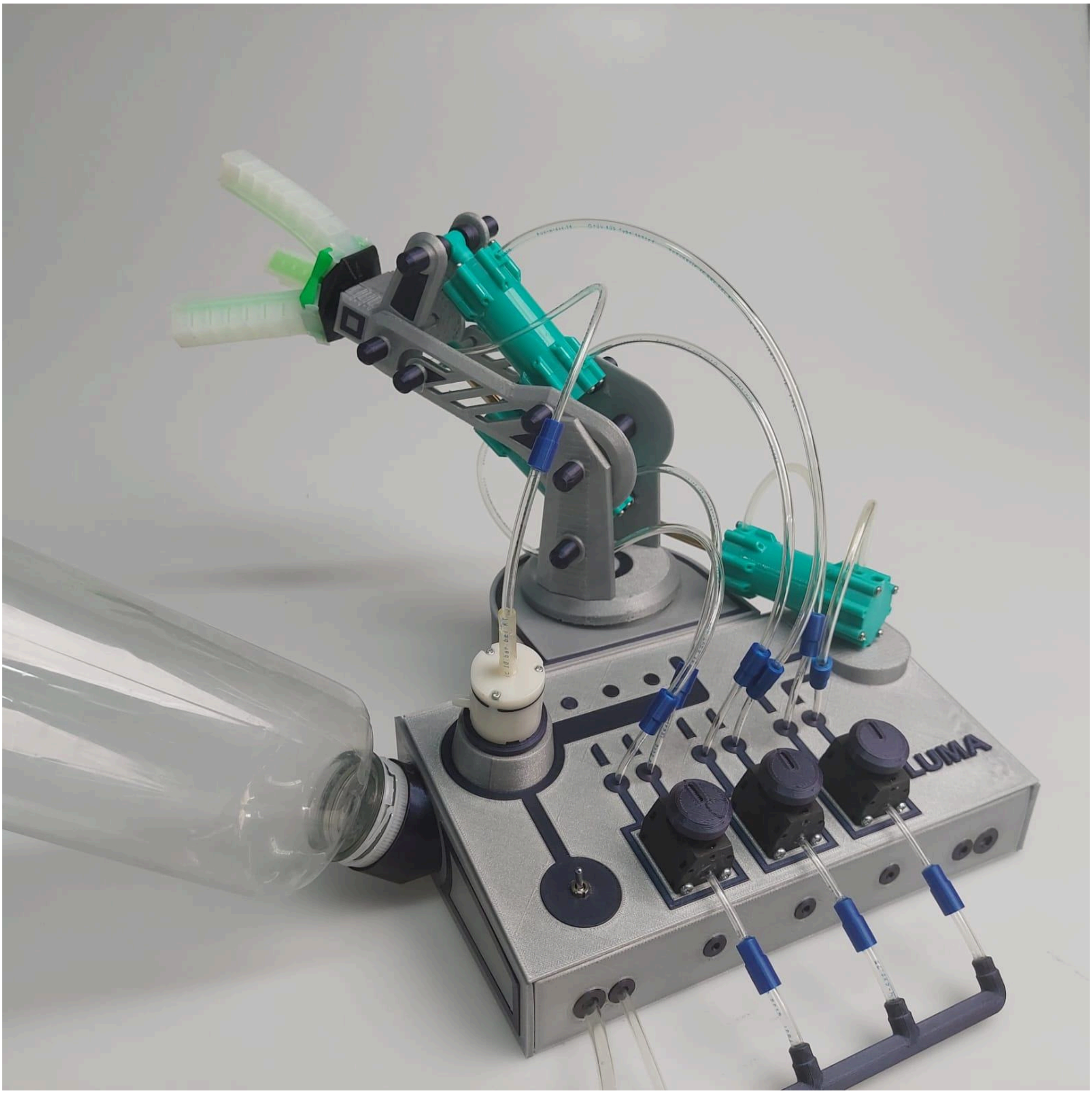
Assembly Guide

Looking good! The last thing we need to do is connect the **valve outputs** to the **cylinder inputs**. The order in which you do this does not really matter that much, as long as you connect the two outputs of **one valve** to the inputs of **one cylinder**. Do not run the outputs of a **valve** to two different **cylinders**.



Assembly Guide

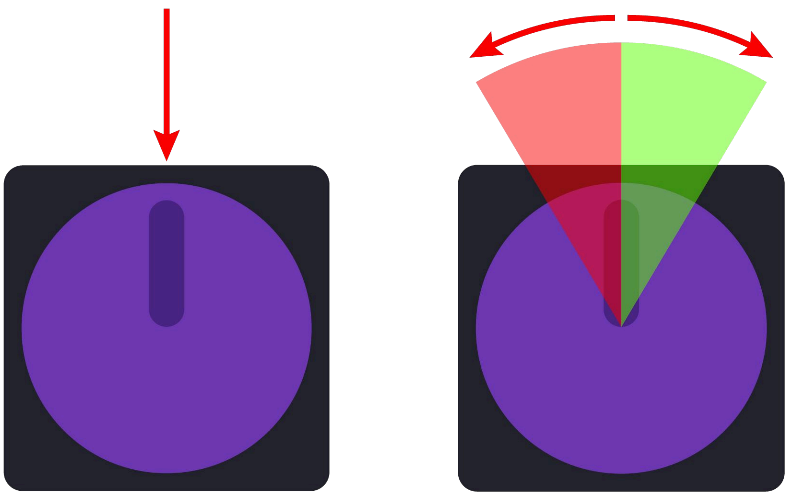
The final product should look something like this. Good job for making it all the way here. Now the final thing to do is actually use it! Check the next page for a small **instruction manual**.



Instruction Manual

Attach the output of the foot pump to the input of the air tank. Start pumping to fill up the tank.

When not using the valves, make sure to keep them in the neutral position, otherwise the valves will leak air. Also, the valves do not need to be turned very far to let air through, so they do not need to be turned all the way down. Small turns left and right is perfect. :)



CHAPTER C: EVALUATION RESULTS

Open questions

Who do you see as the target group for this DIY kit, and why do you think that?

6 antwoorden

Teenagers and above.

People who are somewhat interested in technology/building things, ages from like 8 and anything above that

Kids in like groep 7-8

anyone who is interested in leanring about pneumatics, especially kids, sell on etsy

Elementary or high-school student kids

older children 14+

If this kit was made for you, would you change anything about it? If so, what?

6 antwoorden

The star parts could only include additional information/knowledge about how it works and not instructions.

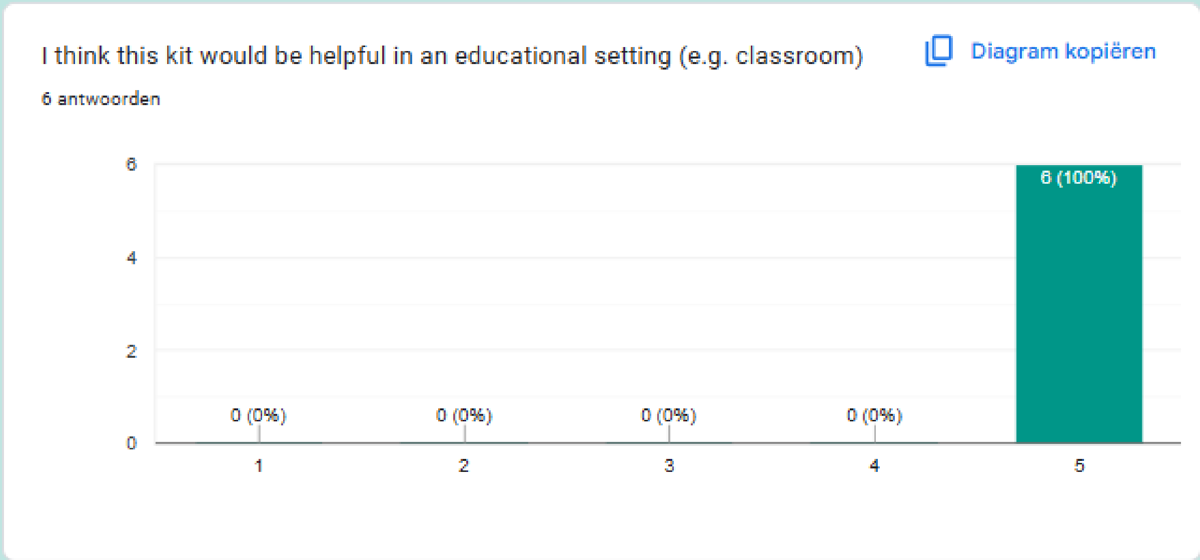
Some pictures were less clear, like of the pistons. So I would make those clearer to know exactly what component to use (especially with similar looking components)

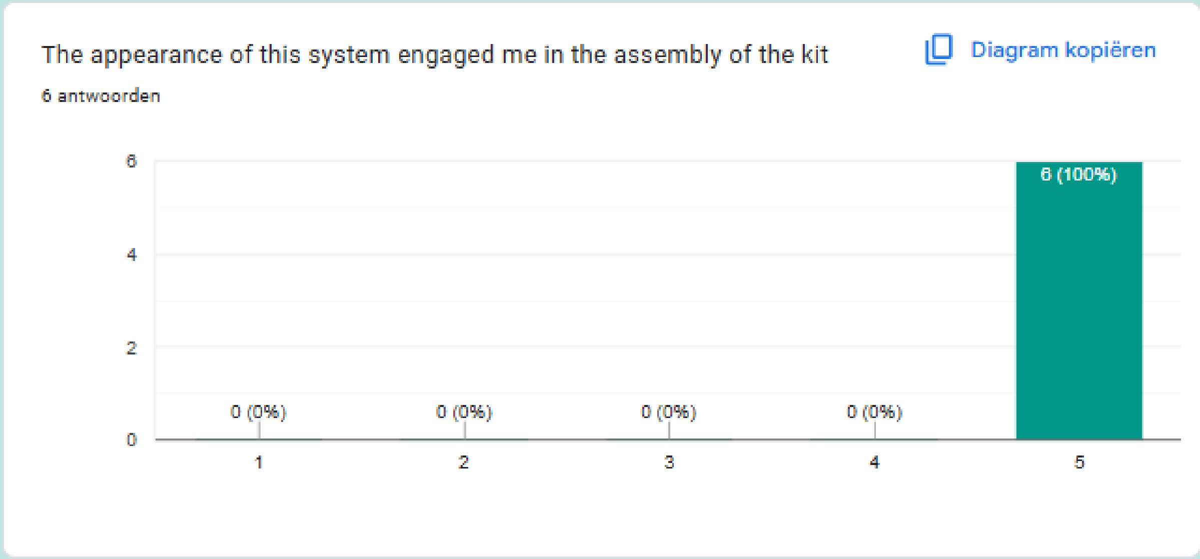
The tubing was hard + some instruction pictures were hard to understand

mak it bigger and also more durable, for example one axis pump kept coming off

The press-fit parts of the components were a bit cumbersome - it might be nice to reiterate or improve upon them

make all the rods the same length, make the swivel have some bearings and use counterweights


I think this kit would be helpful in an educational setting (e.g. classroom)
Diagram kopiëren
6 antwoorden
6
4
2
0
0 (0%)
0 (0%)
0 (0%)
0 (0%)
6 (100%)
1
2
3
4
5

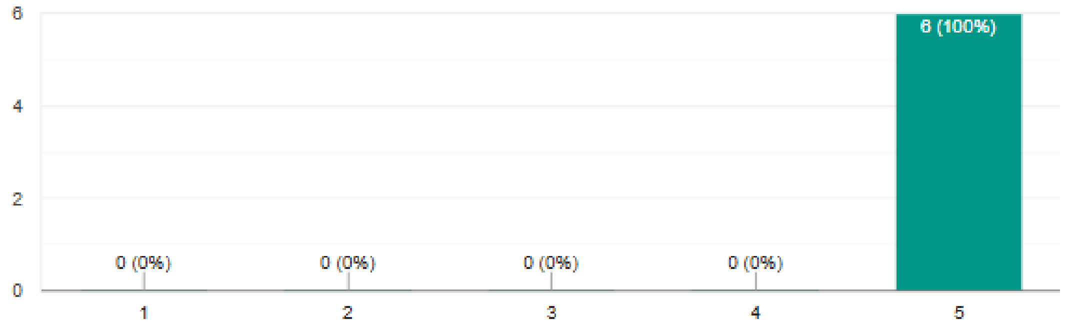

The appearance of this system engaged me in the assembly of the kit
Diagram kopiëren
6 antwoorden
6
4
2
0
0 (0%)
0 (0%)
0 (0%)
0 (0%)
6 (100%)
1
2
3
4
5

Engagement / Enjoyment

I enjoyed building this kit

Diagram kopiëren

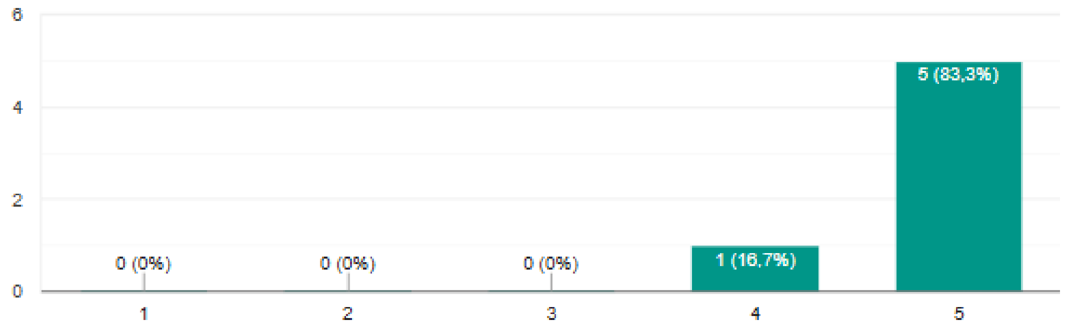
6 antwoorden



I would recommend this kit to others

Diagram kopiëren

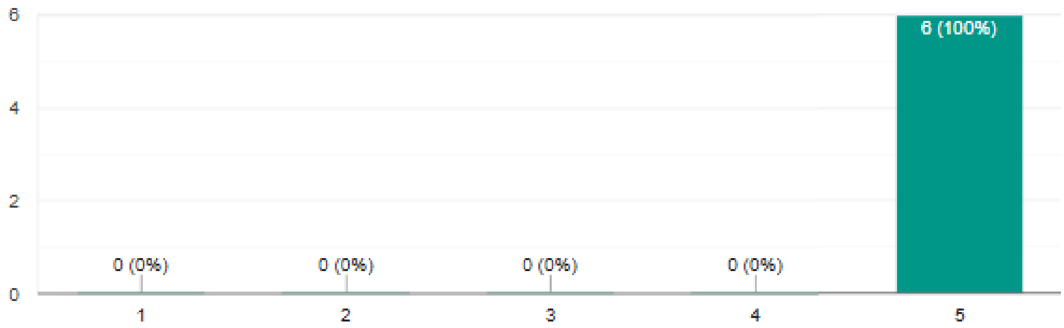
6 antwoorden



I could explain to someone else how this DIY kit works

Diagram kopiëren

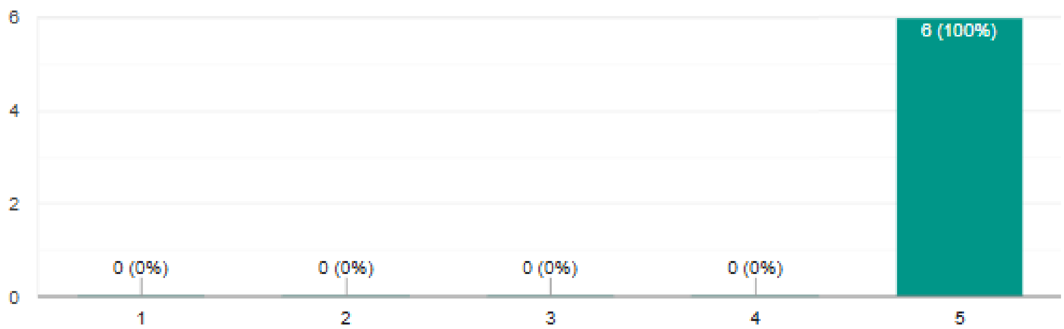
6 antwoorden



This kit makes me want to learn more about soft robotics and pneumatics

Diagram kopiëren

6 antwoorden

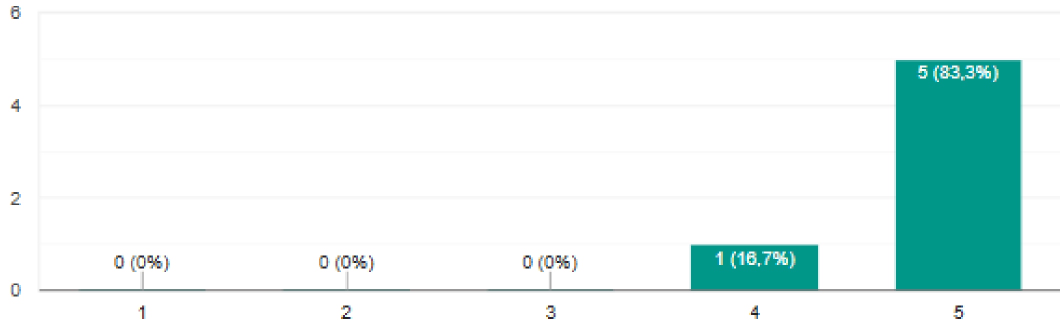


Learning / Educational value

I now understand the basic components of a pneumatic system

Diagram kopiëren

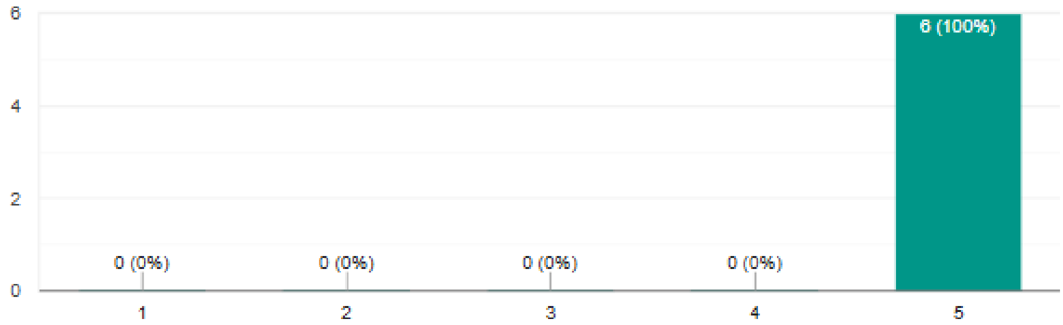
6 antwoorden



I learned something new about soft robotics using this kit

Diagram kopiëren

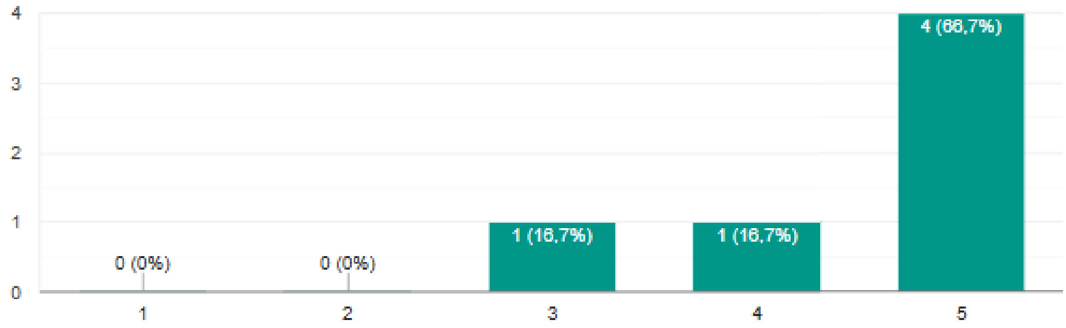
6 antwoorden



The pictures in the instructions helped me during the assembly process

Diagram kopiëren

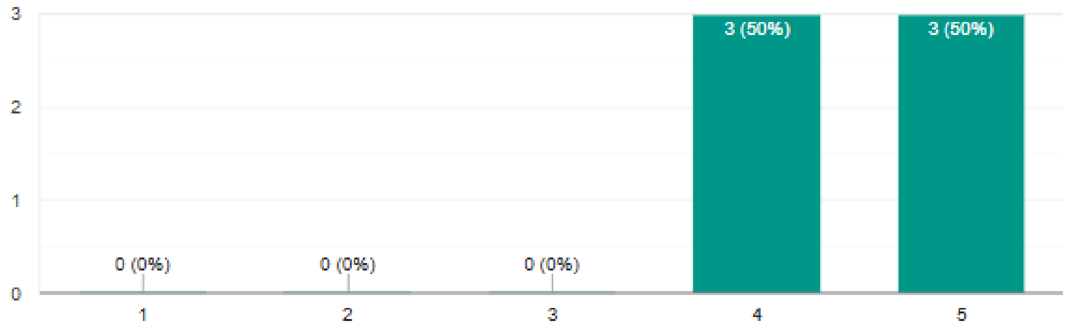
6 antwoorden



I understood what each step was asking me to do

Diagram kopiëren

6 antwoorden

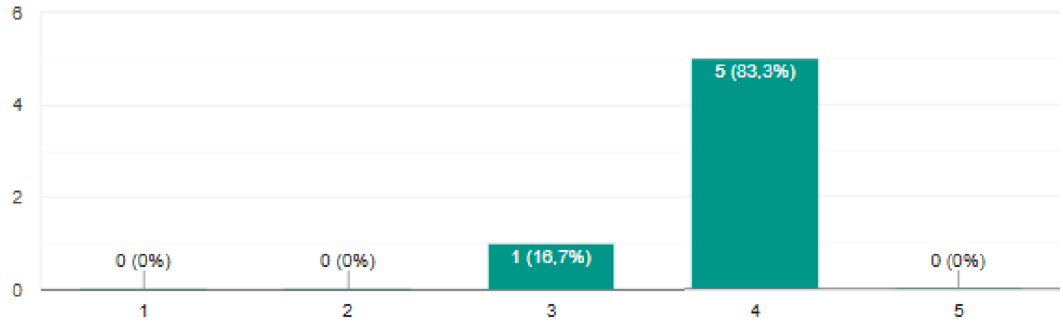


Instructions

The instructions were clear and easy to follow

Diagram kopiëren

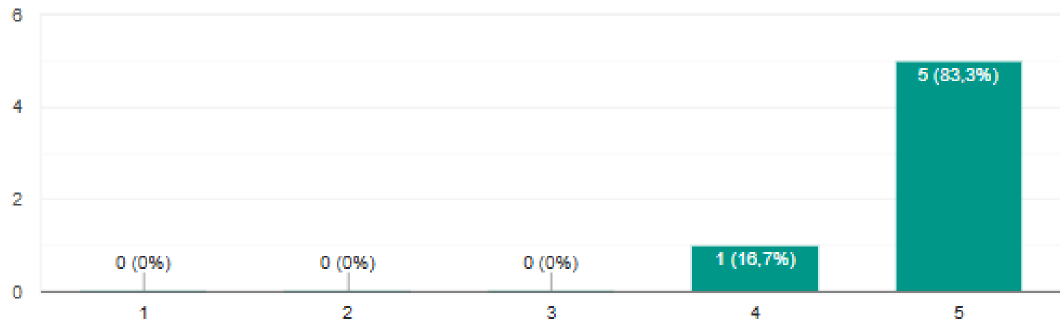
6 antwoorden



The explanations about the different parts of the system helped me understand the system

Diagram kopiëren

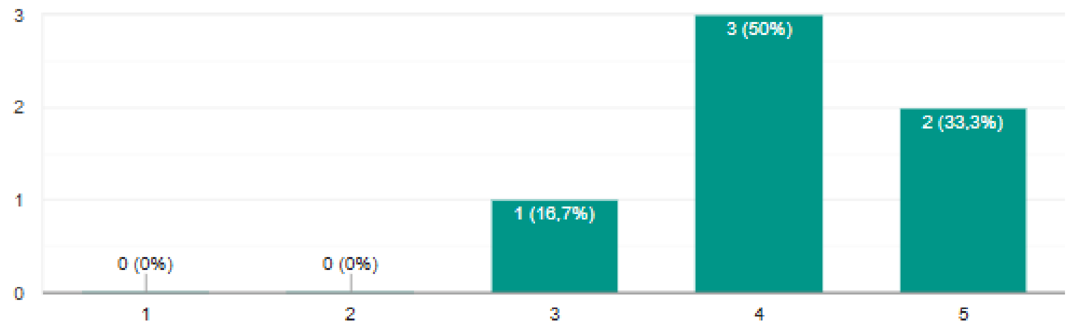
6 antwoorden



The size of the components made them easy to handle

Diagram kopiëren

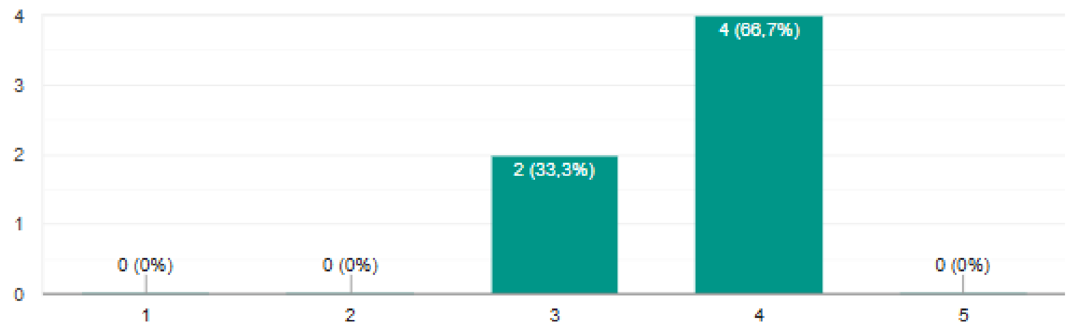
6 antwoorden



The assembly process was straightforward

Diagram kopiëren

6 antwoorden

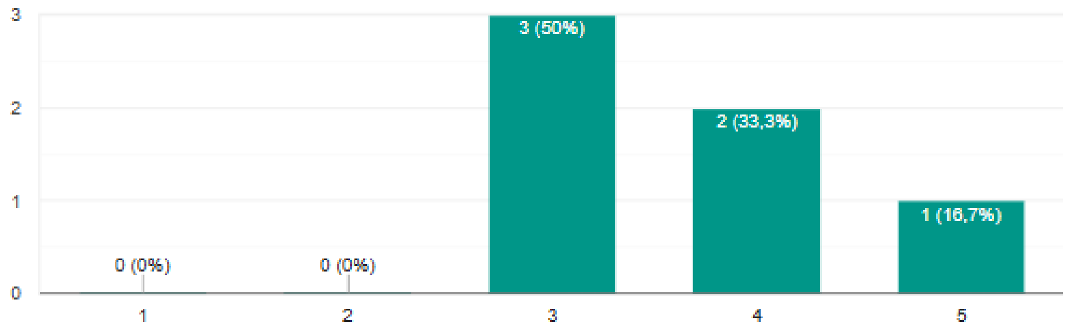


Assembly

I was able to assemble the kit without any external help

Diagram kopiëren

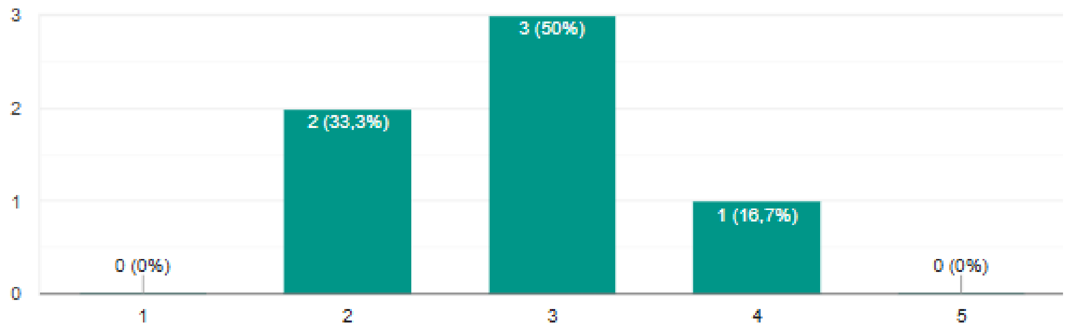
6 antwoorden



Different components of the kit fit together without difficulty

Diagram kopiëren

6 antwoorden



Did you experience any limitations or frustrations?

6 antwoorden

Trying to put the valves sometimes. Numbers on steps would help. "How to connect Tubing" section could go to the first time that it is used part... I thought it was the first step and got confused. I also was confused about the size of the tube. Maybe some parts could be labeled with numbers (cylinders, valves, axis)

Some of the air tubes were hard to insert.

The first part with the fingers was very hard

yes some pieces may fit into wrong places so maybe change colors

1 - the arm was not stable / fell out of the rotating base; 2 - the tubes were sometimes hard to put in the holes; 3 - it was hard to keep all three fingers in place while putting on the clamp

yes it did not rotate without my hands

Do you have any comments or suggestions about the DIY kit as a whole?

6 antwoorden

:)

It brought me back to being a child buildig lego's. Really fun experience. Overall, besides the things I already listed above no comments.

I love the mascot, i would advise to make like a lego guide, and making like drawings of what things you need for each step and the instructions

A few minor tweaks to make the process smoother

I think it is a very cool experience, and I could definitely see this in an lower form school setting, but I did feel like it was a bit "too basic" for university students in my opinion.

Add counter weights, make all the rods the same length, IT IS SUPER COOL KIT

CHAPTER D: INFORMATION LETTER

Graduation Project Evaluation Information Letter

“Integration of Soft Robotics and Pneumatics in an Educational DIY-kit”

This document serves to inform the participant in this research about the contents of this research for them to make an informed decision about the participation in said research.

Purpose of the Research

The goal of this research is to design and evaluate a Do-It-Yourself (DIY) educational kit that teaches some basic principles of soft robotics and pneumatic actuation. By engaging users in hands-on construction, this project aims to improve motivation to learn and understanding of STEM (Science, Technology, Engineering, Mathematics) topics. The kit includes a 3-DOF (degree of freedom) pneumatic robotic manipulator and a soft robotic gripper, alongside a control panel to control the robotic system.

Procedure

As a participant, you will be asked to perform the following tasks.

- Assemble the robotic system using the provided DIY kit and its instruction manual.
- Follow step-by-step instructions and interact with the parts of the kit.
- Fill out a survey to evaluate your experience after completing the kit.

The full evaluation is expected to take approximately 45 to 60 minutes.

Voluntary Participation

Your participation in this study is entirely voluntary. You are free to decline or withdraw at any point without any consequences.

Data Collection and Use

After assembling the kit, you will be asked to complete a survey that measures the following aspects.

- System Usability (based on the System Usability Scale)
- Motivation and interest in STEM learning
- General feedback on the clarity and effectiveness of the kit

All data will be collected anonymously. No personally identifiable information will be stored or shared. The data will only be used for educational and research purposes within the scope of this project. The data from this evaluation will be published in a research paper. Participants may request access to their data and ask to rectify or erase said data.

Potential Risks

There are minimal risks involved. The system is designed to be safe and educational, and the maximum air pressure used (approximately 2 bar) is considered low in the context of this prototype. To ensure safe conduct, do not direct any air stream towards your face and make sure pneumatic tubing is secured. Also, do not use excessive force when using the foot pump, as this might put too much pressure on the system.

Contact Information
If you have any questions or concerns regarding the study, your participation, or use of data, please feel free to contact:
Researcher: Max Vroomans
Email: m.t.m.vroomans@student.utwente.nl

To file any complaint you might have, contact:
Ethics Committee Computer and Information Science: ethicscommittee-cis@utwente.nl

CHAPTER E: CONSENT FORM

Consent Form for Graduation Project: *"Integration of Soft Robotics and Pneumatics in an Educational DIY-kit"*

Please tick the appropriate boxes	**Yes**	**No**
Taking part in the study		
I have read and understood the study information dated ___/___/_____, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	○	○
I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	○	○
I understand that taking part in the study involves completing a survey questionnaire after using the DIY robotic manipulator kit. The responses will be recorded digitally through an online or paper-based questionnaire, filled out directly by the participant. No audio or video recordings will be made. The data collected will be anonymous and used solely for research and educational purposes. No personally identifiable information will be stored, and the data will not be shared with third parties.	○	○
Risks associated with participating in the study		
I understand that there are minimal risks associated with this study. Possible risks may include mild physical discomfort from assembling the DIY kit (minor strain from using hands or small tools), or brief frustration if instructions are unclear or components do not function as expected. There is no collection of personally identifiable information, so there is no risk of identity disclosure.	○	○
Use of the information in the study		
I understand that information I provide will be used for the purpose of evaluating the usability and educational value of the DIY soft robotics kit. The results will be used in a university graduation project report and may also contribute to academic presentations or publications. All data will be anonymized, and no personal information will be disclosed or shared publicly.	○	○
I understand that personal information collected about me that can identify me, such as [e.g. my name or where I live], will not be shared beyond the study team.	○	○
Future use and reuse of the information by others		
I give permission for the anonymized survey questionnaire results that I provide to be archived in Google Forms so it can be used for future research and learning.	○	○

Signatures

______________________ ______________________ ________

Name of participant Signature Date

I have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

_________________________ ___________________ ________

Max Vroomans Signature Date

Study contact details for further information:

Max Vroomans

Email: m.t.m.vroomans@student.utwente.nl

Contact Information for Questions about Your Rights as a Research Participant

If you have questions about your rights as a research participant, or wish to obtain information, ask questions, or discuss any concerns about this study with someone other than the researcher(s), please contact the Secretary of the Ethics Committee Information & Computer Science: ethicscommittee-CIS@utwente.nl